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Role of fibers in controlling unrestrained expansion and arresting cracking in Portland cement concrete undergoing alkali–silica reaction

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Abstract

An experimental study was undertaken to investigate the role of polypropylene or brass-coated steel fibers in controlling unrestrained expansions and delaying and arresting cracking in Portland cement concrete due to alkali–silica reaction. Portland cement concrete and fiber-reinforced concrete (FRC) mixtures were prepared at a w/c ratio of 0.40 using modified Type I cement, reactive fine particles, and coarse limestone aggregates. Prism (5 × 5 × 30 cm) and plate (13.5 × 13.5 × 3 cm) specimens were prepared and cured for 7 or 28 days before exposure to a special treatment to accelerate ASR. Expansion, time of cracking, and ultrasonic pulse velocity were determined over a treatment period of 65 days using prism specimens. Ultimate cracking pattern and extent were determined after a treatment period of 85 days using plate specimens. The results showed that while fibers did not contribute significantly to controlling pre-cracking and post-cracking expansions, they played a significant role in delaying cracks formation and limiting their extent. Considering its lower cost and content, the performance of polypropylene fibers was superior to that of brass-coated steel ones. The potential of brass-coated fibers in arresting ASR cracking was significantly affected by age of concrete when subjected to treatment.

Keywords: Alkali–silica reaction; Expansion; Fibers; Arresting cracking

1. Introduction

During its service life, Portland cement concrete is exposed to physical and chemical attacks, the most widely recognized of which are steel corrosion, alkali silica reaction (ASR), and freezing and thawing. These attacks may lead to deterioration of concrete structures overtime, thus reducing its structural capacity and affecting negatively its serviceability.

Poor quality control of aggregate and cements may lead to using active silica aggregate and high alkali-cement in preparing concrete, thus resulting in an aggressive reaction between the metal alkalis in the pore water of concrete and the silica ions (from amorphous high-content silica aggregate). The product of this reaction is a complex silica gel, which expands by taking up water inducing expansive stresses occasionally large enough to cause cracking and expansion of concrete. Early cases of deterioration due to ASR have been reported in some structures in California in the 1930s [1]. ASR-induced cracks contributed to the deterioration of concrete in reinforcing members, hence reducing substantially its load capacity [2–4]. Cracking produced by ASR would also allow easy intrusion of chloride that may result in steel corrosion during a relatively short period of time [5].

Research on concrete members showed that ASR might create large irreversible concrete and steel strains, which will negatively affect the overall serviceability, strength, and stability of reinforced beams. The maximum reported loss in flexural capacity due to ASR reached as high as 25% [2,3]. It was reported also that expansion in reinforced concrete was greatly reduced as compared to that in plain concrete, and that the resulting cracking was oriented mainly in the direction parallel to reinforcement [4].

Studies concerned with the role of fibers in preventing and/or reducing concrete cracking due to drying shrinking, or creep strains indicated contradictory conclusions [6–12]. While some studies showed that fibers had an insignificant effect on unrestrained shrinkage, others indicated a real contribution of fibers in reducing restrained shrinkage of fiber-reinforced concrete (FRC) [6–9]. As for creep, most investigations indicated that creep strain of FRC with steel

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or polypropylene fibers was higher than that of plain concrete [10,11]. Contradicting results by Mangat and Azari [12] that showed the opposite were reported.

This paper attempts to establish a better understanding of the role of fibers in controlling expansion and/or arresting cracking in concrete due to alkali–silica reaction. Two types of fibers were used at different volumetric fractions of concrete: high performance brass-coated steel at contents of 0.5% and 1.0%; and polypropylene at a content of 0.15%. Plain concrete and FRC mixes were prepared using modified Type I cement, reactive fine particles, and coarse limestone aggregate. Specimens were cured in water at 23 °C for periods of 7 or 28 days before it was subjected to a special treatment in order to accelerate alkali–silica reaction. Expansion and cracking extent were evaluated over immersion period.

2. Experimental program

2.1. Materials

A mixture of fine particles consisting of equal proportions of crushed chert aggregate (containing up to 15% chalcedony) and crushed Pyrex with coarse limestone were used in preparing different mixtures. The coarse limestone had a maximum aggregate size of 12.5 mm. The percentages passing for fine particles were chosen according to ASTM C 1260 requirements for gradation of aggregate tested for ASR activity. The fineness modulus of fine particles was found to be 2.7. The fine particles were crushed using a stone crusher manufactured by Christy Hunt Engineering, England. The coarse limestone aggregate and the fine particles had a bulk specific gravity (SSD) of 2.56 and 2.3, and an absorption of 2.1% and 2.6%, respectively. The petrographic analysis of the natural aggregate indicated the following composition: radial fibrous quartz = 15%; cryptocrystalline quartz = 80%; and phosphate = 5%. The X-ray diffraction analysis of Pyrex used indicated a silica content in excess of 80%. The chemical composition of coarse aggregate used is listed in Table 1.

Table 1
Chemical composition of modified Type I cement and limestone aggregate

Oxide	Modified Type I cement (%)	Limestone (%)
Si_2O	21.21	0.98
CaO	63.69	65.46
Fe_2O_3	3.11	0.31
Al_2O_3	5.54	0.31
MgO	1.5	0.25
SO_3	2.63	0.0
$(Na_2O + 0.658\ K_2O)$	1.30	0.0
IR	0.12	–
LOI	0.96	42.5

IR = insoluble residue; LOI = loss on ignition.

Type I ordinary Portland cement was used, including a modified alkaline content equivalent to 1.3% using KOH powder. The chemical composition of the modified cement is listed in Table 1. FRC mixtures were prepared by adding fibrillated polypropylene fibers with two-dimensional packs of continuous network of stretched and split films at 0.15% or brass-coated steel fibers at 0.5% and 1% by concrete volume. Polypropylene and brass-coated steel fibers were supplied by Harex, USA, and Bekaert, Belgium, respectively. The tensile strength, young modulus, specific gravity, and fiber length of polypropylene fibers are 650–760 MPa, 3.5 GPa, 0.9 g/cm^3, and 1.2 cm, respectively. The yield strength, length, and the diameter for brass-coated steel fibers are 3950 MPa, 0.6 cm, and 0.015 cm, respectively.

2.2. Mix proportions and specimens preparation and conditioning

Plain concrete and FRC mixtures were proportioned at a w/c ratio of 0.40 with equal proportions of coarse and fine particles by weight. Mixing was carried out using a tilting drum mixer of 0.04 m^3 volume according to ASTM method C212 [13]. The fibers used were pre-blended with fine particles before mixing.

Two types of specimens were cast: prisms (5 × 5 × 30 cm) and plates (13.5 × 13.5 × 3 cm). The prisms were used for measuring expansion, and ultrasonic pulse velocity, and monitoring cracks initiation. They were cast by placing concrete in two layers, each consolidated on a vibrating table. Embedded type strain gages (18 × 1.3 × 0.5 cm) with a gauge length of 12 cm and manufactured by Tokyo Sokki Kenkyujo, Japan, were inserted in the prisms after casting the first layer. Specimens' surfaces were finished smooth by a trowel before placed in a moist room for 24 h. Then they were demolded and placed in a water bath to cure at 23 °C for periods of 7 or 28 days.

In order to accelerate ASR, specimens cured for the above periods were placed in a water solution of 0.5 N NaOH at a temperature of 40 °C. The specimens were kept in the solution for about 85 days, during which experimental testing was performed according to the description of Section 2.3. Prior to any testing, all specimens were left in laboratory air to dry and cool down for about half an hour.

2.3. Testing and cracking evaluation

Measurements of expansion were carried out on prisms using a strain indicator, manufactured by Instrument Division, USA. These were terminated before 65 days of immersion in NaOH solution as readings of embedded strain gages showed a continuous reduction. This occurred due to the damage of the concrete in the vicinity of the strain gage, causing its relaxation. Direct and indirect ultrasonic pulse velocity measurements were also taken for prisms according to ASTM test method C 597. The average of two test specimens was taken for expansion and ultrasonic pulse velocity.

In order to evaluate the progress of damage by ASR, plain concrete and FRC prisms were monitored visually for color changes and crack initiation, whereas generated cracking on the surfaces of plate specimens was mapped by marking cracks observed by an optical magnifier. Photos of the mapped cracking pattern were taken for plain and FRC plates. At the same time, crack length and depth measurements were performed on cracked plates by the aid of a special scale.

3. Results and discussion

The high content of stained silica and alkalis in both fine aggregate particles and cement used, respectively, caused an aggressive ASR that started in less than 24 h of conditioning as indicated by the relatively high-induced strain and by the change in color. The color of specimens changed from greenish to whitish as reaction went on. After certain induced strains, cracks appeared on the surfaces of prism and plate specimens. The time to cracking and its extent depended on fiber type and content, and on curing age before the treatment in NaOH solution.

3.1. Role of fibers in controlling ASR expansion

Figs. 1 and 2 depict expansion time history for brass-coated steel and polypropylene FRC, respectively, after being cured for 7 days before ASR treatment. In the pre-cracking stage, the results indicated similar expansion for both plain concrete (0% fibers) and FRC with brass-coated fibers or polypropylene. However, in the post-cracking stage, FRC prisms showed higher expansion than that of plain concrete, and the difference in expansion increased as ASR progressed.

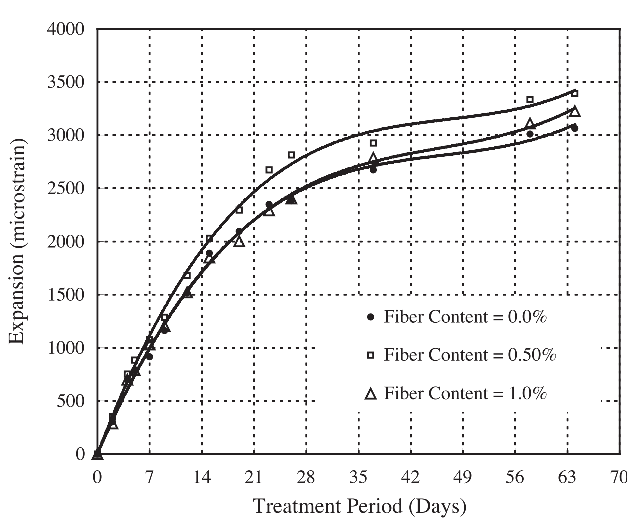

Fig. 1. Expansion time history for plain concrete and for FRC with brass-coated steel fibers immersed in NaOH solution at 40 °C for about 65 days.

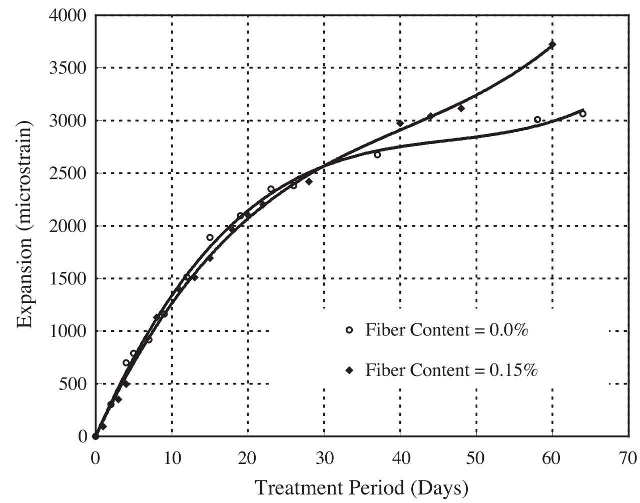

Fig. 2. Expansion time history for plain concrete and for FRC with polypropylene fibers immersed in NaOH solution at 40 °C for about 65 days.

The above behaviors can be explained as follows. In the pre-cracking stage, both plain concrete and FRC had close moduli of elasticity, estimated to range from 30 to 31 GPa. Hence, both showed similar expansions (caused by the swelling of the complex silica gel). In the post-cracking stage, however, the response to the swelling of the silica gel in FRC and plain concrete specimens was different. Because of its higher ductility, FRC expanded more and showed less cracking than that in plain concrete [14]. This argument is supported by the increase in expansion difference between FRC and plain concrete as treatment went on and by the higher cracking extent in plain concrete observed in the post-cracking stage (after 85 days of ASR treatment).

The effect of age at first exposure to ASR treatment is depicted in Fig. 3. As can be noticed, FRC with brass-coated steel fibers showed higher resistance to expansion when

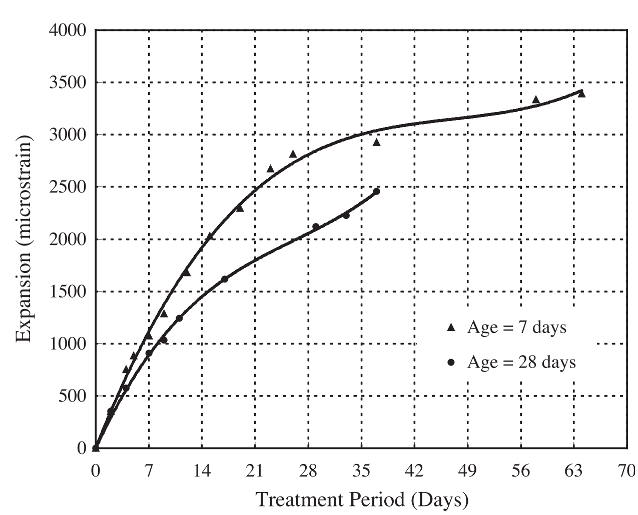

Fig. 3. Expansion time history for FRC with brass-coated fibers immersed in NaOH solution at 40 °C after curing for 7 and 28 days.

Table 2
Time and strain to cracking for plain concrete and FRC prisms

Mix	Fiber content and type	AAE (days)	TTC (days)	Expansion range (micro-strain)	Expansion (micro-strain)
I	0%	7	7–11	946–1295	1121
		28	14–21	925–1237	1081
II	0.50% BCS	7	15–19	2029–2151	2090
III	1.0% BCS	7	32–35	2716–3124	2920
		28	29–33	2122–2225	2174
IV	0.15% PP	7	40–44	2420–3025	2730

AAE = age at exposure to ASR treatment; TTC = time to cracking; BCS = brass-coated steel fibers; PP = polypropylene fibers.

cured for 28 days than that when cured for only 7 days, before exposed to ASR treatment. This may be referred to the relatively higher rigidity of the former. The relatively high brittleness of FRC after being cured for 28 days caused excessive damage around the embedded strain gages. Therefore, the measurements were terminated at a relatively early immersion period [15].

3.2. Role of fiber in delaying cracks initiation

The role of fibers in delaying cracking by ASR can be understood by the aid of Table 2. It should be noticed here that since cracking is random in nature, it was difficult to determine an exact time (or strain) at cracking. Therefore, it was more realistic to define a time or a strain range for identifying the time or strain at which cracking commences. The results clearly indicate that mixes at higher contents of fibers took longer period to crack (higher cracking strain), regardless of fiber type used. This shows the vital role of fibers in arresting cracking, hence delaying its appearance. It should be also mentioned that the effectiveness of fibers in delaying cracking is also dependant on the age at first exposure to treatment; plain concrete or FRC (at 1% brass-coated fibers) that was cured for 7 days showed higher cracking strain than corresponding ones cured for 28 days. This behavior is attributed to the higher elastic stain at cracking of specimens cured for 7 days as compared to that of those cured for 28 days.

3.3. Role of fibers in arresting ASR cracking

This role may be understood through the evaluation of cracking pattern and extent and ultrasonic velocity for plain concrete and FRC undergoing ASR. The cracking pattern and extent depended upon fiber type and content, and curing age before exposure to treatment. Figs. 4 and 5 show typical cracking patterns for plain concrete as compared to those of FRC with brass-coated steel and polypropylene fibers, being cured for 7 days before exposed to ASR treatment. It should be indicated that cracks formed were discontinuous and were distributed mostly next to the prism edges.

To quantitatively evaluate differences between the cracking patterns for different mixtures, Table 3 was developed based on measurements of length and depth of cracks formed on the prism specimens. Three major parameters were adopted to evaluate the extent of cracking, namely, cracking intensity, crack length range, and maximum crack depth. The cracking intensity is defined as total length of crack divided by surface area.

The data of Table 3 indicates a significant role of fibers in arresting ASR cracking. Specimens with fibers received less damage than those of plain concrete and cured for the same period before treatment. This is based on the lower cracking intensity, shorter crack sizes, and lower maximum crack depth for FRC specimens. The parameters of Table 3 showed that the use of higher contents of brass-coated steel fibers had imparted limited improvement to the resistance against cracking. On the other hand, using polypropylene

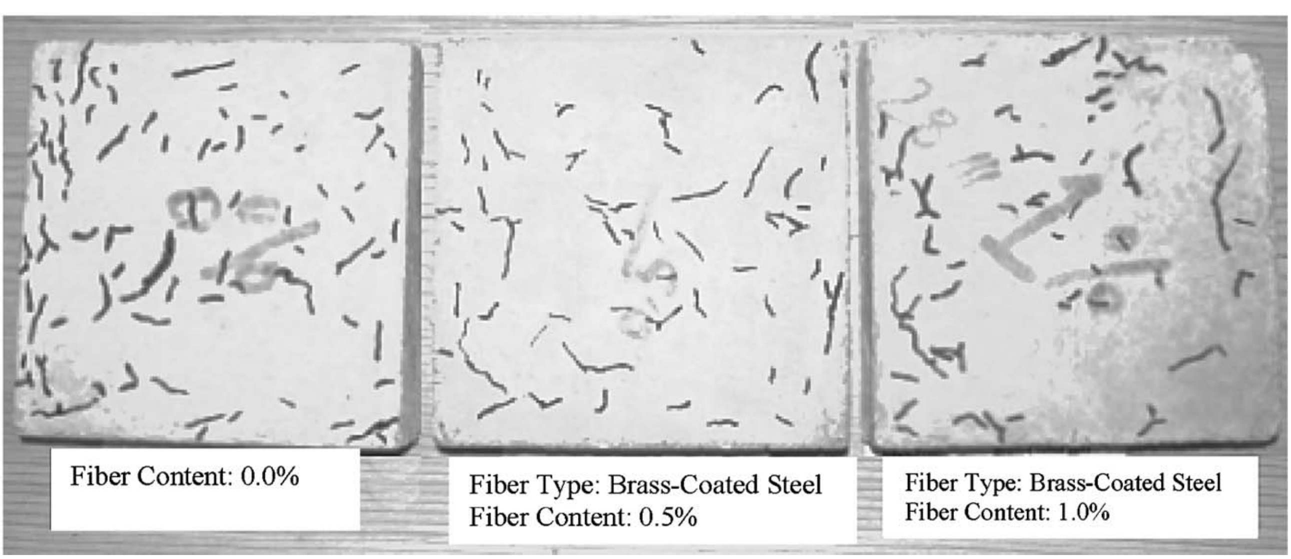

Fig. 4. Cracking pattern in PCC and FRC with brass-coated steel at fiber contents of 0.50 and 1.0% by volume cured for 7 days before exposed to 85 days of ASR treatment.

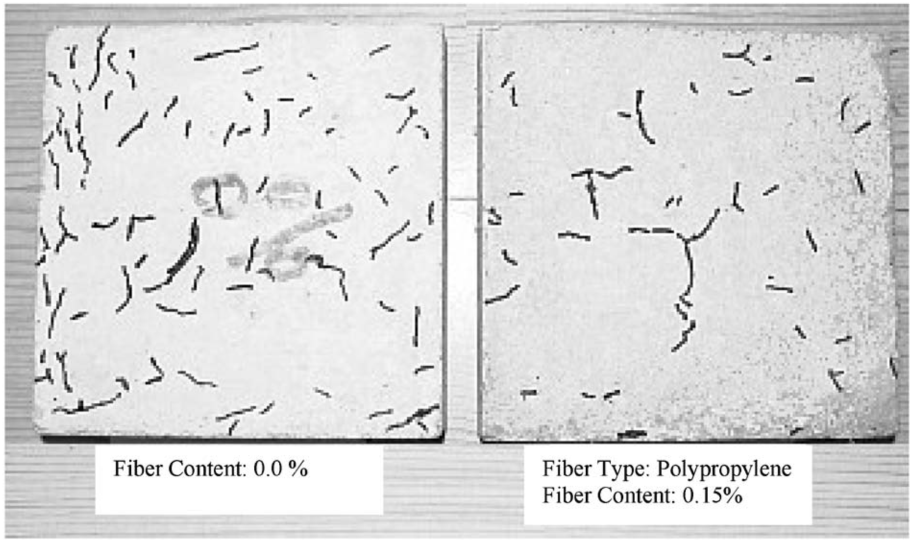

Fig. 5. Cracking pattern in PCC and FRC with polypropylene at fiber content of 0.15% by volume cured for 7 days before exposed to 85 days of ASR treatment.

fibers at a fairly low content contributed to reducing the cracking intensity dramatically, from 1 to 0.45 m/m^2. This reflects a superior performance of polypropylene over brass-coated fibers. The lower cracking extent in FRC specimens are due to the crack-arresting capacity of fibers, which was higher for polypropylene than that for brass-coated steel fibers owning to the former higher aspect ratio, hence bond with surrounding concrete matrix.

The role of fibers in arresting cracking is affected by the age of plain concrete or FRC at time of exposure to ASR treatment. Data of Table 3 reveal that the cracking intensity of FRC with 1% brass-coated steel fibers and cured 28 days was higher than that of the same mix but cured for 7 days before subjected to ASR treatment. As mentioned earlier, such behavior may be due to the increase in brittleness of concrete matrix overtime.

The percentage loss in ultrasonic pulse velocity reached as high as 16% after 55 days of treatment and was not affected significantly by fiber content. The ultrasonic pulse velocity results showed insignificant differences between specimens at varying fiber contents. These are due perhaps to the relatively limited sensitivity of the used nondestructive technique. Nevertheless, the percentage loss after 55 days supported what has been stipulated regarding a significant damage caused by ASR.

Table 3
Cracking pattern characteristics for plain concrete and for FRC underwent ASR

AAE (days)	Fiber content/type	Cracking intensity[a] (m/m^2)	Crack length range (mm)	Max. crack depth[b] (mm)
7	0%	1	1–43	30
	0.50% BCS	0.71	1–34	9
	1.0% BCS	0.68	1–41	17
	0.15% PP	0.45	1–34	7
28	1.0% BCS	0.92	3–38	25

AAE = age at exposure to ASR treatment; BCS = brass-coated steel; PP = polypropylene.

[a] Length of all cracks divided by the surface area.

[b] Maximum crack depth across the depth of prism sides.

4. Conclusions

Based on the results of the present study, the following conclusions can be made:

1. Fibers contribute moderately to controlling the expansion of Portland cement concrete undergoing an active alkali–silica reaction.
2. FRC, made with brass-coated steel or polypropylene fibers, cracked at higher strain than that of corresponding Portland cement concrete.
3. Use of fibers has resulted in limited extent of cracking due to alkali–silica reaction.
4. The cracking extent in FRC, due to alkali–silica reaction, was dependent on both fiber type and content.
5. Polypropylene fibers, having low modulus of elasticity and high aspect ratio, resisted cracking better than brass-coated steel fibers of high modulus of elasticity yet relatively small aspect ratio.
6. The potential of brass-coated fibers in arresting ASR cracking is significantly affected by age of concrete at time of exposure to ASR treatment.

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