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The effects of alkali-silica reaction on the mechanical properties of concretes with three different types of reactive aggregate

This paper investigates the degradation of the mechanical properties of concretes made with three types of aggregate affected by alkali-silica reaction (ASR). Three standard testing methods – ASTM C289, JASS 5N T-603 and ASTM C1260 – were used to identify the reactivity of ASR of the three aggregates selected. The test results show that all three aggregates are potentially deleterious. A new acceleration method based on JASS 5N T-603 and ASTM C1260 was proposed for concrete specimens. In the acceleration method, cylindrical concrete specimens were used, additional alkali material was added to the concrete mixture and the specimens were stored under conditions similar to ASTM C1260. The preconditioned concrete specimens were then used for evaluating the mechanical properties of the ASR-affected concrete in terms of strength and stiffness. The test results show that special attention must be paid to the effects of two opposing mechanisms on the strength and stiffness of concrete: hydration reactions and ASR. Hydration reactions enhance the mechanical properties, whereas ASR does the opposite. The changes in length of concrete specimens were also measured, which showed that the basic trends for change in length and mechanical properties may be different. It is better to examine the effect of ASR on both change in length and mechanical properties. The size and reactivity of the aggregate are very important factors for the mechanical properties of ASR-affected concretes. Within the two-month testing period, the reactive fine aggregate might cause ASR expansion and the reactive coarse aggregates might not.

Keywords: deterioration, ASR, reactive aggregate, aggregate size, concrete

1 Introduction

Solid concrete structures exposed to severe environmental conditions, e.g. dams, pavements, coastal concrete structures, are vulnerable to attacks by various environmental loadings such as temperature fluctuation, moisture variation and aggressive chemicals. Alkali-silica reaction (ASR) of concrete is one of the chemical reactions in concrete that can cause severe damage. In a high-moisture environment, the product of ASR is expansive, which is detrimental to concrete structures [1, 2].

ASR is a chemical reaction between the reactive silica in the aggregate and the alkalis (Na_2O and K_2O) in Portland cement. This chemical reaction produces alkali-silica gel swelling with the absorption of the moisture from the surrounding cement paste. The expansive gel can cause cracking in the concrete. Therefore, the necessary conditions for the expansive ASR gel to form in the concrete are a sufficiently high alkali concentration in the cement, high moisture content in the concrete and reactive aggregates.

In order to control or prevent the occurrence of ASR in concrete, most countries have adopted a limit to the equivalent percentage of alkalis (such as Na_2O) in Portland cement. A commonly used limit is 0.6 %, below which the cement is considered to be low-alkali cement. Low-alkali cement has been considered relatively safe with respect to ASR damage. Recently, however, it has become evident that the critical value of 0.6 % equivalent alkalis was not exactly sufficient to prevent ASR damage. For example, concrete structures in the USA developed deleterious ASR where alkali levels in the cements were as low as 0.45–0.50 % equivalent Na_2O [3]. This means that the equivalent critical alkali level is not always applicable. This is because alkalis do not come exclusively from Portland cement; they may come from other sources such as mineral admixtures, chemical admixtures and aggregate.

It is not only the mineralogical composition of reactive aggregate that is important; the size of the aggregate is also important. The reactive aggregate size corresponding to the largest ASR expansion is called the pessimum size. To investigate the effect of the pessimum size of aggregates, the accelerated mortar bar test (ASTM C1260) was used with mortar bars made with waste glass particles of various sizes [4, 5, 6, 7]. The test results show that a decrease in particle size causes an increase in volume expansion and damage due to ASR. However, when the particle size decreased to a certain level, the fine aggregates did not result in any excessive ASR expansion. This means that the aggregate size plays a key role in expansion due to ASR [8, 9].

In order to predict the ASR volume expansion mathematically when considering the pessimum size effect of reactive aggregate, a theoretical model based on the modi-

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fied version of the generalized self-consistent theory was developed [10]. The model can predict the pessimum size of ASR in mortar bars and was verified with the test data of mortar bars obtained using ASTM C1260.

Many accelerated experimental approaches have been developed to capture the ASR-induced damage in a short period of time. ASTM C1260 and C1293 are methods commonly used in the USA. The National Aggregates Association (NAA) screened aggregates for ASR susceptibility and adopted the following critical values for ASR expansion: 0.2 % for ASTM C1260 and 0.04 % for ASTM C1293 [11].

This paper focuses mainly on evaluating the degradation of the mechanical properties of concrete due to ASR. First, most standard testing methods were developed for mortar bars and aggregate samples, and very few for concrete. It is important to study the effect of ASR on concrete because concrete is the structural material used in construction. Thus, in addition to mortar bars, concrete specimens were made with three different types of aggregate for testing the effect of ASR. Second, most of standard testing methods evaluate the change in length (linear expansion) of mortar bars for ASR damage; very few evaluate the mechanical properties of concrete. It is important to study the effect of ASR on the mechanical properties of concrete because the performance of concrete structures depends directly on the mechanical properties of concrete. Therefore, in addition to measuring change in length for standard testing methods, the mechanical properties of ASR-affected concrete, such as strength and stiffness, were systematically studied.

In order to make sure that the three aggregates selected were ASR-reactive, standard testing methods were used to test the reactivity of the three aggregates. There are many standard testing methods available for ASR, and three of them were used in this study: JASS 5N T-603, ASTM C1260 and ASTM C289. In order to accelerate the ASR process in the concrete samples, a new acceleration method was proposed to precondition the concrete specimens. The new method was based on ASTM C1260 and JASS 5N T-603. The concrete samples made with the three reactive aggregates were preconditioned using the new acceleration method, and the mechanical properties of the ASR-affected concretes were tested and analysed in terms of strength and stiffness. Change in length was also measured. We would like to point out that the present work is an attempt to study the effect of ASR on the mechanical properties of concrete, the new acceleration method was proposed to facilitate the experimental study and more work needs to be done in order to develop a new standard testing method for ASR-affected concrete.

2 Experimental plan

2.1 Properties of coarse and fine aggregates

Various kinds of aggregate are found in the USA. Basalt and similar igneous rocks such as andesite and shoshonite are scattered throughout the state of Colorado. Granite, one of the most commonly used igneous rocks in the USA, is widespread from Colorado Springs to Denver and the Colorado mountain region [12, 13]. The three coarse aggregates used in this study were acquired from three different sources: CS, GJ and WM. The CS aggregate came from the Colorado Springs region, Colorado. The rock type for the CS aggregate was granite, one of the igneous rocks. The GJ aggregate was acquired from the Grand Junction region, Colorado. It was a basalt or andesite, a type of volcanic rock. The WM aggregate came from the state of Wyoming and its geological information was not released by the supplier. Fig. 1 indicates the grading curvse for the three types of coarse aggregate and the fine aggregate used in the present study.

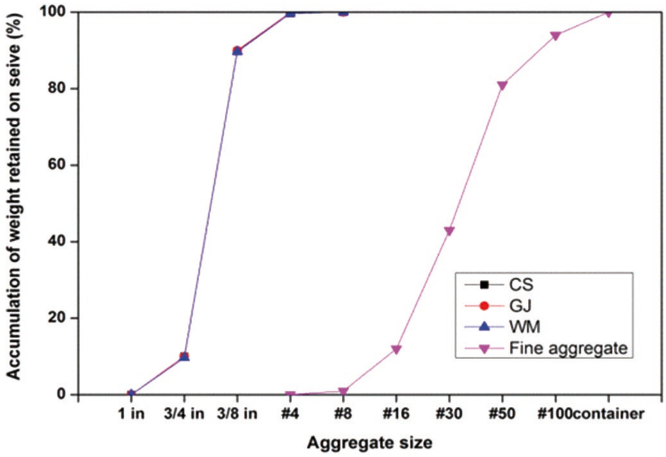

Fig. 1. Grading curves for coarse and fine aggregates

2.2 Three standard testing methods and specimen preparation

The expansive ASR gel that forms in concrete ultimately contributes to the ASR expansion and the formation of internal microcracks in the concrete. In order to investigate the ASR expansion effectively and determine the experimental parameters of ASR-affected concretes, three standard testing methods – JASS 5N T-603, ASTM C1260 and ASTM C289 – were used to examine the reactivity of the three aggregates selected. The specimen preparation and testing methods are different for the three methods. They are outlined here for the reader's convenience.

The JASS 5N T-603 testing method is for measuring the change in length of concrete specimens affected by ASR. The Portland cement used for this study was an ASTM type I/II cement with a high alkali content of 0.79 % as shown in Table 1. This testing method requires that granular sodium hydroxide of 98 % fineness be added to the concrete mixes. Adding the high concentration of alkali material to the concrete mix accelerates the ASR. Three different amounts of NaOH were used. The suffixes 12, 18 and 24 for the concrete specimens indicate the equivalent weight of NaOH 1.2, 1.8 and 2.4 kg/m^3 respectively. Concrete admixtures were not used because the focus of this study was to investigate the effect of ASR on concrete made with reactive aggregates without admixtures. The mix design is shown in Table 2 and the concrete mixing procedure is specified in ASTM C 192. Table 3 lists the properties of the fresh concrete mixes. The prism moulds used for making specimens were 2 inch (50 mm) wide × 2 inch high × 10 inch (100 mm) long. Length measurement was conducted using an SPI digital indicator.

Table 1. Chemical composition (percent by mass)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	Na_2O_{eq}	SO_3	LOI
%	62.5	20.1	5.6	2.0	3.1	0.2	0.9	0.79	3.2	1.7

LOI: loss on ignition.

Table 2. Mix design for JASS 5N T-603

Water kg/m³	Cement kg/m³	Fine aggregate kg/m³	Coarse aggregate kg/m³
165	330	754	1041

Table 3. Properties of fresh concrete mixes

Type of aggregate	Air content (%)	Slump (mm)
CS	4.5	76.2
GJ	4.2	69.9
WM	4.3	73.0

Table 4. Portions retained on sieves

Sieve size		Mass	
Passing	Retained on	%	g
4.75 mm (No. 4)	2.36 mm (No. 8)	10	99.0
2.36 mm (No. 8)	1.18 mm (No. 16)	25	247.5
1.18 mm (No. 16)	600 μm (No. 30)	25	247.5
600 μm (No. 30)	300 μm (No. 50)	25	247.5
300 μm (No. 50)	150 μm (No. 100)	15	148.5

Its measuring range is 0.0–1.0 inch (0.0–25.4 mm) and its resolution is 0.00005 inch (0.00127 mm). The testing period was six months and the length variations were measured once a month.

The ASTM C1260 testing method is for measuring the change in length of mortar bars. The quantities of materials for making mortar bar specimens are 440 g of cement and 990 g of fine aggregate. Therefore, coarse aggregates were not used in this test. The testing period was 14 days. The fine aggregates were produced by crushing coarse aggregates as shown in Fig. 2. The portions of fine aggregates with different particle sizes are prescribed in Table 4 and the required water-cement ratio is 0.47 by mass. Different Portland cements of type I/II were used. They have different alkali contents of 0.59, 0.79 and 0.9 %. The mortar mixing procedure was Practice C 305. The specimen size was 1 × 1 × 11 inch (25.4 × 25.4 × 279.4 mm) and at least three specimens were made for each mix design using one type of Portland cement with a specific alkali content. After demoulding, the mortar bar specimens were cured in a fog room for 24 h (temperature 23 °C, relative humidity 100 %). Immediately after curing, the specimens were placed in a container with 1 *N* NaOH solution at 80 °C for 14 days. The changes in length were recorded with the same equipment as used in the JASS 5N T-608 test. For the two weeks of the testing period, the change in length of every specimen was measured once a day.

Fig. 2. Crushed fine aggregates

The ASTM C289 testing method is for testing the chemical reactivity of aggregates. No Portland cement was used in this test. The specimens prepared from the three different aggregates were placed in 1 *M* NaOH solution at 80 °C for 24 h. A chemical method was used to determine the potential reactivity of the aggregate.

3 Test results and discussion of the three standard testing methods

Fig. 3 shows the ASTM C289 test results, which provides quantitative information about deleterious aggregates, not numeric values of the potential ASR of aggregates. The Sc and Rc results for each aggregate are shown in Fig. 3 to compare with the calibration curves. In Fig. 3, the blue dot is for the results of CS aggregate, the red dot for GJ aggregate and the black dot for WM aggregate. It can be seen clearly from Fig. 3 that CS and WM aggregates can be considered deleterious, whereas GJ aggregate is potentially deleterious. Therefore, all three aggregates used in this study are potentially deleterious.

Fig. 4 shows the change in length of concrete specimens measured in accordance with JASS 5N T-603. The ASR expansion of the specimens was recorded for six months. All alkali contents in concrete specimens were much higher than 0.6 %, the critical alkali content for low-alkali Portland cement. This was because, as described earlier, large amounts of additional NaOH were added to the concrete mixes. The scattering of the test data is quite large in Fig. 4a; the effect of alkali content on ASR expan-

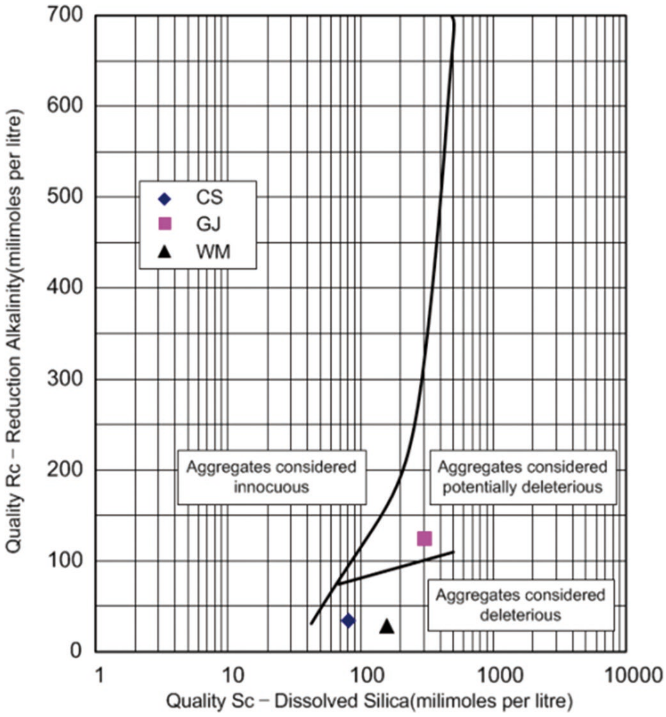

Fig. 3. ASTM C289 test data and the division between innocuous and deleterious aggregates

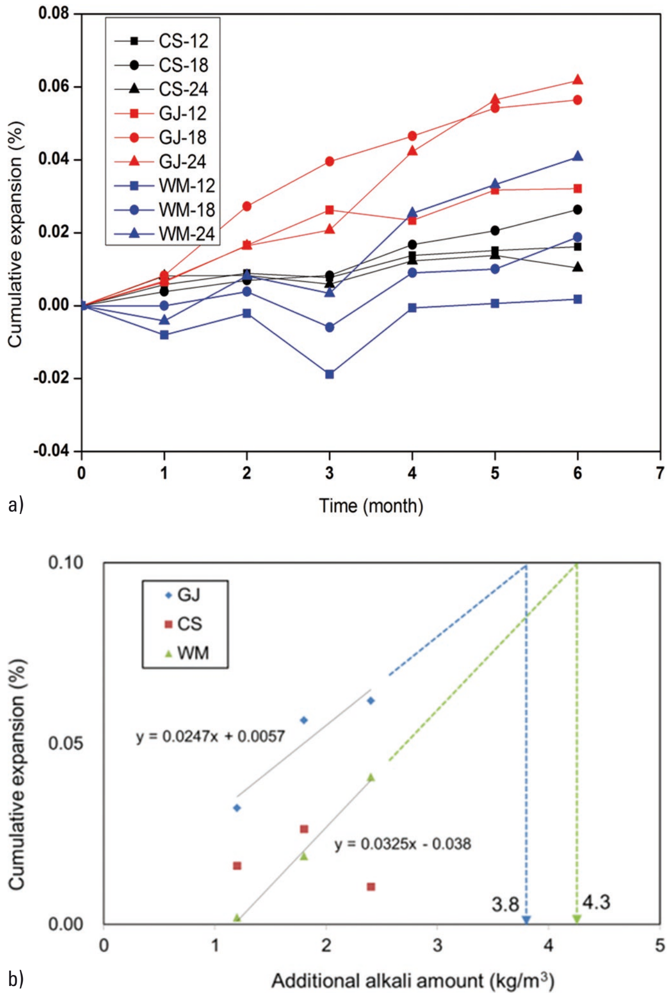

Fig. 4. ASR expansion test data and critical amount of NaOH in JASS 5N T-603: a) change in length test data for six months, and b) critical alkali amount for ASR expansion in concrete made with three different aggregates

sion is not clearly shown. However, the trend shown in the test data of JASS 5N T-603 is very consistent. The concrete specimens with GJ aggregate obviously swelled with additional alkali, whereas CS and WM aggregates did not provide clear evidence as to whether the aggregates are reactive or not. In this testing method, the critical ASR expansion of concrete specimens is considered to be 0.1 % over the six months. As a comparison, the final ASR expansion of each concrete specimen is marked with dots in Fig. 4b. The critical amount of additional alkali in concrete may be predicted based on the test data shown in Fig. 4b. It can be seen that the critical alkali contents of GJ and WM aggregates can be estimated as 3.8 and 4.3 kg/m^3 respectively, corresponding to the 0.1 % expansion.

Fig. 5 illustrates the expansions of mortar bars measured according to ASTM C1260. It can be clearly seen that the alkali contents (0.59, 0.79 and 0.9 %) in the Portland cement had important effects on the ASR expansion of the mortar bars. In Fig. 5a, the ASR expansion data of GJ specimens with the 0.59 % alkali content (slightly lower than the critical alkali content) are between 0.1 and 0.2 %. However, in Figs. 5b and 5c, the expansions of CS and WM specimens with 0.59 % alkali content is below 0.1 %. This means that GJ aggregate is more reactive than CS and WM aggregate. Nevertheless, with increasing alkali content in mortar bar specimens, the ASR expansion increased in all specimens significantly, which indicates that alkali content in Portland cement is an extremely important factor. High alkali content can activate ASR expansion of aggregate which may be not reactive with low-alkali cement. In Fig. 5a, GJ aggregates with the cement with 0.59 % alkali content resulted in 0.1667 % expansion during the testing period, while the same aggregates with the alkali contents of 0.79% and 0.9% expanded up to 0.5591 %. The other test results in Figs. 5b and 5c also followed the same trend. It is important to point out that the increment in the alkali content of 34 % (from 0.59 to 0.79 %) resulted in a much higher percentage of ASR expansion – up to 230 %. However, when the equivalent alkali content reached 0.9 %, the ASR expansions did not increase significantly over those for 0.79 %. So it seemed that, at a fixed time, the ASR expansion increases with increasing alkali content in the cement, but only to a certain value, say 0.8 to 0.9 %, thereafter the ASR expansion does not increase with increasing alkali content. These results are limited to the short testing period used in this study. Apparently, more research should be conducted on this topic. Fig. 5d presents a summary of the final expansions of concrete specimens with different alkali contents and different types of aggregate. It is clear from the figure that GJ aggregate is much more reactive in terms of ASR than the other two aggregates.

4 Acceleration method based on ASTM C1260 and JASS 5N T-603 for concrete specimens

As indicated earlier, the JASS 5N T-603 testing method is for concrete specimens, but, it takes 180 days to obtain

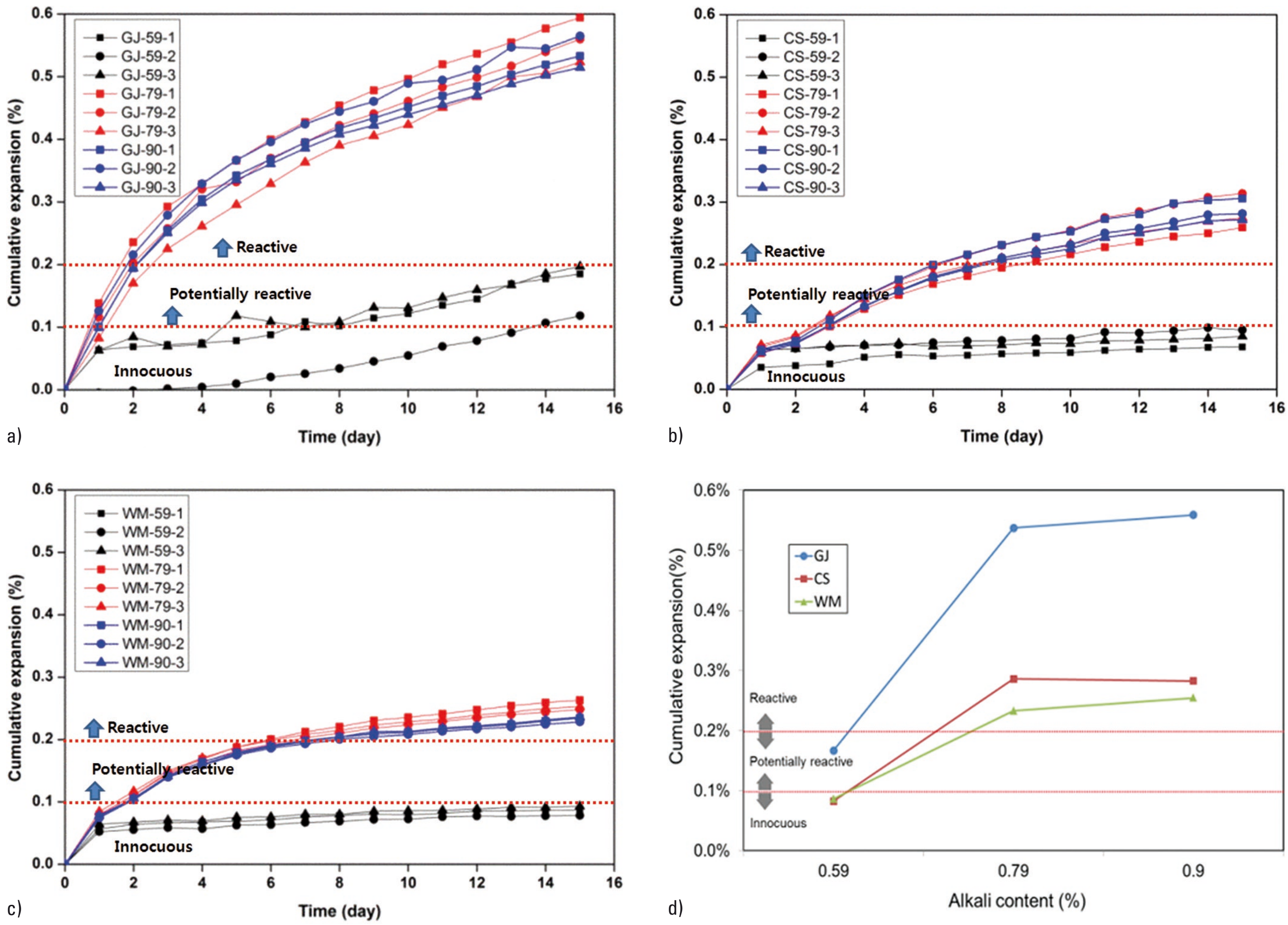

Fig. 5. Change in length of reactive aggregates according to alkali content (equivalent alkali levels of 0.59, 0.79 and 0.90 %): a) GJ aggregate, b) CS aggregate, c) WM aggregate, and d) final ASR expansion for different alkali contents

results; the ASTM C1260 takes only 14 days, but it is for mortar bars not concrete specimens; and ASTM C289 is for aggregate not concrete. Based on the test data of the three standard testing methods, an acceleration method was proposed in this study to accelerate ASR in concrete samples so that the deterioration of mechanical properties of ASR-affected concrete can be tested. Several important parameters for accelerating ASR, such as adding NaOH to concrete mixes, using high-alkali cement and extending the testing period, were discussed in previous sections. Moreover, using a high testing temperature is another method commonly used to accelerate a chemical reaction in a material. Among the three standard test methods, the testing conditions used in ASTM C1260 were adopted and modified to accelerate ASR in concrete specimens. In order to capture clearly the effect of higher alkali content on ASR expansion in concrete, Portland cement with a high equivalent alkali content was used as shown in Table 1. In addition, granular sodium hydroxide (NaOH) amounting to 5.6 kg/m^3 was added during the mixing process in a similar way to JASS 5N T-603. The quantity of additional alkali is increased up to 50 % of the critical alkali amount used for GJ aggregate as shown in Fig. 4b. Cylindrical concrete specimens were used with a size of 3 inch (76.2 mm) diameter × 6 inch (152.4 mm) high. Concrete specimens made with the same three types of aggregate were prepared and cured under the standard conditions for 28 days (23 °C and 100 % relative humidity), then submerged in an alkaline solution (same concentration and same temperature as ASTM C1260) for about two months.

The purpose of this new acceleration method is to precondition the concrete specimens so that the mechanical properties such as strength and stiffness of ASR-affected concrete can be tested. To examine the variation in strength and stiffness of the concrete specimens, compression tests were carried out after 2, 4, 6 and 8 weeks.

5 Test results and discussion of ASR-affected concrete preconditioned by new acceleration method

5.1 Strength and stiffness of ASR-affected concrete

The compressive strength was obtained from the maximum stress in a stress-strain curve. The stress-strain curves of the ASR-affected concrete specimens were tested at different times (different acceleration periods). Fig. 6 shows the test results of the mechanical properties of the ASR-affected concrete specimens in terms of the immersion times and reactive aggregates. Fig. 7 shows the strains corresponding to the peak stresses at different immersion times. During the first four weeks of the testing period, the concrete strength gradually increased and then decreased,

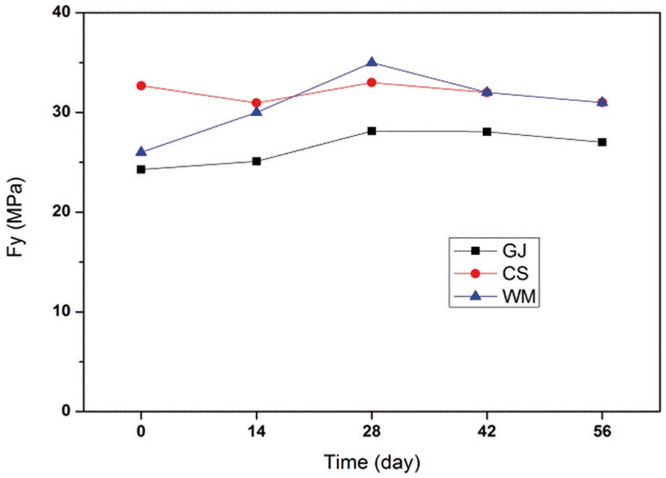

Fig. 6. Compressive strength vs. immersion time

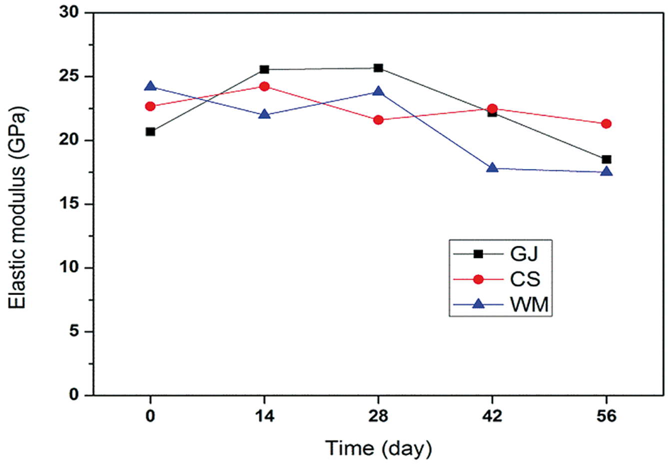

Fig. 8. Elastic moduli vs. immersion time

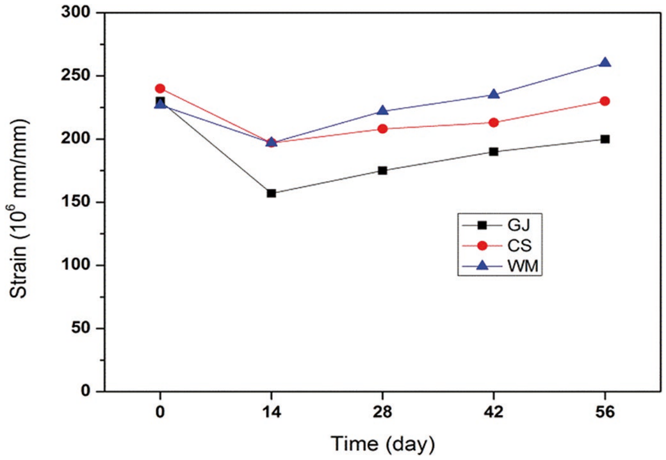

Fig. 7. Peak strain vs. immersion time at peak stress

although the total variation in compressive strength is not large for different immersion times. On the other hand, the strain at peak stress suddenly decreased and then increased continuously. The variations in the stress and strain of the ASR-affected concrete specimens may be explained by two mechanisms that occurred in the concrete at the same time. One is the effect of the hydration reactions of Portland cement which contributed to the increase in compressive strength and stiffness. The other is the effect of ASR that led to the reduction in the mechanical properties. The compressive strength and stiffness of the concrete affected by ASR were under the combined effect of the two opposing mechanisms. For the strains corresponding to the peak stresses, the variation shown in Fig. 7 can also be explained by the two opposing mechanisms: at the beginning of the testing period, the effect of hydration reactions dominated and thus the strains decreased (stiffness increased); thereafter, the effect of ASR became stronger, which resulted in the increased strains in the concrete (and thus decreased stiffness).

Fig. 8 shows the stiffness of concrete affected by ASR. The stiffness can be characterized by the modulus of elasticity of the concrete. To determine the modulus of elasticity experimentally, the chord method (E_{chord}) was used in this study. This procedure is described in ASTM C469 and the equation to calculate the modulus of elasticity using test data is:

$$E_{chord} = \frac{f_2 - f_1}{\varepsilon_2 - \varepsilon_1}$$

where $\varepsilon_1 = 50$ microstrain, f_1 is the stress corresponding to ε_1, $f_2 = 40\,\%$ of ultimate stress f_c and ε_2 is the longitudinal strain at f_2.

The trend for stiffness is similar to that for the strength. In the first four weeks, the slightly increased stiffness can be explained by the dominant hydration reactions, whereas the decreased stiffness after the first four weeks indicates that the detrimental effect of ASR became more significant. These results agree with other test results available in the literature [2,14,15].

5.2 External appearance of ASR-affected concrete

Fig. 9 shows the surface cracks and colour changes of the concrete specimens after being submerged in NaOH solution for 56 days. It can be clearly seen that surface cracks occurred due to ASR expansions of coarse aggregate beneath the concrete surface. Moreover, coloured spots on the surface of the concrete specimens can be seen in Fig. 9: dark grey spots on GJ aggregate and yellow ones on CS and WM aggregates. Those are evidence of progressive ASR.

5.3 Interactive effect of hydration reactions and ASR

The mechanical properties of concrete are affected not only by the ASR-induced damage, but also by the hydration reactions of the Portland cement. The former causes the reduction in the mechanical properties of concrete and the latter enhance them. In order to distinguish the interaction between the two opposing mechanisms, additional tests were designed and conducted using the same GJ concrete specimens submerged in hot water (not in hot alkali solution). In this case the hydration reactions were the dominant effect and the ASR was kept to a minimum because there was no alkali solution involved. The addi-

(a) GJ (b) CS (c) WM

Fig. 9. Surface cracks in three different specimens after 56 days in NaOH solution

tional test results of normalized strength and stiffness are shown in Figs. 10 and 11 respectively, where "GJ" represents the specimen made with GJ aggregate submerged in alkali solution and "Additional" the specimen made with GJ aggregate submerged in hot water.

In Fig. 10, for the first four weeks, both strength curves increased due to the effect of hydration reactions. After four weeks, the strength of the concrete specimens in hot water continuously increased up to 10 %, while that of the GJ specimens in alkali solution decreased because of ASR. The results of normalized stiffness in Fig. 11 further demonstrate this phenomenon: the normalized stiffness of the specimens gradually increased up to about 7 %, while those of GJ aggregates rose to 24 % for the first month because of the contribution of hydration reactions and then dropped by about 30 % due to ASR.

From the test results it seems that tri- and di-calcium silicate minerals (C_3S and C_2S) in the cement react with water in the alkali solution and produce calcium-silicate hydrate (C-S-H) gel and calcium hydroxide (Ca(OH)2). During the first month, C3S exerts an effect on the early strength of concrete up to about 80 %. After that, C_2S plays the leading role in developing the strength of concrete as shown in Fig. 12. At the same time, reactive aggregates are in a hydroxyl-rich medium. By the second month, the effect of ASR becomes more significant. The high temperature of 80 °C accelerates the ASR, a swelling gel formed from ASR increases in volume with imbibing water. Even though the hydration reactions progress continuously, the ASR-induced damage can exhibit a more dominant effect on the mechanical properties of the concretes.

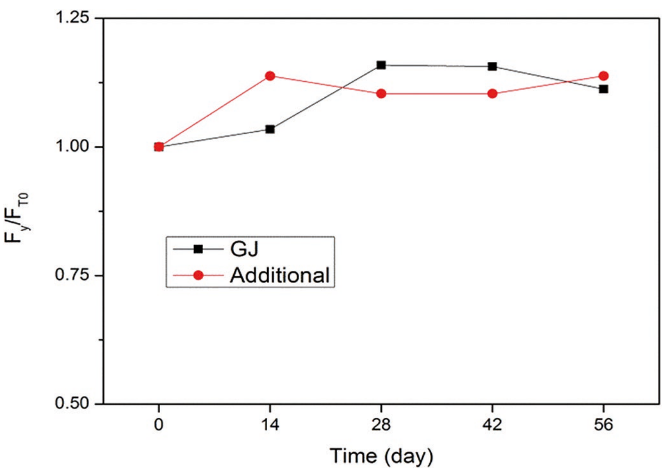

Fig. 10. Normalized stress of additional specimen to observe hydration effect

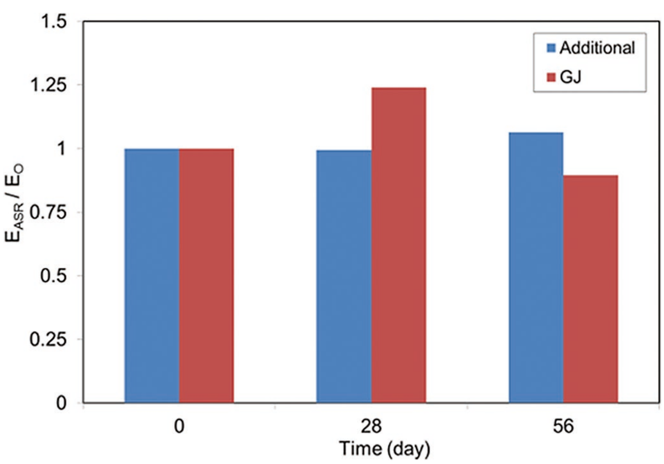

Fig. 11. Elastic moduli of additional specimen to observe hydration effect

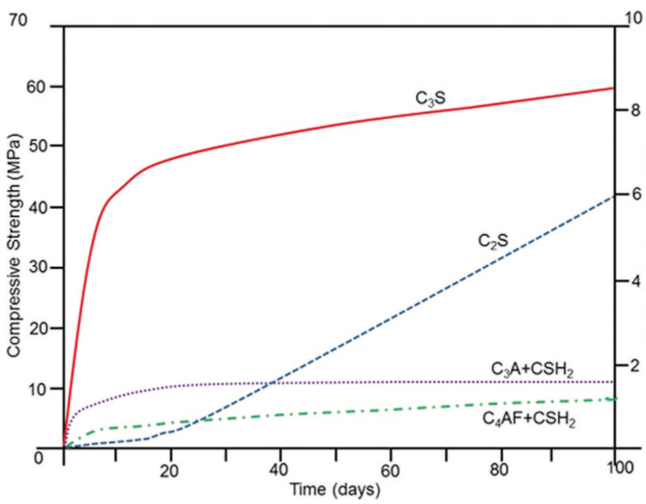

Fig. 12. Compressive strength development in paste of pure cement compounds [17]

5.4 Change in length of concrete specimens

Fig. 13 shows the change in length of concrete cylindrical specimens under the new acceleration method. The test results indicate that the length of specimens decreased gradually over time, which is different from the continuous expansion in the test data of ASTM C1260 for mortar bars. Thus, the change in length results are important. The trend for the mechanical properties of ASR-affected concrete and the trend for change in length may be different. The change in length might not exhibit a severe problem, but that does not mean there is no problem for the mechanical properties. Hence, there is a need to examine the effect of ASR on both change in length and mechanical properties. There is also a need to find the reasons for the difference. One possible reason is the dimensional effect of specimens.

The aspect ratios of specimens used in the JASS 5N T-603 and ASTM C1260 methods are 1:5 and 1:11 respectively. The aspect ratio of the cylindrical concrete specimen was 1:2. The expansion of the long mortar bar used in ASTM C1260 can be considered as uniform over the cross-section because the alkali solution can penetrate from the surface to the centre of a mortar bar (distance = 0.5 inch [12.7 mm]) quickly, whereas the ASR expansion of the cylindrical specimen over the cross-section is not uniform since it takes a longer time for the alkali solution to reach the centre of a cylinder (distance = 1.5 inch [38.1 mm]) and thus there is an alkali concentration distribution in the radial direction of the cylinder. The alkali content at the edge of a cylinder is higher than that at the centre. The non-uniform alkali concentration over the cross-section can lead to non-uniform ASR expansion, which is more complicated than the 1D expansion of the thin mortar bars. The measurement of change in length was conducted at the centre of the cylinder. This topic should be studied in more depth in the future.

ASR expansion will eventually occur in the concrete specimen, but it did not occur during the testing period, which is due to the fact that only the coarse aggregate used in the concrete specimens was reactive aggregate, and the fine aggregate was not. A large particle size for a coarse aggregate corresponds to a small surface area, which determines the low ASR rate.

5.5 Effect of fine aggregates

As shown in the above test results, the strength and stiffness of ASR-affected concrete did not decrease during the first month or two [2], whereas the ASR expansion of mortar bars in ASTM C1260 can reach a significant level in 14 days. The difference is caused by the size of reactive aggregate [8, 9, 17], i.e. the larger the size of reactive aggregates, the slower the rate of ASR reactivity [18].

The concrete specimens used in the above tests were made with the three types of reactive coarse aggregate and commercial sand, which is not reactive. In order to capture the effect of fine aggregate, additional specimens were prepared. There were two additional testing groups: non-reactive fine aggregates and reactive fine aggregates. The reactive fine aggregates were prepared by crushing the reactive coarse aggregates in accordance with the quantities of the sand particle sizes specified in ASTM C1260. Fig. 14 illustrates the test results for the change in length of concrete specimens; concrete specimens with reactive fine aggregates reacted quickly with the sodium hydroxide solution and expanded within the 14-day testing period. In the case of non-reactive fine aggregate, however, ASR expansion did not occur for the first two weeks under the same testing conditions. So the effect of aggregate size on ASR rate is very significant. Therefore, the long-term durability performance of concrete structures under severe environmental conditions such as high humidity, high temperature and extremely aggressive chemicals heavily depends on the reactivity and size of aggregates.

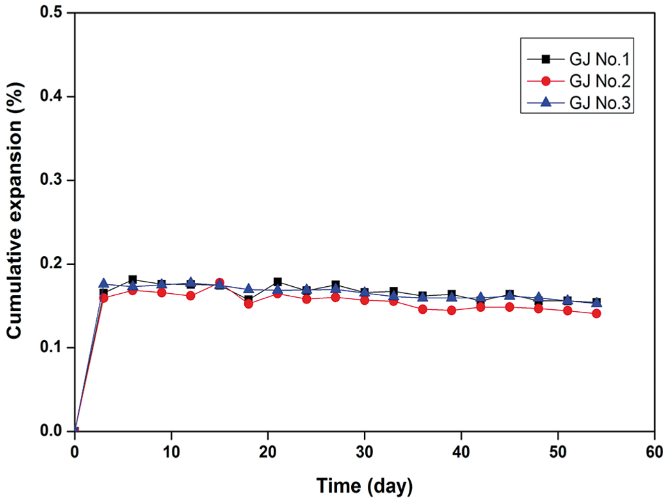

Fig. 13. Change in length of GJ concrete specimens affected by ASR

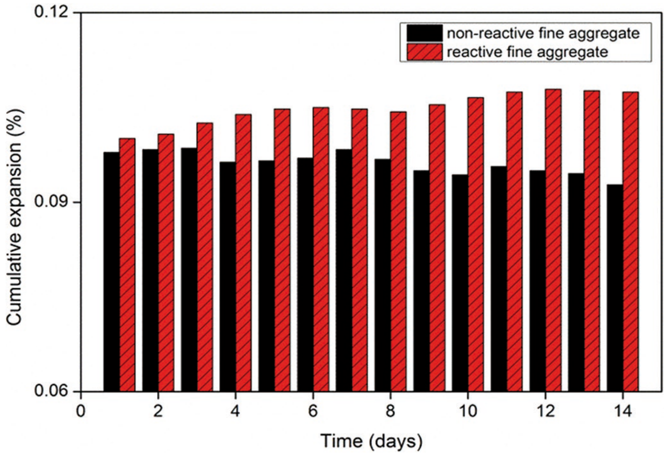

Fig. 14. Effect of early ASR expansion according to reactivity of fine aggregate

6 Conclusions

In order to examine the deterioration of the mechanical properties of concrete affected by ASR, three different types of aggregate (CS, GJ and WM) were selected and used in the present study. Three standard testing methods (ASTM C289, JASS 5N T-603 and ASTM C1260) were employed to examine the ASR reactivity of the aggregate. Based on the test data of the three standard testing methods, all three aggregates may be considered to be potentially deleterious. Afterwards, cylindrical concrete specimens were made with the three types of aggregate for studying the effect of ASR on the mechanical properties of the concretes. A new acceleration method was proposed based on ASTM C1260 and JASS 5N T-603 for accelerating ASR in concrete specimens, and the strength and stiffness of concrete specimens conditioned by the new method were tested every two weeks for two months.

1) The results from ASTM C289 indicate that all aggregates are potentially deleterious. The results from JASS 5N T-603 show that the trend for expansion of concrete bars was very consistent, but the ASR expansion of the concretes was not clear. GJ aggregate obviously expanded, but not the other two. The critical alkali content of GJ coarse aggregates was estimated to be about 4 kg/m^3 for 0.1 % expansion. In ASTM C1260, all types of aggregate reacted quickly, as indicated by the linear expansion, depending on the equivalent alkali content in the cement. GJ aggregate especially was more sensitive to ASR expansion than the other two aggregates. With increasing alkali content in the cement, ASR expansion increased tremendously up to 0.8–0.9 % of cement content. Above that, there is no significant increase in ASR expansion.
2) A new ASR acceleration method based on ASTM C1260 and JASS 5N T-603 was used to investigate the degradation of the mechanical properties of the concretes. Cylindrical specimens measuring 3 inch (76.2 mm) diameter × 6 inch (154.2 mm) high were prepared with additional alkali added in the concrete mixes, and then immersed in high-temperature, high-alkaline solution for 56 days. The concrete specimens were tested for strength and stiffness during the 56 days. The results show that the compressive strength varied over the testing period. The strength of concrete gradually increased over the first four weeks and then decreased. The same trend was observed in the test data for concrete stiffness. There are two possible mechanisms responsible for this phenomenon: hydration reactions and ASR. The hydration reactions helped to enhance the strength and stiffness and the ASR was responsible for the reduction in the mechanical properties.
3) The interaction between the two opposing mechanisms of hydration reactions and ASR was also studied. Concrete specimens were submerged in hot water without alkali. The test data were compared with the data obtained with alkali solution. The mechanical properties of the concrete gradually increased, whereas those of the same concrete submerged in alkali solution decreased, which is evidence of the contribution of the hydration reactions without ASR.
4) The change in length of concrete specimens under the new acceleration method was measured. The results show that the concrete specimens did not expand as the mortar bars did during the testing period, which means that the basic trends of concrete specimens for change in length and mechanical properties might be different. As a result, all of concrete specimens should be tested to evaluate the effect of ASR.
5) Aggregate size is a very important factor for the deterioration of the mechanical properties of ASR-affected concrete. Tests were conducted to show the effect of reactive fine aggregates on the mechanical properties of ASR-affected concrete. The concrete specimens made with both reactive fine and coarse aggregates reacted quickly with the alkali solution and expanded faster than the concretes made with non-reactive fine and reactive coarse aggregates. Therefore, the deterioration behaviour of concrete structures under the effect of ASR depends on the size distribution of aggregates.

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