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Contribution of fiber reinforcement in concrete affected by alkali–silica reaction

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ABSTRACT

Fiber reinforced concrete (FRC) is a high performance material that is frequently used for structures in contact with aggressive environments, because the fibers can control the propagation of cracks. This paper analyzes the residual properties of FRC after the alkali–silica reaction has taken place. The potential contribution of different types of fibers for mitigating the degradation process and their effects on the mechanical and transport residual properties are discussed. The expansions, presence of cracks, compressive strength and modulus of elasticity, and the behavior under flexural loads were evaluated. Steel fibers were the most efficient for reducing the crack density, followed by synthetic macrofibers. The coefficient of air permeability followed the same tendency, showing the positive effect of macrofibers in transport properties. Concretes incorporating steel or synthetic macrofibers conserve their original post-peak loading capacity when severe alkali–silica reaction damage has taken place.

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1. Introduction

The incorporation of fibers into concrete controls cracking processes, resulting in great improvements of the material toughness and structures durability. Steel fiber reinforced concrete has been used for decades in tunnels, precast elements, pavements and bridge decks. During the last years many advances in fiber concretes have appeared such as the development of new synthetic and glass macrofibers, the use of self compacting fiber reinforced concretes [1–4], new standards for mechanical characterization tests [5,6] and the introduction of design criteria for fiber reinforced concrete (FRC) in the structural design codes [7].

Although in many cases fibers are incorporated to extend the service life of the structures due to their contribution to control cracking, there exist areas of limited research as the effects of fibers on concrete permeability and porosity or their benefits in the control of diverse degradation processes in concrete. Some studies on cracked FRC under sustained loading show that fibers modify crack patterns, with narrower and closely spaced cracks [8–11]. Other studies related to concrete permeability indicate that fibers reduce internal cracking and improve impermeability [12–14]. It has also been found that as the content of fibers increases, the benefits are greater [15]. On the contrary, some authors have found that fibers increment water and gas permeability [16] while comparing mixes of equal workability.

FRC is frequently used in structures that are in contact with soils or immersed in aggressive environments since the fibers can control the propagation of cracks at both the micro and macro levels. For example, after a year of exposure to a marine environment, FRC shows less severe corrosion than normal concretes, and for cracks of 0.1 mm wide or narrower, the fiber sections remained intact; the corrosion of the steel fibers was not significant being only an esthetic problem and, in addition, improvements in the residual properties of FRC have been found [17,18].

Synthetic microfibers are recommended to prevent cracking and spalling by exposure to fire, nevertheless there is not information about the efficiency of synthetic macrofibers [19–21]. In concretes incorporating steel fibers [22] although concrete stiffness changes due to exposure to high temperatures, fibers still contribute to the residual capacity despite the matrix was severely damaged.

When Alkali–Silica Reaction (ASR) develops the failure mechanism of concrete is clearly affected. Under compressive loads the growth and propagation of matrix cracks tend to start earlier, the ability of aggregates to control cracking decreases and premature failure occurs. In tension, the differences in the crack pattern of sound and damaged concretes are also reflected in the shape of the load deflection curves. Damaged concretes show an increased non-linearity before the peak and a more gradual softening, which indicates that extensive meandering and branching of cracks are taking place [23]. The use of fibers can have a positive economic impact in the construction of dams, to prevent

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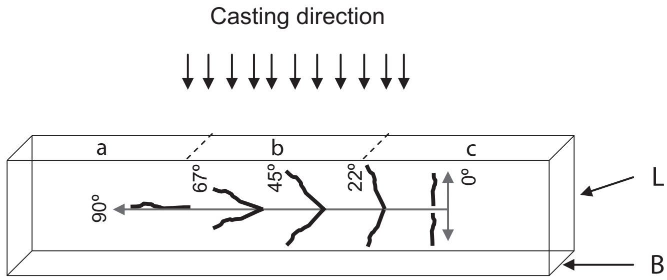

Fig. 1. Scheme of the sectors evaluated for the assessment of crack pattern.

or control the development of deleterious processes [24,25]. Even though fibers could not completely avoid the start of the cracks, they can control their propagation and limit their aperture reducing the permeability and decreasing the degradation rate. It was also found that in the case of ASR, the reductions in the bond capacity of steel or synthetic macrofibers are smaller than the decreases in matrix strength [26].

It is widely recognized that the incorporation of fibers has a positive effect on controlling crack growth, and limiting the crack widths; however, some doubts appear regarding the performance of FRC when suitable conditions for the development of ASR exist. Do fibers change the rate or the total expansions produced by the ASR? Does the type of fiber, steel or synthetic macrofibers, modify the damage produced? Does the use of microfibers modify or control the reaction? After concrete was damaged by ASR, how significant are the changes in the residual capacity (postcracking behavior)?

The main objective of this paper is to analyze the residual properties of FRC after ASR has taken place. The potential contribution of different fibers for mitigating the degradation process and their effects on the mechanical and transport residual properties is discussed.

2. Experiences

FRC with different grades of damage produced by ASR was studied. The expansion over time, presence of cracks, compressive strength and modulus of elasticity, and the behavior under flexural loads were evaluated.

2.1. Materials and mixtures

With the aim of analyzing the effects produced on the residual properties of FRC by the development of ASR, eight concretes with similar mixture proportions (water/cement ratio = 0.42, cement content = 380 kg/m^3) and different alkali contents and fiber types were prepared.

Ordinary Portland cement (Na_2O_{eq} 0.73%), a natural siliceous sand (fineness modulus 2.07) and a 19 mm maximum size granitic crushed stone (fineness modulus 6.91) were used. In addition, to promote the development of ASR, a highly reactive crushed stone (19 mm maximum size, fineness modulus 6.54) was incorporated as a part (40%) of the coarse aggregate. The reactive rock is a quartzitic sandstone, with some chalcedony and opal in the matrix. To obtain plastic concretes, a high range water reducing admixture was used.

Three types of fibers were incorporated: hooked-end steel fibers (S), synthetic macrofibers (M) and synthetic microfibers (m). The S fibers were typical low carbon hooked-end steel fibers, 50 mm in length and 1.00 mm in diameter, with a tensile strength higher than 1100 MPa and an elongation lower than 4%. The M fibers were modified olefin macrofibers with embossed surface, 60 mm in length and 0.62 mm in diameter, 640 MPa tensile strength and a modulus of elasticity of 10 GPa. The m fibers were 12 mm long multifilament polypropylene fibers.

Six fiber concretes named S1, S2, M1, M2, m1 and m2, and two reference concretes without fibers (R1 and R2) were prepared. The concretes were identified according to the type of fiber used. Concretes S1 and S2 incorporated 40 kg/m^3 (0.5% in volume) of steel fibers; concretes M1 and M2 included 3 kg/m^3 of synthetic macrofibers (0.3% in volume) and concretes m1 and m2 contained 1 kg/m^3 of synthetic microfibers (0.1% in volume). These fiber contents were adopted based on the volume of fibers usually incorporated in typical applications of FRC as ground-supported slabs. In concretes R1, S1, M1 and m1 no external alkalis were added and the total alkali content (supplied by the cement) was equal to 2.8 kg/m^3. To enhance the ASR in concretes R2, S2, M2 and m2, NaOH was added in the mixing water to achieve a total alkali equal to 4 kg/m^3. Reference concretes had a slump equal to 100 ± 10 mm and when fibers were incorporated it was reduced to 60 ± 20 mm. The air content was 4 ± 1%.

Table 1
Testing program.

Concrete	Total alkalis (kg/m^3)	Fibers type and content	Age (days)	Expansion (%)	Tests
R1	2.8	None	28	0.009	a, e
			122	0.035	a, e
			380	0.105	a, e
R2	4.0	None	28	0.004	a, e
			168	0.185	b, c, d
			371	0.218	a, e
S1	2.8	40 kg/m^3 hooked-end steel fibers	28	0.006	a, e
			189	0.052	b, c, d, f
			380	0.092	a, e
S2	4.0	40 kg/m^3 hooked-end steel fibers	28	0.011	a, e
			168	0.118	b, c, d, f
			371	0.130	a, e
M1	2.8	3 kg/m^3 synthetic macrofibers	28	0.004	a, e
			167	0.060	b, c, d, f
			380	0.087	a, e
M2	4.0	3 kg/m^3 synthetic macrofibers	28	0.011	a, e
			164	0.182	b, c, d, f
			372	0.190	a, e
m1	2.8	1 kg/m^3 synthetic microfibers	28	0.003	a, e
			168	0.056	b, c, d, f
			380	0.099	a, e
m2	4.0	1 kg/m^3 synthetic microfibers	28	0.010	a, e
			168	0.190	b, c, d, f
			371	0.196	a, e

a: Bending tests (f_L, f_{max}, f_{R1}, f_{R2}, f_{R3}, f_{R4}) − 75 × 105 × 430 mm prisms.
b: Bending tests (f_L, f_{max}, f_{R1}, f_{R2}, f_{R3}, f_{R4}) − 150 × 150 × 600 mm prisms.
c: Crack survey (crack width and crack density) − 150 × 150 × 600 mm prisms.
d: Air permeability − 150 × 150 × 600 mm prisms.
e: Compression tests (f'_c, E) − 100 × 200 mm cylinders.
f: Compression tests (f'_c, E) − 150 × 300 mm cylinders.

2.2. Experimental program and testing methods

Prisms and cylinders were cast with each concrete to be tested at ages between 28 and 370 days. The specimens were compacted by

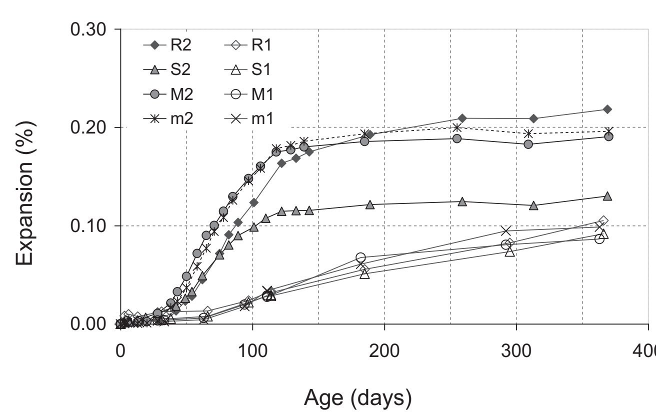

Fig. 2. Linear expansions.

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