Behavior of Fiber Reinforced Concrete Exposed to Alkali and Salt Solution: A Comparative Study in Microscale

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1. Introduction

Alkali silica reaction is one of the major deterioration processes in reinforced concrete structures which affects materials and mechanical properties. This results in decreased strength, permeability and stiffness leading to loss in durability and premature failure in structures. ASR is initiated with the presence of sufficient alkalis (Na₂O and K₂O), reactive silica and enough moisture content. ASR gel is produced with the reaction between hydroxyl ions from Portland cement hydration, and amorphous silica in the aggregate under the presence of moisture. The alkali silica gel imbibes surrounding moisture and expands. This yields internal stresses at the mortar aggregate interface which subsequently induces cracks in concrete.

The reactive forms of silica such as opal (amorphous), chalcedony (cryptocrystalline fibrous) and tridymite (crystalline) are susceptible to cause ASR¹). It is recommended to limit the amount of alkali content in cement repressed as sodium oxide equivalent (Na2Oeq) to 0.6%, when using a reactive aggregate (ASTM C150). In contrast, the use of low alkali cement may not effectively prevent alkali aggregate reaction in severe alkaline environment²⁾. Chemical method, petrographic analysis and rapid mortar bar test methods have been widely used (ASTM C1260, C289, C295). Limiting the total alkali content in concrete (Na₂O_{eq}) to 3 kg/m³ is another effective way to control deleterious expansion due to ASR in concrete. The effect of environment and exposure conditions such as relative humidity, temperature, presence of external alkalis and salt solutions are also considered important aspects that control the rate of alkali aggregate reaction and corresponding expansion. RH higher than 80% is necessary to initiate ASR. Previous studies indicate that exposure to salt solutions can be even more aggressive than to alkali solutions

Chemical Analysis (Oxide)	Coarse Aggregate	Fine Aggregate	
Fe ₂ O ₃ (%)	7.67	20.342	
K ₂ O (%)	2.06	2.323	
CaO (%)	7.62	8.210	
SiO ₂ (%)	59.9	65.86	
Al ₂ O ₃ (%)	16.8	-	
MgO (%)	1.93	-	
Na ₂ O (%)	2.81	-	
MnO (%)	-	0.4289	
$TiO_2(\%)$	-	2.0882	
Alkali (Na ₂ O _{eq})	0.455	0.125	

Table 1. Chemical Composition

because they release hydroxyl ions which increases the alkalinity of concrete³⁾. The ASR damage can be observed in the form of map cracking on the surface of concrete.

In the past few decades, several studies assured that the use of steel fiber in concrete improved the structural strength, decreases permeability and controls crack width. It has also been investigated that they control expansion and reduce microcracking due to alkali silica reaction depending on fiber type and volume fraction, as reported by various researchers 4, 5). ASR gradually reduces tortuosity of concrete, allowing other deleterious substances such as sulphates, chlorides etc to penetrate inside. The process is followed by corrosion, which reduces the durability and serviceability of concrete in the long term. Hence, the development of prevention techniques in order to overcome damage due to coupled effects of two or more deterioration processes is necessary. This research is an attempt to examine such coupled effects of alkali silica reaction and chloride ion penetration in steel fiber reinforced concrete. Normal strength concrete specimens fabricated with low alkali cement, river sand and a reactive coarse aggregate were prepared. The effect of addition of normal and high strength steel fibers at 40°C was studied.

2. Experimental Procedure

Тур

Young's Modulus (GPa)

Tensile Strength (GPa)

Plain concrete, normal and ultra-high strength fiber reinforced concrete having target compressive strength of 35-40 MPa at 28 days were fabricated. Steel fibers having different shapes, anchorage strengths and ductility were selected whereas, parameters such as length, aspect ratio and volume fraction were kept constant for both types of fiber reinforced concrete mixes. Low alkali Portland cement containing alkali content (Na₂O_{eq}) of 0.48%, river sand as fine aggregate and a reactive coarse aggregate from a local source was used.

Table 2. Steel Fibers					
e of Steel Fiber	Normal	High			
	Strength	Strength			
Length (mm)	60	60			
Diameter (mm)	65	65			

210

1.16

210

2.36

Table 2 Steel Fiber

Table 3 Mix Design								
Mix Type	Cement	Fine	Coarse	Water	Fiber			
	(kg/m^3)	Aggreg	Aggreg	(kg/m^3)	(kg/m			
		ate	ate		3)			
		(kg/m^3)	(kg/m^3)					
PC					0			
SRFC	318	818	1093	181	15			
UHSRFC					15			

The reactivity of coarse aggregate was confirmed by JIS A 1145:2007 chemical test method. The total alkali content of concrete expressed as sodium oxide equivalent (Na_2O_{eq}) was 2.1 kg/m³. The reactive aggregate had water absorption of 2.28%, and bulk density of 1540 kg/m³. Chemical composition of the fine and coarse aggregates, properties of steel fiber and mix design are listed in Tables 1, 2 and 3 respectively.

Fifteen prisms measuring 40 cm x 10 cm x 10 cm (length x width x height) prisms, water cured for 14 days at room temperature were fully submerged in 1 N NaOH solution at 40°C. After ten weeks, all the specimens were taken out and wiped to remove excess NaOH from the surface. They were then shifted to 3% NaCl solution (by mass) for ten more weeks.

Plastic tanks that can tolerate high alkali environment were used to submerge the specimens. Temperature of 40 ± 2 °C was maintained using electric heater having a calibrated automatic temperature control dial with the range of 30 to 80 °C. After the alkali and salt water exposure was completed, the specimens were removed from the solution and air dried for 24 hours.

3. Testing

Three-point bending test according ASTM C 78 was conducted on the prisms. Deflection control universal testing machine was used to conduct three-point bending. Concrete prisms were loaded at the rate of 0.1 mm/min until fracture. 12 mm diameter cores from ASR damaged and combined ASR and chloride environment damaged prisms were taken out. The samples obtained from each type of concrete mix were gold coated for qualitative and quantitative analysis using scanning electron microscopy equipped with energy dispersive X-ray spectroscope (SEM-EDS).

4. Results and Discussions

Figure 1 shows the first crack strength of undamaged prisms, prisms damaged due to ASR and prisms damaged due to coupled effect of ASR and chloride ion penetration. The ASR prisms showed an increase in strength followed by a declining trend in prisms damaged due to ASR and chloride environment. The same trend was observed in all types of the concrete mixes. The ratio of final strength (damaged) to initial strength (undamaged) termed as "strength reduction factor" was used to analyze the change in strength (Figure 2).

The SEM (EDS) analysis at the location of micro-cracking and in the vicinity of ASR gel in each sample revealed the following results:

Plain Concrete: Micro-cracking was observed in ASR and combine ASR and salt environment damaged specimens. These micro-cracks were filled with ASR gel (Figure 3). Further quantitative analysis of these gels indicated a higher percentage of calcium oxide and lower percentage SiO₂ for ASR damaged specimens as compared to combine deteriorated specimens near cracks (Figure 4a and 4b). Comparing % by mass of CaO and



□ Undamaged ■ ASR Damaged ■ ASR and Chloride Ion Damaged

Figure 1. Effect of ASR and Chloride Environment Damage on First Crack Strength (MPa)



Figure 2. Strength Reduction Factors Corresponding to Exposure Conditions



Figure 3. SEM: Quantitative Analysis of ASR gel in PC exposed to (a) Alkaline Environment (b) Alkaline and Salt Environment

SiO for the specimens exposed to salt solution, it was deduced that the rate of damage increased.

The specimens exposed to NaOH solution, alkali and hydroxyl ions reacted with silica and the later product reacted with calcium. This yielded calcium alkali silicate gel. As the reaction progressed, the concentration of alkali in pore solution decreased with the increase in calcium concentration. The result was the production of ASR gel rich in calcium that caused increase in first crack strength. Such hypothesis was also given previously while studying 'safe reaction' for ASR in opal ⁶.

For the specimens that were continuously exposed to NaOH solution followed by NaCl solution, strength reduction was observed possibly due to the production of Friedel's salt. NaCl gives hydroxyl ions by converting to Friedel's salt. These ions rapidly accelerate ASR reaction and dissolves silica. The equation is given as;



Figure 4 (a) Composition of ASR Damaged PC Specimen



Figure 4 (b) Composition of ASR and Salt Damaged PC Specimen



Figure 5. Quantitative Analysis of ASR gel in SFRC exposed to (a) Alkaline Environment (b) Alkaline and Salt Environment



Figure 6 (a) Composition of ASR Damaged SFRC Specimen



Figure 6 (b) Composition of ASR and Salt Damaged SFRC Specimen



Figure 7. Comparison of Percentage Increase/ Decrease in First Crack Strength exposed to Alkaline Environment and Combined Alkaline and Salt Environment

C₃A + 2NaC1 + Ca(OH)₂ + 10 H₂O C₃A.CaC1₂.10H₂O + 2Na + 2(OH)⁻

Hence increased deterioration by NaCl exposure diminished the first crack strength.

Steel Fiber Reinforced Concrete: Production of ASR gel and evidence of micro-cracking were also observed in SFRC (Figure 5). Quantitative analysis of gels in both cases indicated comparable values of CaO and SiO₂ in ASR and combine damaged specimens. The amount of SiO₂ at different locations ASR damaged specimens were as good as in ASR and chloride damaged specimens (Figure 6a and 6b). Addition of NaCl increased the rate of ASR reaction in SFRC decreasing its strength, but the damage was less than plain concrete. Figure 7 shows the percentage increase or decrease in first cracked strength for all the mix types at different exposure conditions. The negative values indicate decrease in strength. Addition of fiber to concrete mix improved concrete endurance against damage by alkali and chloride environment. Strength reductions in PC and SFRC were 11.48% and 4.7% respectively.

Ultra-High Strength Fiber Reinforced Concrete: Similar to PC and SFRC, USFRC also experienced micro-cracking due to ASR gel as shown in Figure 8). Quantitative analysis of ASR gel produced from alkaline exposure and that produced from alkaline and chloride environment yielded almost similar amount of CaO and SiO₂ as shown in Figure 9a and 9b. Although the specimen were deteriorated and cracked, unusual



Figure 8. SEM: Quantitative Analysis of ASR gel in SFRC exposed to (a) Alkaline Environment (b) Alkaline and Salt Environment



Figure 9 (a) Composition of ASR Damaged UHSFRC Specimen



Figure 9 (b) Composition of ASR and Salt Damaged UHSFRC Specimen

increase in strength was observed (Figure 7). Such an increment in strength can be related to addition of high strength fiber. Properties such as higher anchorage strength, higher tensile strength and ductility were able to prevent strength loss. Orientation of fiber is another crucial factor that can result in increment, as fibers are randomly oriented in the mix.

5. Conclusions

The following conclusions can be drawn from the study in this paper:

- Addition of steel fiber to concrete improves durability against alkali and chloride environment. As the first crack strength loss in SFRC and UHSFRC was less than PC.
- Despite the fact that the total alkali of concrete was less than 3 kg/m³, considerable micro-cracking in all the specimens was observed.
- Exposure to salt solution after alkali solution aggravates alkali silica reaction.
- Production of calcium rich ASR gel increased the first crack strength in plain concrete, which eventually decreased due to dissolution of silica.
- SFRC and UHSFRC also experienced the same strength increment, and were able to prevent strength loss by 6.78% and 20.2% respectively.

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