International Journal of Concrete Structures and Materials
Vol.18, No.1E, pp.63~70, June 2006

Alkali-Silica Reaction of Crushed Stones

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(Originally published in Korean version of ***Journal of KCI***, Vol.17, No.1, February 2005)

Abstract: This study tested the alkali-silica reactivity of various types of crushed stones, following the specifications of ASTM C 227 and C 1260, and the results obtained from the tests were compared. This study also analyzed the effects of particle size and grading of reactive aggregate based on the expansion of mortar-bar due to an alkali-silica. The effect of mineral admixtures to reduce the detrimental expansion caused by the alkali-silica reaction was investigated based on the method specified by ASTM C 1260. The mineral admixtures used in this study were fly ash, silica fume, metakaolin and ground granulated blast furnace slag. The replacement ratios of 0, 5, 10, 15, 25 and 35% were uniformly applied to all the mineral admixtures, and the replacement ratios of 45 and 55% were additionally applied for the admixtures that could sustain the workability at these ratios. The results indicate that replacement ratios of 25% for fly ash, 10% for silica fume, 25% for metakaolin and 35% for ground granulated blast furnace slag were the most effective in reducing the expansion due to the alkali-silica reaction under the experimental conditions of this study.

Keywords: crushed stone, alkali-silica reaction, fly ash, silica fume, metakaolin, ground granulated blast furnace slag.

1. Introduction

Since the first report on the damage to the concrete structures due to an alkali-silica reaction (ASR) by T.E. Stanton in 1940, copious cases of damage have been reported in many countries. However, the damages have never been reported in Korea, except for one kind of domestic crushed stone, which was classified as deleterious in 1992[1]. Reflecting the domestic situation of having insufficient amount of natural aggregates and increasing needs for crushed stones, it is necessary to examine the alkali-silica reaction of the crushed stones. The alkali-silica reaction generally forms reactive products that can cause excessive expansion and cracking or popouts in concrete. There are several test methods to identify alkali reactivity of aggregates. In general, crushed stones are tested by a petrographic examination, a chemical method, and a mortar-bar method. The most reliable method is mortar-bar test, but it takes 3 to 6 months for the complete test. This study tested alkali-silica reactivity of different types of crushed stones in the form of granitic, volcanic, metamorphic and sedimentary rocks. Samples were collected from twelve local aggregate manufacturing companies in Korea. Alkali-reactivity of various rock types was evaluated using ASTM C 227[2] and C 1260[3], and the test results of the two test methods were compared. This study also analyzed the effects of particle size and grading of reactive aggregate expansion due to an alkali-silica reaction in a mortar-bar test. Pozzolan materials such as silica fume[4], fly ash[5] and ground granulated blast furnace slag[6] have been used to improve the quality of concrete and cement mortar. These materials are mineral admixtures that play important roles according to their chemical and physical characteristics. Kaolin[7-9] as a new pozzolan material of cement admixture, a kind of clay material, is well known as a raw material for pottery, which is widely scattered around the world (especially in Korea). Mineral admixtures (pozzolan materials such as silica fume, fly ash, ground granulated blast furnace slag and metakaolin) have numerous effects. Among all these effects, only the reduction of excessive expansion caused by alkali-silica reaction was investigated in this study.

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2. Experimental program

2.1 Materials

Cement - Ordinary Portland cement manufactured in Korea was used in this experiment. The chemical composition of the cement is given in Table 1. The cement contains an alkali content of 0.75% as equivalent Na_2O ($Na_2O_{eq} = 0.658\ K_2O + Na_2O$).[10] Thus, it is classified as "high alkali cement."

Aggregates - Crushed granitic, volcanic, metamorphic and sedimentary rocks collected from ten local aggregate manufacturers and used in this experiment are tabulated in Table 2. Recycled aggregate[11] and natural sand commonly used in Busan and Kyongsang-Namdo area were tested and compared with other crushed sands. The recycled aggregate used in the experiment was derived from Deokcheon second bridge (reinforced concrete slab bridge), which was demolished in 1998.

Mineral admixtures - Metakaolin (MK) obtained by calcining

Table 1 Chemical composition of cement (%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
20.5	6.0	3.1	61.6	3.2	2.1	0.95	0.12

Table 2 Rock types and collection location of the aggregates used in this study.

Aggr. No.	Location of sampling aggregate	Rock types
1	Buk-Gu, Busan	Recycled aggregate
2	Buk-Gu, Busan	Natural sand
3	Ulju-Gun, Ulsan	Sedimentary rock
4	Jinhae, Kyungnam	Altered volcanic rock
5	Kimhae, Kyungnam	Granitic rock
6	Kimhae, Kyungnam	Granitic rock
7	Kimhae, Kyungnam	Volcanic rock
8	Kimhae, Kyungnam	Granitic and andestic rock
9	Masan, Kyungnam	Metamorphic rock
10	Buk-Gu, Ulsan	Volcanic rock
11	Buk-Gu, Ulsan	Volcanic rock
12	Bonghwa, Kyungbuk	Metamorphic rock

kaolin at a domestic company in Hadong & Sancheong area was used in this study. Ground granulated blast furnace slag (GGBFS) produced from an iron foundry in Gwang Yang, Korea, was used. Silica fume (SF) of densified dry powder, that was imported from abroad, was also selected. Finally, fly ash (FA) obtained from the silos at a thermal power plant in Dangjin, Korea, was used. It has been classified into low-calcium Class F fly ash. The chemical compositions of mineral admixtures are presented in Table 3.

2.2 Testing method

2.2.1 Physical property test of aggregates

The tests in accordance with the KS F 2504 (testing method for density and absorption of fine aggregate), KS F 2505 (testing method for bulk density of aggregate), and KS F 2511 (testing method for amount of material finer than 0.08 mm (0.003 in.) sieve in aggregate) were carried out to investigate the physical property of aggregates.

2.2.2 Mortar-bar test

Mortar-bar test method specified by ASTM C 227 The mortar-bar test method by ASTM C 227 is used to determine the potentially expansive alkali-silica reactivity of cement-aggregate combinations by measurement of the increase (or decrease) in length of the mortar bars. Cement-aggregate combinations having a mean mortar-bar expansion of more than 0.1% at six months are considered deleterious. In case that the results for six months are not available, combinations of mean mortar-bar expansion of more than 0.05% at three months are considered as to assess the potentially deleterious alkali-silica reactivity. Proportioning of mortar-bar is 1 part of cement to 2.25 parts of graded aggregate by mass and uses the necessary amount of mixing water to produce a flow of 105 to 120. Specimens were cast in 25×25×300 mm (1×1×12 in.). The samples were placed in a moist cabinet maintained at a temperature of 38±2°C and relative humidity (RH) of more than 95%. The test specimens were measured after 14 days and then every month for a period of 1 year. Measurements were continuously taken at 15 months, 18 months and 24 months even after 1 year. In each case, three specimens were tested, and their average length change was recorded.

Mortar-bar test method specified by ASTM C 1260 - The mortar-bar test based on ASTM C 1260 is a method for predicting the alkali-silica reaction through the assessment of expansion of mortar bars after soaking in sodium hydroxide solution for 14 days. Aggregates having a mean mortar-bar expansion of 0.10% or less at 16 days after casting (at 14 days after the zero reading) are considered harmless. Expansion of more than 0.20% is an indicative of reactive aggregates. Between 0.10% and 0.20%, the aggregates may be potentially reactive; they might exhibit either innocuous or deleterious behavior in the field performance. Mortar bars were cast with a graded aggregate-cement ratio of 2.25 and a water-cement ratio of 0.47. Mortar-bar specimens were cast in a mold of 25×25×300 mm (1×1×12 in.) in size. Immediately after casting, the test specimens were stored for 24 hours in a room at the temperature of 23°C. Then, the specimens were removed from the molds, and the initial length was measured. After the initial reading, they were immersed in water in a closed container, while the temperature was maintained at 80°C for a period of 24 hours. Then, the length of the specimens was measured. This is the zero reading. Then, the test specimens were immersed in a closed container of 1N sodium hydroxide solution maintained at 80°C. The length change of mortar-bar was measured at 3, 6, 9, 12 and 14 days after the zero reading. After the 14 days period as recommended by ASTM C 1260 procedure, measurements up to 42 days at an interval of 7 days were taken at approximately the same time each day in this study.

2.2.3 Effects of particle size and grading of reactive aggregate on alkali-silica reaction

This study analyzed the effects of particle size and reactive aggregate grading on expansion of mortar-bar due to an alkali-silica reaction. Reactive aggregate used in this experiment was a metamorphic rock.

The aggregates used in this experiment were analyzed using the sieve analysis in accordance with the regulations of ASTM C 1260. The aggregates of singular particle size were retained through the No.8 (2.5 mm (0.1 in.)), No.16 (1.2 mm (0.05 in.)), No.30 (0.6 mm (0.02 in.)), No.50 (0.3 mm (0.01 in.)) and No.100 (0.15 mm (0.006 in.)) sieves. And, aggregates of particle size retained through the No.16 (1.2 mm (0.05 in.)) and No.100 (0.15 mm (0.006 in.)) sieves were mixed at the ratios of 0.85 : 0.15, 0.55 : 0.45 and 0.30 : 0.70, respectively. Aggregates that were made by recombining the portions retained through the 2.5~0.15 mm (0.1~0.006 in.) sieves at

Table 3 Chemical composition of admixtures (%).

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	LOI
MK	51.7	40.312	1.825	0.486	3.314	0.992	0.469	0.02	0.003	2.612
GGBFS	33.439	14.932	0.098	5.68	43.249	0.195	0.295	0.215	0.014	0.325
FA	51.832	26.275	7.429	1.082	6.512	0.491	1.079	0.149	0.721	3.844
SF	94.296	0.141	0.36	0.913	0.108	0.311	1.632	0.263	0.119	1.214

Table 4 Proportions of aggregate mixing.

Retained through \ Case	Mass (%) 1	2	3	4
No.8 (2.5 mm (0.1 in.))	5	10	5	5
No.16 (1.2 mm (0.05 in.))	35	25	5	5
No.30 (0.6 mm (0.02 in.))	45	25	55	45
No.50 (0.3 mm (0.01 in.))	10	25	20	15
No.100 (0.15 mm (0.006 in.))	5	15	15	30
Fineness modulus	3.25	3.10	2.65	2.40

the grading as prescribed in Table 4 were tested by the aggregate mixing. Mortar bars used for this test were prepared in accordance with ASTM C 1260 and immersed in 0.5 N, 1 N and 2 N NaOH solutions, respectively, kept at 80°C. Then, the change in the length of the specimens was measured at 14 days of aging.

2.2.4 The effect of mineral admixtures replacement on alkali-silica reaction

The replacement proportions of Portland cement by mineral admixture (SF, FA, GGBFS, MK) were 0, 5, 10, 15, 25 and 35%, respectively. And the replacement ratios of 45 and 55% were additionally applied for the admixtures that could maintain the workability. The mixing proportions of mortars are presented in Table 5. Three specimens were prepared in accordance with each replacement ratio. Following the procedure specified by ASTM C 1260, the length change of mortar bars was measured at 3, 6, 9, 12 and 14 days after the zero reading.

3. Experimental results and discussion

3.1 Physical property of aggregate

Most of the crushed stones used in this study had a density between 2.5 gf/cm^3 (156 pcf) and 2.6 gf/cm^3 (162 pcf). At the same time, aggregate 1 (recycled aggregate), 5 (granitic rock) and 7 (volcanic rock) had a density that was lower than other aggregates and absorption, that was three times higher than the others as shown in Fig. 1 and 2. Even though aggregate 5 and 6 was consisted of the same kind of rock (granite), they had different density and absorption from each other. This difference is construed to result from the fact that the physical properties of aggregates are affected by the mineral composition, grain size, weathered condition, etc., because aggregate 5 was granite that was subjected to heavy weathering. The recycled aggregate (aggregate 1) and crushed stones (aggregate

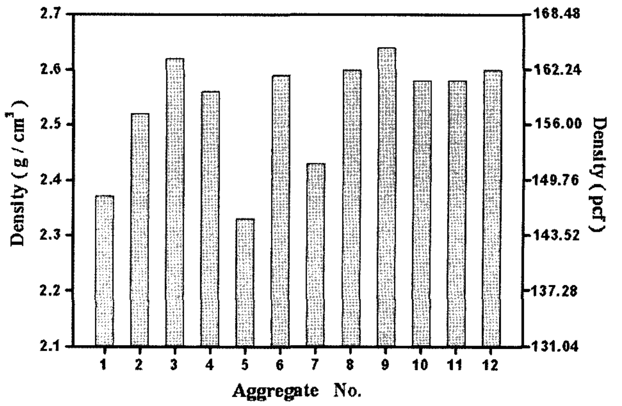

Fig. 1 Density of aggregates.

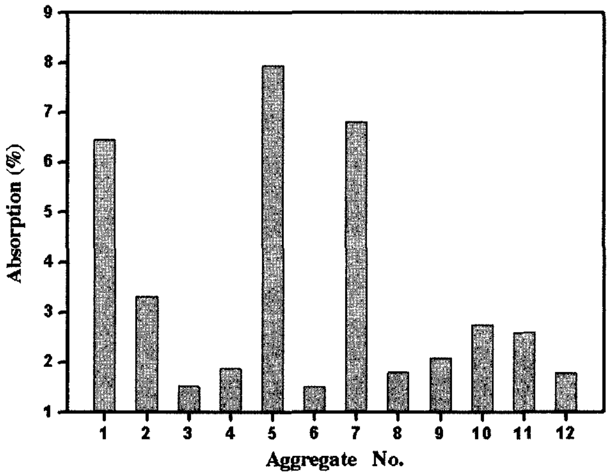

Fig. 2 Absorption of aggregates.

3~12) used in this test had the bulk density, which was higher than that of natural sand (aggregate 2), as shown in Fig. 3. It is necessary to examine the difference in the amounts of material finer than 0.08 mm (0.003 in.) contained in natural sand and crushed stone because of numerous micro particles that are present in crushed stone. Micro particle can be produced by the impact from the crushing process. As shown in Fig. 4, the amount of micro particles contained in aggregate 3 (sedimentary rock), 4 (altered volcanic rock), 5 (granitic rock) and 6 (granitic rock) were similar to that of aggregate 2 (natural sand). The other aggregates had the particles finer than 0.08 mm (0.003 in.) sieve in the amount that was four to five times greater than the natural sand (aggregate 2). Particularly,

Table 5 Mixing of mortars.

Admixture replacement ratio by the mass (%)	W/C	Unit weight, g (lb) Water	Cement	Admixture	Fine aggregate
0	0.47	206.8 (0.456)	440 (0.970)	-	990 (2.183)
5	0.47	206.8 (0.456)	418 (0.922)	22 (0.040)	990 (2.183)
10	0.47	206.8 (0.456)	396 (0.873)	44 (0.097)	990 (2.183)
15	0.47	206.8 (0.456)	374 (0.825)	66 (0.146)	990 (2.183)
25	0.47	206.8 (0.456)	330 (0.728)	110 (0.243)	990 (2.183)
35	0.47	206.8 (0.456)	286 (0.631)	154 (0.34)	990 (2.183)
45	0.47	206.8 (0.456)	242 (0.534)	198 (0.437)	990 (2.183)
55	0.47	206.8 (0.456)	198 (0.437)	242 (0.534)	990 (2.183)

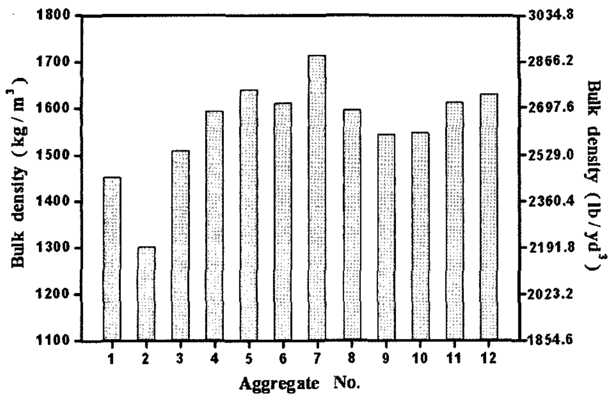

Fig. 3 Bulk density of aggregates.

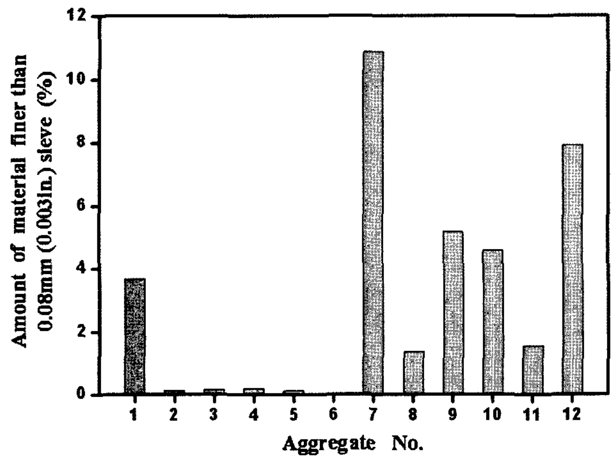

Fig. 4 Amount of fine materials retained through 0.08 mm (0.003in.) sieve.

aggregate 7 (volcanic rock) and 12 (metamorphic rock) showed a difference of almost tenfold. In the case of the aggregate 1 (recycled aggregate), this might be due to the cement paste contained in the recycled aggregate. It is deemed that crushed stones exhibited this difference due to problems in the process rather than physical property.

3.2 Mortar-bar test result

Mortar-bar test results in accordance with ASTM C 227 as depicted in Figs. 6, 8 and 10 showed that all the aggregates did not exhibit expansion of more than 0.1% at six months. Therefore, they are deemed innocuous in accordance with the regulation of ASTM C 227. The length change of mortar-bar was also measured for over 24 months in order to examine the slow-reacting aggregate. The result shows that the expansion of all the aggregates did not exceed 0.05% after 24 months (Figs. 6, 8 and 10). In this study, borosilicate glass of Mo-Sci Corporation ensured of alkali-silica reaction by IOWA Department of Transportation was tested as the standard material to examine whether the use of ASTM C 1260 method was appropriate. The result plotted in Fig. 5 shows expansions of more than 0.25% at 14 days after the zero reading. The results of mortar-bar test in accordance with ASTM C 1260 are shown in Figs. 7, 9 and 11. As shown in Figs. 7 and 11, aggregate 3 (sedimentary rock) and 9 (metamorphic rock) show expansion of more than 0.2% at 14 days. Therefore, they are estimated as reactive aggregate in accordance with the regulation of ASTM C 1260. The length change of mortar-bar was also measured four more times up to 42 days after the normal 14 days period of testing. The results of length change indicated that aggregate 3 (sedimentary rock) and 9 (metamorphic rock) should be identified as reactive aggregate, which showed an expansion of more than 0.3% at 42 days. As shown in Fig. 12, cracks in the shape of a turtle's back broke out irregularly. Following the test procedure specified by ASTM C 1260, sedimentary and metamorphic rocks showed higher expansion than granitic rock, and it was construed that these expansions were related to crystallinity of constituent minerals. A secondary mineral of fine-granule that has a low crystallinity is contained in sedimentary and metamorphic rock by cementation. Thus, the result indicates that these minerals, that have a low crystallinity, are chemically unstable. The expansions of aggregate 4 (altered volcanic rock) and 10 (volcanic rock) were below 0.1% at 14 days after the zero reading but exceeded 0.1% at 42 days whereas aggregate 5~8 (Fig. 9) showed expansion of less than 0.5% at 42 days. Moreover, in the case of aggregate 5~8, even though the test period was extended to 42 days, no change in the expansion rate was observed. Expansion of aggregate 4 (altered volcanic rock) and 10 (volcanic rock) was close to the potential reactivity level and increased continually in contrast to that of aggregate 5~8 as shown in Figs. 7 and 11. Therefore, these aggregates may be potentially expansive. Even for the aggregates deemed to be innocuous in accordance with the regulation prescribed in ASTM C 227, its expansion was to be considered excessive if the expan-

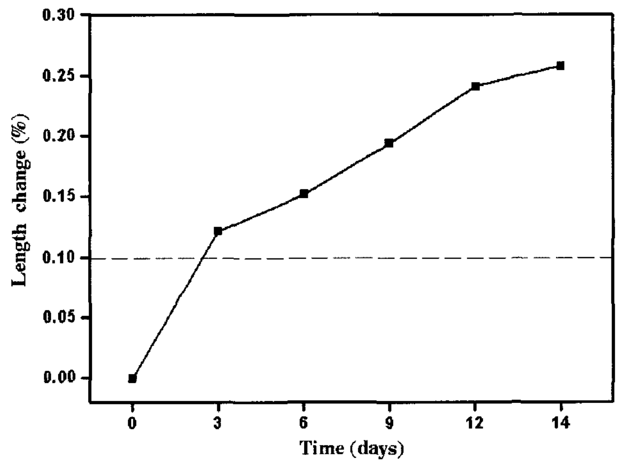

Fig. 5 Length change of mortar-bar containing borosilicate glass.

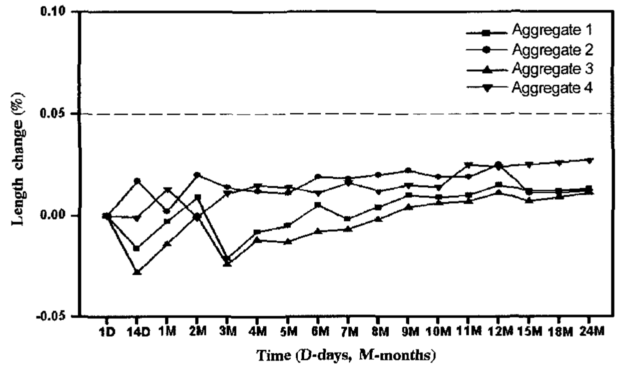

Fig. 6 Expansion of mortar bars according to ASTM C 227 (Aggregates 1~4).

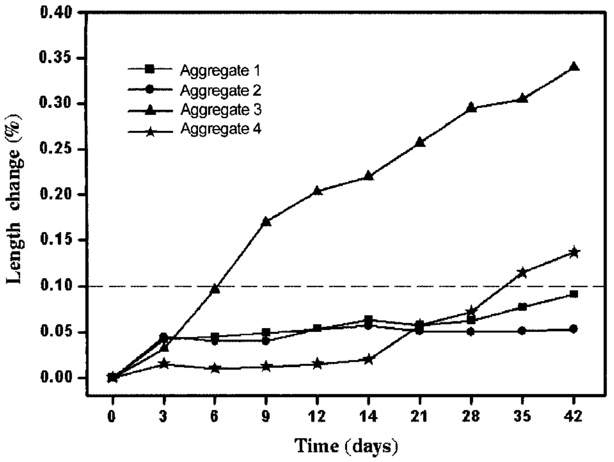

Fig. 7 Expansion of mortar bars according to ASTM C 1260 (Aggregates 1~4).

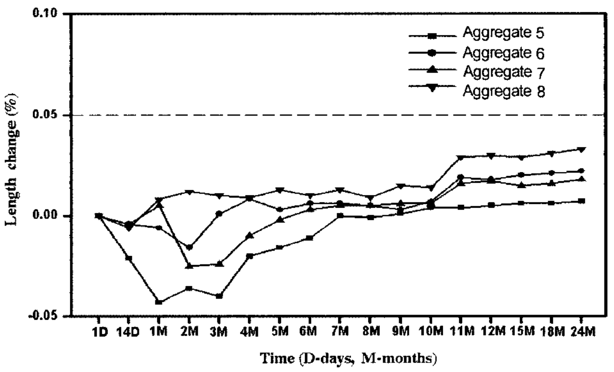

Fig. 8 Expansion of mortar bars according to ASTM C 227 (Aggregates 5~8).

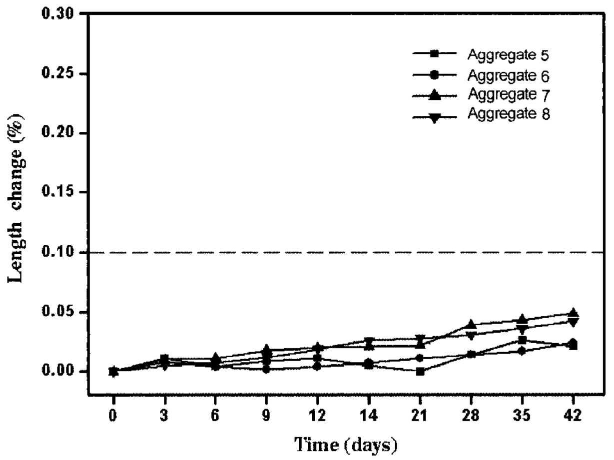

Fig. 9 Expansion of mortar bars according to ASTM C 1260 (Aggregates 5~8).

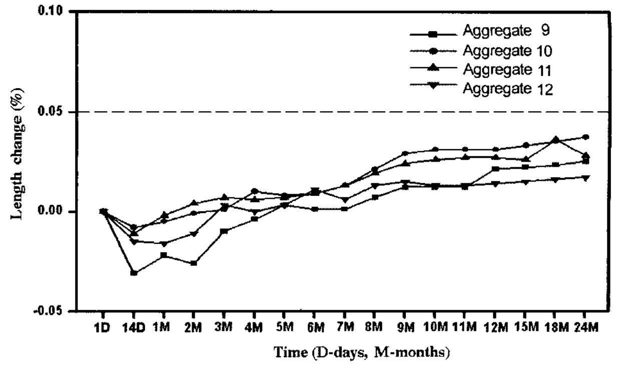

Fig. 10 Expansion of mortar bars according to ASTM C 227 (Aggregates 9~12).

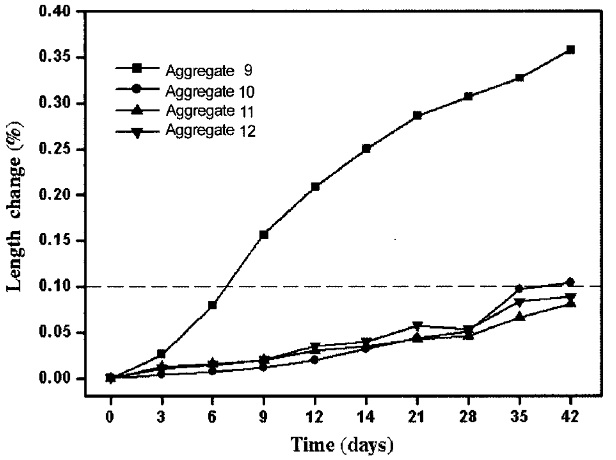

Fig. 11 Expansion of mortar bars according to ASTM C 1260 (Aggregates 9~12).

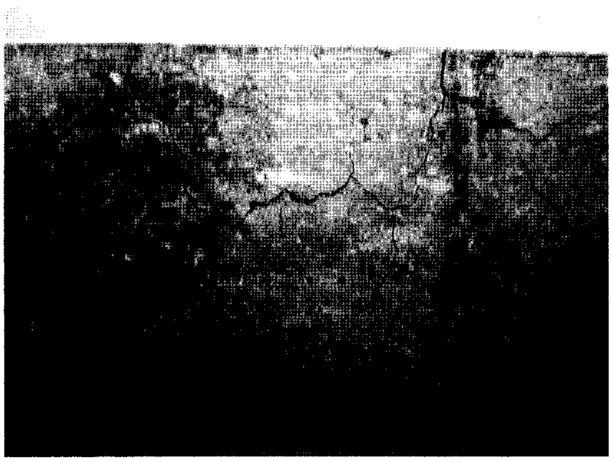

Fig. 12 Cracks caused by the alkali-silica reaction of the crushed stone used in the experiment.

sion exceeded 0.05% at three months or 0.1% at six months. Therefore, ASTM C 1260 method is useful in identifying slowly reacting aggregates as well as finding reactive aggregate within a short period of time. In addition, the experimental results of following the procedures of both methods indicate that, if concrete structure is exposed to an environment that adds alkali, alkali-silica reaction could be more prone to occur. Therefore, ASTM C 1260 method is recommended as the method of choice in testing for alkali-silica reaction of crushed stones as tested in this environment.

3.3 Effects of particle size and reactive aggregate grading on alkali-silica reaction

As depicted in Fig. 13, the expansion rate of mortar-bar increased with an increase in the concentration of NaOH solution for each particle size. Expansion rate of mortar-bar with respect to proportions of aggregate mixing retained through the No.16

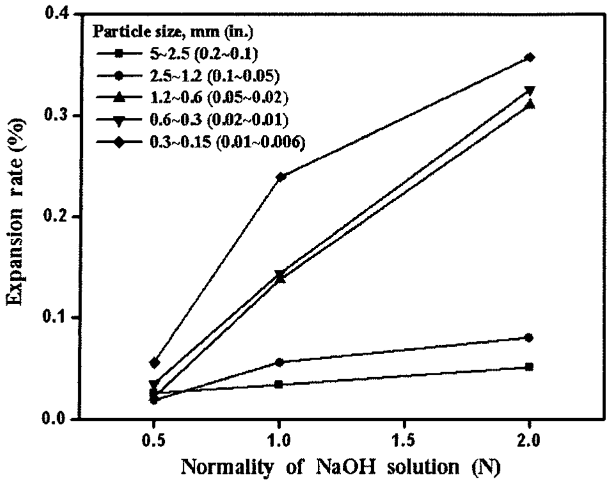

Fig. 13 Relationship between concentration of NaOH solution and expansion rate.

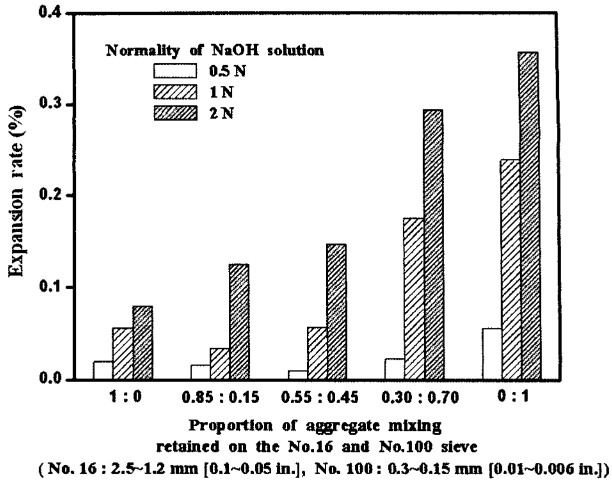

Fig. 14 Relationship between proportions of aggregate mixing retained through the No.16 and No.100 sieves and expansion rate.

(1.2 mm (0.05 in.)) and No.100 (0.15 mm (0.006 in.)) sieve is plotted in Fig. 14. Expansion rate increased with an increase in the proportion of aggregate blending retained through the No. 100 sieve (0.3~0.15 mm (0.01~0.006 in.)) for mortar bars immersed in 0.5 N, 1 N and 2 N NaOH solution. Also, length change increased with an increase in the concentration of NaOH solution for each proportion. As shown in Fig. 15, the expansion rate increased with a decrease in the fineness modulus of the reactive aggregate for each concentration of NaOH solution. These results indicate the following-the smaller particle size of reactive aggregate or the smaller fineness modulus, the more expansion of the aggregate by the alkali-silica reaction due to an increase in the surface area of the aggregate. Also, as the concentration of the alkali solution gets higher, the more alkali-silica reaction occurs.

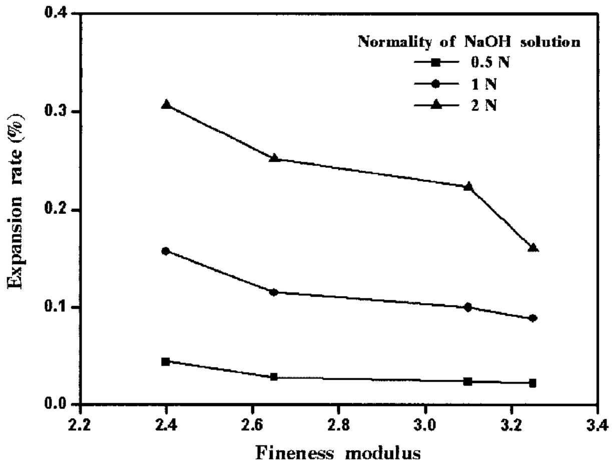

Fig. 15 Relationship between fineness modulus and expansion rate.

3.4 Effect of mineral admixtures replacement on alkali-silica reaction

The length change of mortar bars in response to various replacement ratios of mineral admixtures (FA, SF, MK and GGBFS) is plotted in Figs. 16~19. The reactive aggregate used in this study showed that physical effects of mineral admixture on alkali-silica reaction differed according to the level of replacement. The mortar-bar containing 5% replacement of cement by MK showed an expansion in excess of 0.2% at 14 days after the zero reading. The expansion can be distinguished whether it is deleterious or potentially reactive based on the judgment criterion. 5% MK cement replacement induced alkali-silica reaction rather than mitigating it. 35% GGBFS cement replacement resulted in the length change similar to 10% FA, 10% SF and 15% MK replacement for the cement (Figs. 16~19). In the case of mortar bars containing respectively 5% FA, 5% SF, 15% GGBFS and 10% MK, expansion exceeded 0.1% of 14 days at 10 days. This result shows that the use of these replacement ratios is not sufficient to control the alkali-silica reaction. As depicted in Fig. 16, 25% FA cement replacement resulted in the expansion similar to the expansion of 35% and 45% FA replacement. Thus, 25% FA cement replacement seems to be effective in controlling the moderately reactive aggregate used in this study. SF replacement in the amount greater than 10% showed the effect of mitigating an alkali-silica reaction. Also, as shown in Fig. 17, 10% SF cement replacement reduced the expansion to a level close to that of 15% and 25% SF replacement. This result was also presented by Malvar (2002).[12] This cause is definitely being examined in the present test result (The result of this study concurs with the previous report). On reactive aggregate used in the study, 10% SF cement replacement reduced the ASTM C 1260 expansion from more than 0.2% (As for the reactive aggregate used in this study, the replacement of cement by SF in the amount of 10% of the mass reduced the expansion to below 0.2%, the standard specified by ASTM C 1260). The expansion by the alkali-silica reaction was mitigated effectively as MK replaced the cement in the amount greater than 15%. A 25% MK cement replacement resulted in the length change similar to that of a 35% MK replacement (Fig. 18). Thus, it was found that the optimal cement replacement ratio by MK was 25% in consideration of the length change with aging. As shown in Fig. 19, 55% GGBFS cement replacement exhibited the lowest expansion, but 35% GGBFS cement replacement resulted in reducing the expansion to a level close to that of 10% SF cement replacement. This result indicates that the optimal ratio for the cement replacement by GGBFS is 35% for the reactive aggregate used in this study. It is construed that the inhibition of the concrete expansion due to an alkali-silica reaction by admixing

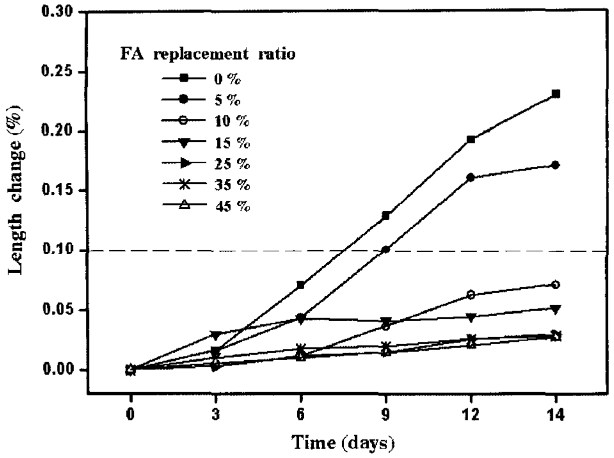

Fig. 16 Expansion of mortar bars according to various replacement ratios of fly ash.

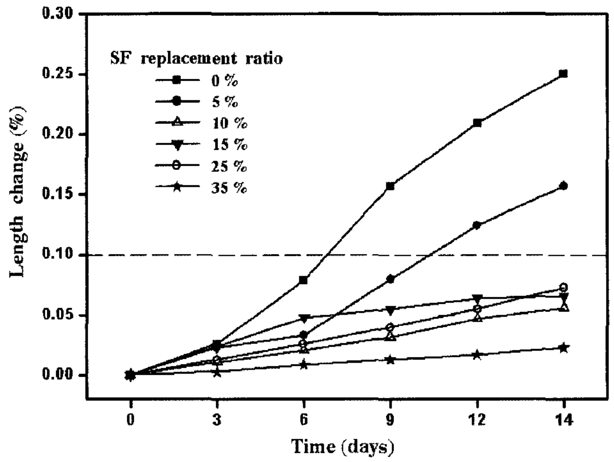

Fig. 17 Expansion of mortar bars according to various replacement ratios of silica fume.

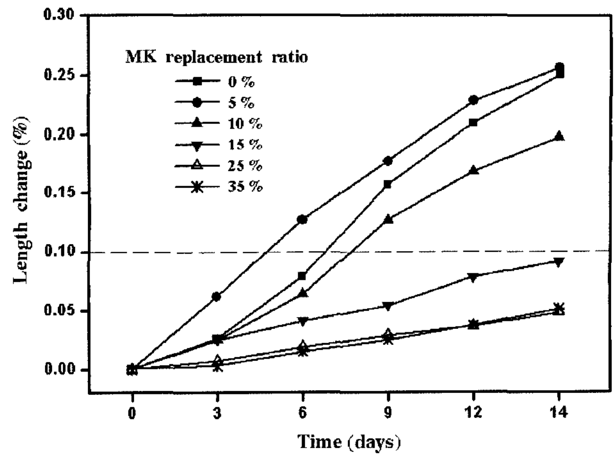

Fig. 18 Expansion of mortar bars according to various replacement ratios of metakaolin.

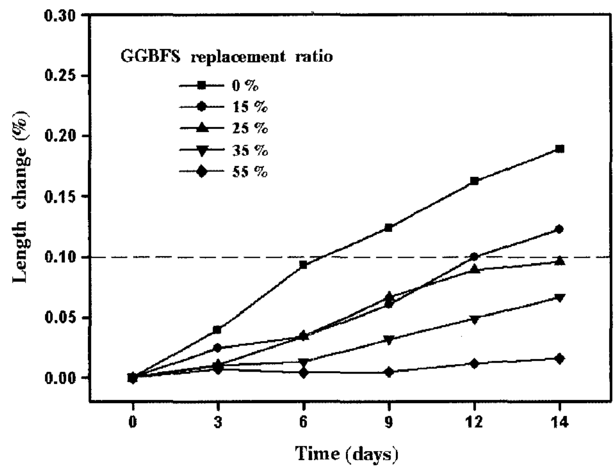

Fig. 19 Expansion of mortar bars according to various replacement ratios of ground granulated blast furnace slag.

of mineral admixtures was the result of combined processes (1) that the formation of deleterious alkali-calcium-silicate gel was inhibited and (2) the penetration of alkali solution into concrete was retarded due to the formation of denser, more homogeneous cement paste caused by pozzolanic effect.

4. Conclusions

Based on the results of this study, the following conclusions are drawn:

1) All the aggregates used in this study were presumed to be innocuous by the ASTM C 227, but some sedimentary and metamorphic rocks were identified as reactive aggregates by the ASTM C 1260 method;

2) For the crushed stones used in Korea, the result that did not appear with ASTM C 227 for over 24 months appeared with ASTM C 1260 in a short period of time. (With respect to the crushed stones used in Korea, the test procedure of ASTM C 227 did not indicate deleterious expansion problem even after over 24 months whereas the test procedure of ASTM C 1260 identified the expansion problem in a fairly short period of time.) Thus, for the crushed stones of Korea, ASTM C 1260 method is the method of choice to identify slowly reacting aggregates, causing the concrete expansion problem due to the alkali-silica reaction. Moreover, ASTM C 1260 method is the recommended method to test for reactive aggregates used in the concrete structure subjected to an environment of alkali ions added from outside sources;

3) The smaller particle size of reactive aggregate or the smaller fineness modulus resulted in more significant expansion of the aggregate by the alkali-silica reaction due to an increase in the surface area of aggregate. Also, as the concentration of the alkali solution gets higher, the more alkali-silica reaction occurs;

4) In the case of reactive aggregate, that showed expansion of more than 0.2% in accordance with the ASTM C 1260 method, replacement ratios of 25% for fly ash, 10% for silica fume, 25% for metakaolin and 35% for ground granulated blast furnace slag were the most effective in reducing the expansion caused by an alkali-silica reaction under the experimental conditions. The replacements of the cement by these mineral admixtures were found to prevent the expansion problem caused by the alkali-silica reaction of the reactive aggregates used in this study; and

5) For crushed stones of Korea, the examination for possible deleterious alkali-silica reaction should be conducted, and the use of mineral admixtures is recommended to reduce the damage by such alkali-silica reaction.

References

1. Lee, J. H. and Kim, S. W., "A Study on the Alkali-Aggregate Reactivity in Crushed Stone by Chemical Method," *Proceedings of the Korea Concrete Institute, Korea*, Vol.4, No.2, November 1992, pp.25~30.

2. ASTM C 227, "*Standard Test Method for Potential Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)*," 1997.

3. ASTM C 1260 "*Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*," 2001.

4. Moon, H. Y., Lee, S. T., You, J. H., and Choi, K. S., "Resistance on the Magnesium Sulfate Attack of Mortars with Silica Fume," *Proceedings of the Korea Concrete Institute, Korea*, Vol.14, No.1, May 2002, pp.379~384.

5. Lee, C. Y., Choi, S. H., Kang, S. H., and Lee, K. M., "Influence of Fly Ash Content with Respect to the Fresh and Mechanical Properties in Concrete," *Journal of the Korea Concrete Institute, Korea*, Vol.11, No.6, December 1999, pp.25~33.

6. Kim, H. and Jee, N. Y., "A Study on the Chloride Ion Penetration Characteristic of Concrete containing Ground Granulated Blast Furnace Slag," *Proceedings of the Korea Concrete Institute, Korea*, Vol.13, No.1, May 2001, pp.997~1002.

7. Kim, Y. T., Ahn, T. H., Kang, B. G., Lee, J. Y., and Kim, B. G., "A Fundamental Study of Matakaolin as a Pozzolanic Material," *Proceedings of the Korea Concrete Institute, Korea*, Vol.13, No.2, November 2001, pp.281~286.

8. Won, J. P., Kwon, Y. S., and Lee, j. J., "Properties of High-Performance concrete Containing High-Reactivity Metakaolin," *Journal of the Korea Concrete Institute, Korea*, Vol.14, No.3, June 2002, pp.349~356.

9. Kim, J. M., Lee, S. S., and Kim, D. S., "A Study on the Strength Properties of Concrete containing Meta-Kaolin," *Proceedings of the Korea Concrete Institute, Korea*, Vol.15, No.1, May 2003, pp.47~52.

10. Yoon, J. H., Jaung, J. D., and Lee, Y. S., "An Experimental Study on the Alkali-Silica Reaction of Crushed Stones," *Journal of the Korea Concrete Institute, Korea*, Vol.6, No.2, April 1994, pp.108~117.

11. Jun, S. S., Lee, H., Hwang, J. Y., Jin, C. S., and Park, H. J., "An Experimental Study to Determine the Mechanical Properties of Recycled Aggregate Separated from Demolished Concrete and Recycled Aggregate Concrete," *Journal of Engineering Geology, Korean Society of Engineering Geology, Korea*, Vol.13, No.3, September 2003, pp.345~358.

12. Malvar, L. J., Cline, G. D., Burke, D. F., Rollings, R., Sherman, T. W., and Greene, J. L., "Alkali-Silica Reaction Mitigation: State of the Art and Recommendations," *ACI Materials Journal*, Vol.99, No.5, September-October 2002, pp.480~489.