Mitigation of expansive Alkali Silica Reaction with Microfibers

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ABSTRACT: Alkali silica reaction (ASR) generates expansive forces that cause cracking and strength loss. In addition, the newly created cracks facilitate the ingress of harmful reagents from the environment resulting in faster degradation of the material. Most current remedies to mitigate ASR utilize a chemical approach. This paper, however, reports results on mitigating ASR through a mechanical approach that focuses on controlling the cracking due to ASR. Since these cracks start as microcracks at the reactive aggregate/matrix interfaces, microfibers were chosen to control these microcracks at the reaction site at onset. Microfiber reinforcements successfully reduced the cracking and strength reduction due to ASR. Furthermore, the resistance to crack propagation due to microfibers decreased the reactivity of the aggregates and lead to a reduction in alkali silica gel formation.

Keywords: Alkali silica reaction, microfibers, crack formation due to ASR, gel formation, low viscosity alkali silica complex, expansion.

1. INTRODUCTION

Alkali silica reaction (ASR) is a chemical reaction between the alkalis and hydroxyl ions in the pore solution and the silica present in aggregates. Hydroxyl ions attack the silicon-oxygen bond of the silica, creating an alkali-silica gel. The AS gel imbibes water, expands and thereby exerts internal pressures which sometimes could be far in excess of that which concrete can sustain (Swamy 1991).

The most common way of reducing expansion due to ASR is i) by modifying the chemical environment in which the alkali silica reaction takes place, for example by avoiding reactive aggregates or using low alkali cement or ii) by changing the expansion characteristics of the AS gel through the addition of mineral admixtures or lithium salts (Malvar 2001). However, influencing the reaction chemistry or expansion characteristics of the AS gel reveals mixed results on their effectiveness in reducing the expansion and hence damage associated with ASR. As little as 0.5% of a defective aggregate may be enough to cause

damage to the concrete. On the other hand, it is not possible to determine beforehand with certainty the rocks that are vulnerable, but experience has indicated certain classes of material that should be treated with caution. Unfortunately, more and more quarries containing non-reactive aggregates are being depleted. Low alkali cement may not be sufficient to prevent ASR since alkalis can derive also from aggregates, mineral and chemical admixtures, and from external sources such as from deicing salts and marine environments. The alkalis from external sources have quick and devastating effects on concrete susceptible to ASR. The results on addition of mineral admixtures and lithium salts on reducing expansion and damage associated with ASR are contradictory due to their variations in chemical compositions (Hobbs 1986) and concentrations (Kawamura & Fuwa 2003).

Due to these aforementioned shortcomings, a different approach to mitigating ASR was explored. Whereas the chemical approach discussed above focuses on either preventing the formation of the AS gel or its expansion characteristics, the mitigation of

ASR in the new approach modifies and controls the cracking process associated with ASR.

Cracks initiate in response to tensile stresses exerted onto the matrix by the expansive processes associated with the formation of the AS gel. Once a crack initiates, its propagation will occur in a brittle manner (i.e. with decreasing expansion stresses) due to the lack of energy absorbing mechanisms that resist crack growth. Crack formation due to expansive processes occurs in close vicinity to the reaction sites. Since these cracks initiate as microcracks they need to be influenced at this stage prior to them becoming macrocracks. One effective way to enhance the resistance to crack propagation is through fiber reinforcements. However, for this type of application conventional fibers are not as well suited because their large diameters cannot bridge small microcracks at onset. To influence these small microcracks, steel microfibers (SMF) were used.

The effect of microfibers on alkali-silica reaction was investigated using two different specimen configurations but same test method (ASTM C1260). The cracking, strength and expansion characteristics due to microfibers were determined using crushed opal aggregates with the same size distribution as the sand aggregates. The influence of microfibers on reactivity and gel formation was investigated using a rod shaped aggregate of constant diameter embedded in the control and microfiber reinforced mortar. This novel method also lends itself to determine the reaction products in detail.

2 EXPERIMENTAL Procedures

2.1 Crushed opal as reactive aggregate

The following experiments were conducted with crushed opal aggregates: a) Microscopy analysis on cracking due to ASR, b) Flexure and crack propagation tests to measure the deterioration of the mechanical properties due to ASR, and c) Expansion measurements. For these experiments, the steel microfiber content was either 0% or 7% by volume. The total amount of opal as reactive aggregates constituted 5% of the total fine aggregates by mass. Specimens (2.5cm x 2.5cm x 28.58cm) with 25.4cm gage length were cast in steel mould. After casting, the specimens were stored in the fog room at room temperature and demolded after 24 hr. The demolded specimens were cured in water at 80°C for 6 days before submerging them in aqueous 1 N sodium hydroxide (NaOH) solution in order to be able to compare and be consistent with previous work on the

effect of SMF on ASR (Garci Juenger & Ostertag 2002); (Turanli et al. 2001). The specimens were then exposed to 1 N sodium hydroxide solution at 80°C.

Strength properties of the specimens (2.5cm x 2.5cm x 28.58 cm) with and without steel microfibers were measured in third point loading, after they were exposed to the NaOH solution for 0, 7 and 14 days. Three beams were tested for each exposure time. For the crack propagation measurements, compact tension specimens (5cm x 5cm x 6 mm) were tested after exposure to the sodium hydroxide solution for 0, 7 and 14 days. Three specimens were tested for each exposure time. Detailed information on the loading device and testing procedure can be found in (Ostertag & Yi 2000). For the expansion measurements, the lengths of the beams were measured after 0, 2, 6, 9, and 12 days of exposure to the alkali solution.

2.2 Pyrex rod as reactive aggregate

Unreinforced and steel microfiber reinforced specimens with a Pyrex rod (5.27± 0.01 mm diameter) as the reactive aggregate embedded in their center were used to a) determine the difference in reactivity of the reactive aggregates in presence of a SMF reinforced matrix, b) for microprobe analysis to reveal and determine the chemical composition of the solid alkali-silica reaction, and c) for Inductive Coupled Plasma Spectroscopy (ICP) to determine the composition of the liquid alkali-silica complex.

The mortar (with 0 and 7 vol % of steel microfibers) was placed in two layers, each layer with approximately 12mm (½") in thickness. Each layer was compacted by a steel rod until there is no apparent decrease in volume. After the first layer was placed into the form, the rod was inserted into the mortar and covered with the second layer of mortar. The specimens cured in a water batch heated to 80°C and subsequently submerged into a 1 N NaOH aqueous solution.

The reactivity of the Pyrex rod due to ASR in the control and microfiber reinforced mortars was determined by carefully measuring the remaining diameter of the Pyrex rod after it had been exposed to the alkali solution for up to 77 days. The prisms from each set were removed from the NaOH solution at intervals of 7-8 days. For the microprobe analysis, thin sections of mortar specimens with smooth surfaces were prepared. The liquid ASR products were extruded from the ASR site around the Pyrex rod. The chemical composition of the liquids obtained from the mortars with and without steel microfibers were

analyzes by Inductive Coupled Plasma Spectrometry (ICP).

3. RESULTS AND DISCUSSION

3.1 Crushed opal as reactive aggregate

Cracking characteristics: Whereas long cracks filled with a gel like substance emanated from the AS reaction sites in the control specimens, only a few short cracks with small crack opening displacements were found in the microfiber reinforced mortar specimens even after exposure time of 35 days to the 1 N NaOH solution. The resistance to crack propagation is associated with microfibers bridging and pinning the crack surfaces in the crack wake (Yi & Ostertag, 2001).

Strength characteristics: The flexural strength of reinforced and unreinforced beams was tested in third point loading. The strength of the plain mortar deteriorated rapidly as the exposure time in the NaOH solution was increased. The flexural strength of the control beams reduced by as much as 77% during the 0 to 7 day exposure to the NaOH solution. On the other hand, the reduction was only 12% for the 7vol% SMF specimens. The unreinforced specimens recovered some of their strength loss (12%) after being exposed to NaOH solution for 14 days. The strength increase may be attributed to the filling of the cracks with AS gel.

   For the crack propagation measurements, the maximum load required in propagating a crack in the unreinforced and SMF reinforced compact tension specimens was recorded before (at 0 days) and after the specimens were exposed to 7 and 14 days to 1 N NaOH solution. The maximum load decreased with increasing exposure time to NaOH solution for the unreinforced mortar with the largest reduction between 0 to 7 days of exposure to the NaOH solution (top of fig. 1). However, the maximum load remained nearly constant for the SMF reinforced mortar specimens (bottom of fig. 1). The lack of strength degradation due to SMF supports their effectiveness in controlling cracks associated with ASR.

*Expansion characteristics***:** The expansion of the control specimens far exceeded that of the SMF mortars specimens. The steel microfibers are very effective in delaying the expansion. The highest rate of expansion occurs during the first 2 days of exposure for the control specimens
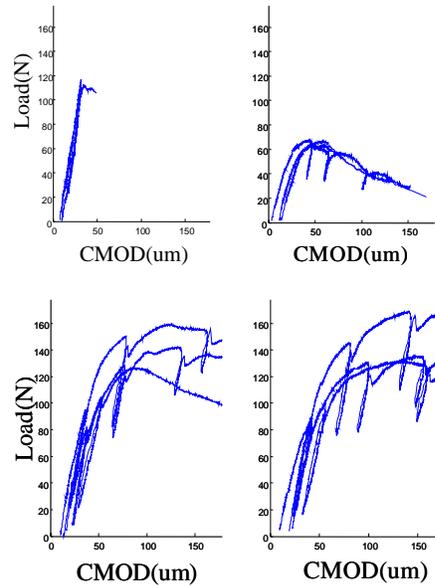
Figure 1: top P-CMOD plots: control specimens before (left) and after 7 days exposure to NaOH (right); bottom P-CMOD plots: SMF specimen before (left) and after 7 days exposure to NaOH (right)

while steel microfiber reinforced specimens showed slow initial expansion for the same period. The steel microfibers not only reduce the initial expansion but also the overall expansion compared to the control prisms. After being exposed to the 1 N NaOH solution for up to 12 days the SMF mortar bars expands only 33%, three times less than the control specimens. Thus, it is plausible that the difference in expansion between the control and SMF mortars will increase even further with time.

   Steel microfiber reinforced mortar specimens are hence proved to be effective in reducing expansion by delaying crack initiation and crack extension as evidenced by microcopy analysis, flexure strength and crack propagation measurements. However, for a better understanding on ASR mechanisms, the following question needs to be answered: could the decrease in expansion, cracking and hence lack of strength loss be due to a reduction in gel formation triggered by the presence of the steel microfibers? Reactive opal aggregates with their irregular shapes and sizes are not well suited to answer this question. The results would be inconclusive because the reactivity of the opal aggregates will not only be influenced by the steel microfibers but also by the size of the aggregates. Therefore, the opal aggregates were replaced by a reactive rod of constant diameter in order to study the effect of microfibers on reactivity and gel formation.

3.2 Pyrex Rod as Reactive Aggregate

Reactivity of Pyrex rod and ICP analysis: The Pyrex rod in SMF mortar reacted far less compared to the unreinforced mortar at same exposure times to NaOH solution. Figure 2 show backscattered images of the remaining cross sections of the Pyrex rods in plain and SMF mortar specimens after 35 days exposure to the NaOH solution. Both images have the same actual scanning area of 6mm by 6mm with the Pyrex rod in their center. For both specimens, the reaction takes place from the outer surface of the reactive rod and continues toward the center. Radial cracks are easily detectable in the unreinforced matrix, but not in the SMF mortar specimens at this magnification. The steel microfibers, which show up white in the backscattering mode, are located close to the reaction site. The reaction rate is 72% faster in the control versus the SFR mortar. This high reactivity of the control specimens causes the faster expansion observed.

When the specimens were cut for the reactivity measurements, white precipitates and a watery liquid, presumably an alkali-silica complex, were lost resulting in a cavity between the remaining Pyrex rod and the mortar. The cavity extends along the whole length of the Pyrex rod. The cavity (dark region surrounding the reactive rod shaped aggregates in fig. 2) was subsequently filled with epoxy used to aid in polishing the surface. Although most of the alkali-silica complex is lost during the preparation of the thin sections, solidified layers of AS gel are observed close to the mortar. The composition of the solid AS gels in the SMF mortar specimens differ in their Ca and Na concentration. The gel closer to the mortar matrix exhibits a higher Ca concentration compared to the gel closer to the Pyrex rod, whereas, the latter is richer in Na concentration compared to the gel close to the mortar matrix.

The reactivity and composition of the ASR products can be elucidated based on the concentrations of the reactants. Therefore, additional beams with Pyrex rods were prepared, the low viscosity alkali silica gel extracted and its chemical composition analyzed by Inductively Coupled Plasma Spectrometry (ICP). Most of the published work is based on the chemistry of the pore solution, which is obtained by squeezing bulk concrete or mortar subject to ASR (Durant et al. 1990). The pore solution, unfortunately, lacks information that is specific to the ASR site. ICP analysis revealed a higher concentration of Na and Si ions in SMF reinforced composites compared to the control

a)

b)
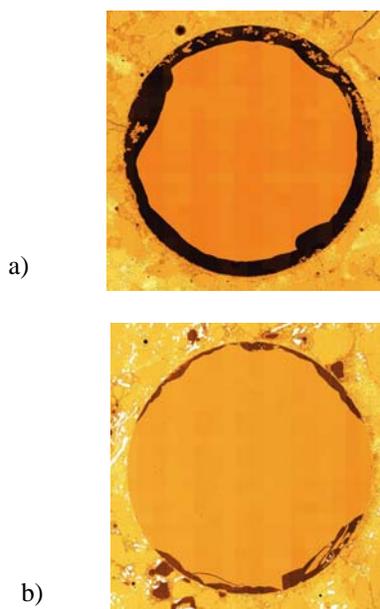
Figure 2: Backscattered images of the remaining cross section of the Pyrex rod in a) unreinforced and b) microfiber reinforced mortar after exposure to 1 N NaOH (aq) for 35 days

specimens. Higher concentrations found in the SMF mortar can be attributed to the lack of crack formation due to steel microfibers. Once a crack formed, the silica gel flows away from the reaction site, reducing the concentration of the alkali silicates at the original ASR site.

Furthermore, the concentration of Na ion is much higher than that of the external NaOH bath ($\approx$1 mol/l) for both the control and SMF specimens. Thus, this high Na concentration confirms that the sodium hydroxide solution permeates through the mortar and reacts with the Pyrex rod forming the alkali-silica complex. The lower reactivity of rod shaped aggregate embedded in the SMF mortar can also be deduced from the higher silicon ion concentration which slows down further dissolution of silica in the reactive aggregate.

4. CONCLUSION

The mechanical approach of using microfibers to mitigate the cracking and strength loss proved successful in specimens exposed to alkali silica reaction. In SMF mortars the cracking was considerably reduced which prevented the strength degradation commonly observed due to ASR. Steel microfibers exert closure stresses onto crack surfaces,

which requires a higher driving force for crack extension. The higher resistance to crack extension reduces the crack length in SMF mortar specimens, which reduces the amount of AS gel that can leave the reaction site compared to unreinforced mortar specimens. The reduced migration of AS gel away from the reaction site may be responsible for the increased sodium and silica ion concentration that was observed in the AS liquid at the reaction site in the SMF mortar specimens. The higher ion concentration may be the reason for the reduced rate of the alkali-silica reaction. In other words, the faster reactivity observed in the plain mortar bars was induced by early crack initiation and low crack growth resistance which loosened the restrain around the Pyrex rod and allowed faster ingress of external reagents and extrusion of the silica complex out of the reaction site.

5. REFERENCES

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