

New approach in mitigating damage caused by alkali–silica reaction

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Introduction

Alkali–silica reaction (ASR) is a chemical reaction between the alkali and hydroxyl ions produced by portland cement hydration and certain types of silica present in the aggregate. The stages that are involved in causing damage due to ASR are shown schematically in Fig. 1. The alkali ions and hydroxyl ions in the pore solution of the hydrated cement paste react with amorphous or poorly crystalline silica in the aggregates to form alkali silica (AS) gel. The AS gel expands by imbibing water and the resulting pressure exerted onto the surrounding mortar matrix causes extensive cracking and strength loss.

The traditional approach to prevent ASR has focused on either preventing the ASR or reducing the expansion of the gel by modifying the chemical environment in which the ASR takes place. Examples are: (i) avoiding reactive aggregates, (ii) using low alkali cement, or (iii) either adding mineral admixtures [1–4] or lithium salts [5, 6]. Avoiding reactive aggregates and limiting the alkali content in cement seem to be the easiest way to prevent damage in concrete due to ASR. Unfortunately, since costs dictate that aggregates and cement be produced locally, this apparently simple solution can be rather challenging. Furthermore, quarries with adequate aggregates are being depleted and using non-ideal aggregates may be a necessity in the future. Influencing the reaction chemistry by adding

mineral admixtures to concrete had mixed results in terms of its effectiveness in reducing the expansion and hence damage associated with ASR. The mixed results are because of the wide variety of reactive aggregate types and sizes and cement types, and because of variations in chemical compositions [7] and agglomerations [8, 9] of mineral admixtures. Therefore, it is of interest to investigate alternative forms of mitigating ASR.

This paper reports on mitigating the damage associated with ASR by controlling crack formation. Since strength reduction associated with ASR is due to cracking utilizing fibers to control and minimize crack formation seems to be a promising alternative. Cracks initiate in close vicinity to the reactive aggregates and need to be influenced at onset before they become dominant macrocracks. Therefore steel fibers of relatively small diameters are utilized in this study since they are more effective in interacting with these small cracks than conventional steel fibers commonly used in fiber-reinforced concrete.

Materials and experimental study

A reactive type of river aggregate was used in the experiments. The aggregate is composed of granite, feldspar, limestone, latite, quartz, biotite, pyroxene, sandstone, and hornblende. The volcanic glass in the latite is the reactive part of the aggregate. Steel fibers are 6 mm in length and 160 μm in diameter with a tensile strength of 2,200 MPa. They are brass coated to protect them from corrosion.

To measure expansion associated with ASR, mortar specimens with these reactive aggregates were cast, cured in 80 °C water bath for 1 day and immersed in a 1 N NaOH solution stored at 80 °C following the ASTM C1260 procedure [10]. Exposing the specimens to a 1 N NaOH solution at 80 °C accelerates the ASR. This test was chosen

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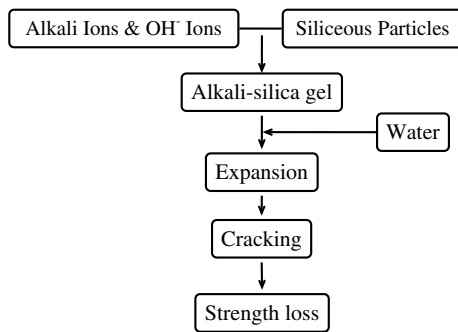


Fig. 1 Schematic illustrating deterioration due to ASR

because it is effective in evaluating the effect of matrix modifications on ASR [11–13], however, it induces ASR under different conditions than those in practice due to its high temperature and high alkali concentration. The specimens contained 0, 1, 3, 5 and 7% of steel fibers by mortar volume. Three specimens were cast for each fiber volume fraction. After curing, the specimens were placed in a 1 N NaOH solution at 80°C for 30 days and the length monitored periodically. The ASTM C-1260 standard requires only 14 days of immersion in the alkaline solution, however these samples were monitored for a longer period to investigate if the steel fibers simply delay initial expansion or reduce total expansion.

Two sets of un-reinforced and fiber-reinforced prisms ($4 \times 4 \times 16 \text{ cm}^3$) with reactive aggregates were cast and tested in both flexure and compression according to ASTM C 348 and ASTM C 349, respectively. Set I investigates if the steel fibers have indeed the potential to resist crack initiation and crack propagation. These specimens were *not* exposed to 1 N NaOH solution and were cured for 3, 7, and 28 days in a water bath held at room temperature. Three specimens were cast for each fiber volume fraction, ranging from 0 to 0.07, and for each curing time, respectively. Set II on the other hand investigates the strength degradation due to AS gel formation and expansion as a function of exposure time to 1 N NaOH solution. The specimens were prepared according to ASTM C-1260. Bars were tested after 3, 7 and 28 days of exposure to the 1 N NaOH solution, respectively. Three specimens were tested at each exposure time for fiber volumes of 0, 1, 3, 5 and 7%, respectively. Un-reinforced and steel fiber-reinforced specimens were epoxy impregnated and polished for microstructural analysis using scanning electron microscopy (SEM).

Experimental results and discussion

Expansion results

The results of expansion versus exposure time for mortar bars immersed in 1 N NaOH solution are plotted in Fig. 2.

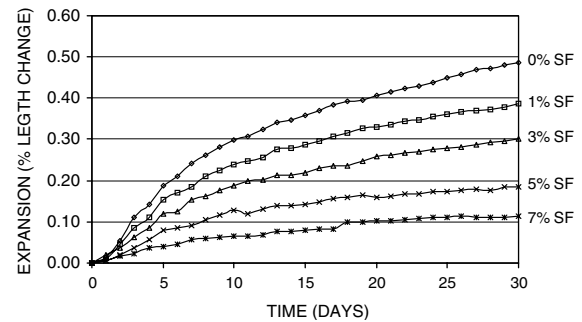


Fig. 2 Expansion versus exposure time for un-reinforced and steel fiber-reinforced mortar bars exposed to 1 N NaOH solution

Each data point represents the average of 3 specimens. The un-reinforced specimens reveal the highest expansion with 0.35% at 14 days and 0.49% after 30 days of exposure to NaOH solution. The expansion, however, decreased with increasing fiber volume fraction. The specimens containing 7 vol% of fibers exhibit the least expansion of 0.08% at 14 days and 0.11% at 30 days.

Microstructure analysis

Exposing the control and fiber-reinforced specimens to the NaOH solution causes the reactive aggregates to crack as shown in Fig. 3. However, the cracking is not confined to the aggregates. Radial cracks also initiate in the matrix surrounding the reactive aggregates and propagate away from the aggregate into the mortar matrix. The cracks in the matrix were mainly influenced by the fiber reinforcements since far less or even none of these cracks could be observed in the fiber-reinforced composites compared to the control specimens.

Strength results

The flexure and compressive strength results as a function of curing time and fiber volume fraction for specimens *not*



Fig. 3 SEM micrograph of cracked aggregate due to ASR in un-reinforced matrix

Table 1 Flexure and compressive strength of mortar bars for different fiber volumes and curing time

Fiber volume (%)	3 days		7 days		28 days	
	Flexure strength (MPa)	Compressive strength (MPa)	Flexure strength (MPa)	Compressive strength (MPa)	Flexure strength (MPa)	Compressive strength (MPa)
0	3.1	31.7	3.5	39.4	4.1	43.3
1	3.3	35.6	3.9	44.5	4.5	58.1
3	4.0	38.8	4.6	45.4	5.5	63.6
5	4.4	34.4	4.7	44.7	6.9	65.6
7	5.1	35.3	5.8	44.3	7.0	63.8

The specimens were cured in water held at room temperature

Table 2 Flexure and compressive strength of mortar bars after exposure to 1 N NaOH solution

Fiber volume (%)	3 days		7 days		28 days	
	Flexure strength (MPa)	Compressive strength (MPa)	Flexure strength (MPa)	Compressive strength (MPa)	Flexure strength (MPa)	Compressive strength (MPa)
0	3.3	39.5	2.5	30.5	2.7	32.6
1	3.8	40.1	3.0	40.5	2.9	37.1
3	4.2	45.3	4.3	44.4	4.7	45.6
5	4.9	48.5	5.3	47.3	5.8	52.1
7	6.0	48.2	6.2	47.4	6.6	54.3

The specimens were cured in 80 °C water bath for 1 day and immersed in 1 N NaOH solution held at 80 °C

exposed to 1 N NaOH solution are given in Table 1. Each data point represents the average of three specimens. The flexure strength increases with increasing fiber volume fraction. The fibers are indeed effective in controlling crack initiation and crack formation and hence have the potential to resist and mitigate cracking associated with the expansion of the AS gel.

The flexure and compressive strength results of specimens exposed to NaOH solution are given in Table 2. Both the compressive and the flexure strength of the specimens without fiber reinforcement decreased considerably between 3 and 7 days of exposure time to 1 N NaOH solution. The cracking associated with the expansive AS gel formation is responsible for the observed strength reduction. No further strength degradation was observed between 7 and 28 days of exposure time to NaOH solution which may be due to cracks being filled with AS gel.

The specimens of set II (after 3 days exposure to NaOH) exhibit a higher flexure and compressive strength compared to set I (after 3 days of curing). The higher strength can be attributed to the higher curing temperature which accelerates hydration and densification of the matrix and fiber/matrix interface. The important result, however, is the lack of strength loss for specimens reinforced with fiber volume fractions above 0.01 compared to the un-reinforced matrix after both were exposed to ASR (Table 2). In addition, SEM analysis revealed considerably less cracking around the reactive aggregates in steel fiber-reinforced specimens compared to the un-reinforced specimens. The

reduced cracking and lack of strength degradation confirms that these steel fibers are effective in mitigating damage due to ASR.

Summary

An alternative approach to prevent damage associated with ASR was discussed. This approach focuses on using steel fibers to control cracking associated with the volumetric expansion of the AS gel. The mortar specimens without fibers exhibit excessive cracking and hence reduction in compressive and flexural strength due to ASR. Cracking associated with ASR was successfully controlled and minimized with steel fibers at fiber volumes beyond 1% as confirmed by both microstructure analysis and lack of strength degradation for specimens exposed to 1 N NaOH solution for up to 28 days. Furthermore, the expansion associated with ASR was reduced with increasing fiber volume fraction. The lack of crack formation prevented the AS gel from leaving the reactive aggregates and hence confined it to the reaction sites.

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