Construction and Building Materials 105 (2016) 262–268

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental observations of self-consolidated hybrid fiber reinforced concrete (SC-HyFRC) on corrosion damage reduction

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HIGHLIGHTS

- Reduced corrosion rates in high performance hybrid fiber reinforced composites.
- Corrosion associated longitudinal cracks are suppressed in these composites.
- Control specimens are severely damaged after 2 year exposure to corrosion.

ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form 20 November 2015
Accepted 10 December 2015

Keywords:
Reinforcement corrosion
Concrete durability
Hybrid fiber reinforced concrete
Splitting crack

ABSTRACT

Correlations between the rate of corrosion damage in reinforced concrete and observable cracking have been established by a multitude of design codes. Based on this relationship, it is inferred that cracking prevention may provide a suitable corrosion protection scheme capable of enhancing the durability/life expectancy of reinforced concrete exposed to potentially corrosive environmental conditions. A self-consolidated hybrid fiber reinforced concrete mixture is tested under a chloride-induced corrosive environment to determine the role of crack suppression in both the initiation and the propagation phases of corrosion damage. It is observed that in the presence of the hybrid fiber reinforcement, chloride migration rates are not significantly altered by the introduction of moderate cyclical mechanical loading in contrast to conventional concrete samples. Furthermore, the accumulation of damage in the propagation phase of reinforcement corrosion is significantly altered by the suppression of splitting cracks emanating radially outward from the reinforcing bar surface. While not a corrosion elimination scheme, the incorporation of hybrid fiber reinforcement is nonetheless capable of prolonging the life expectancy of a given reinforced concrete element and providing an increased measure of durability.

1. Introduction

Chloride-induced corrosion of embedded reinforcing steel in concrete is associated with a multitude of environments (marine exposure, de-icing salts in cold weather climates, etc.) and is consequently problematic across many regions of the world. From the standpoint of life cycle assessment, a commonly cited model by Tuutti [1] prescribes a bilinear response to represent an initiation phase, during which corrosion damage accumulation is insignificant due to passivation of the steel surface, and a propagation phase during which active corrosion steadily increases the corrosion damage index. Similarly, the *fib* Model Code (2006) [2] suggests the same zero damage initiation phase but takes into account the influence of different levels of corrosion-induced cracking upon relative corrosion rates by representing the corrosion propagation phase as a multi-linear response with increasing damage accumulation rates associated with more dramatic damage states. Under such models, the accessibility of concrete carbonation or chloride ions determines the duration of the initiation phase with the transport/migration of both mechanisms strongly tied to the quality and soundness (crack/defect free quality) of the cover layer of concrete existing between the exposed surface and the reinforcing bar depth [3]. Upon depassivation of embedded reinforcement brought on by chlorides transported from external sources, significantly greater rates of iron oxidation occur. The production of volumetrically greater iron-oxide corrosion products at the interface between steel reinforcement and the surrounding concrete matrix is then responsible for a build-up in expansive stress. With low tensile strength and mechanical toughness, this region of surrounding concrete has a limited capacity to withstand corrosion product accumulation prior to the onset of cracking [4]. Such cracks, occurring radially from the bar location, not only degrade the composite mechanical performance of the concrete but also increase the

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http://dx.doi.org/10.1016/j.conbuildmat.2015.12.076
0950-0618/

mobility and availability of ions species participating in the corrosion reactions thusly accelerating the propagation phase of corrosion damage [5,6].

The potential for concrete durability enhancement afforded by microfiber reinforcement has been investigated by many researchers on a variety of environmental phenomena including but not limited to corrosion damage, alkali-silica reaction and frost action [7–9]. Predominantly, due to the manner in which fiber reinforcement provides strengthening and toughening to the cementitious matrix, the role of fiber reinforcement is to suppress crack generation [10,11] through which reaction kinetics are potentially altered via chemical or mechanical confinement [12–14]. It is inferred that this confinement effect is most effective in fiber reinforced matrices that display strain/deflection hardening properties [15,16], where toughening mechanisms are available beyond the formation of an initial crack. In order to achieve sufficient toughening within a concrete matrix (having both coarse and fine aggregate) while having a workable total fiber content, the synergistic relationships of multiscale hybrid blends of fiber reinforcement can be utilized [17] with the work of Blunt and Ostertag [18] advanced herein.

Investigations of crack influence on chloride induced corrosion have in the past often relied on artificially induced cracks by the placement of temporary shims [19,20]. Specimens constructed in such a manner have the advantage of having well defined crack openings and locations conducive to optimal placement of monitoring equipment. However, this method ignores examining transverse cracks in the presence of associated longitudinal cracks. Longitudinal splitting cracks, aligned with the direction of tensile reinforcement, having been developed during real loading conditions due to incongruent displacements between the cementitious matrix and reinforcing bar, can play an important role on determination of the overall area of depassivated steel [21,5]. The influence of fiber reinforced concrete mixtures to restrain longitudinal crack development and propagation in excess of the restraint offered by conventional concrete has previously been shown through tension stiffening tests of steel fiber [22] and hybrid fiber mixtures [23]. Similarly, the restraint of splitting crack development afforded by fiber reinforcement has been identified in direct bar-pullout testing [24] and lap splice testing [25].

Taking into account the inherent problem of reinforcement corrosion in a reinforced cementitious composite, this paper summarizes experimental work conducted during an investigation of self-consolidating hybrid fiber reinforced concrete to assess its durability performance. The influence of crack resistance towards both mechanical loading and environmentally-induced loading is addressed with the implications of in situ damage present at the onset of environmental attack being investigated. Importantly, the performance of the high performance material is judged not only on the basis of corrosion rate suppression but also the persistence of characteristic high performance composite mechanical performance as judged through deflection hardening behavior.

2. Materials and methods

In order to differentiate the role played by concrete cracking in the corrosion of embedded steel reinforcing bars, two concrete mixtures, a reference and a self-consolidated hybrid fiber reinforced concrete (SC-HyFRC), were fabricated to have similar water to binder ratios and paste contents. Each mixture was enhanced by the addition of superplasticizer and viscosity modifying admixtures to meet the criteria of self-consolidating concrete (used at dosages of up to 4 mL/lb of binder and 10 mL/lb of binder respectively), the individual impact of such chemical admixtures on corrosion performance was not assessed. To maximize the benefits of fiber reinforcement within a volumetric constraint of 1.5%, two types of fibers were utilized, 0.2 volume percent of a polyvinyl alcohol (PVA) microfiber having a length of 8 mm and aspect ratio of 200 and 1.3 volume percent of a hooked-end steel macrofiber having a length of 30 mm and an aspect ratio of 55. Concrete mix proportions, provided in Table 1, also display the replacement of portland cement by Class F fly ash at a rate of 25% by mass being a concession considered in order to control the carbon footprint of the high binder demand typical of self-consolidating fiber reinforced concrete mixtures. For both mixture types a consistent curing protocol of 7 days in a 96% relative humidity, 23 °C fog room followed by 21 days of curing in ambient lab conditions was followed.

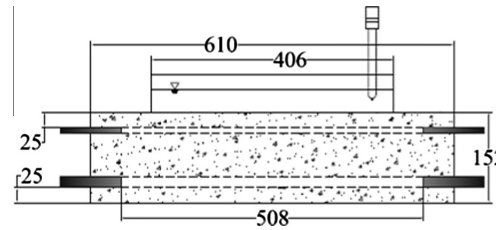

Fig. 1. Reinforced concrete beam geometry (mm), with positioning of the ponding dam and reference electrode shown.

Conventional low-carbon steel reinforcing bars with diameters of 9.5 mm and 19 mm were embedded in the concrete mixtures to monitor corrosion activity. Prior to concrete casting, the surface of each bar was cleaned by sand blasting to remove the mill scale in order to eliminate any effects caused by micro defects in said layer [26], while the ends of each bar were insulated to limit the exposed steel surface area to a region embedded within concrete. Reinforced concrete beam samples with top and bottom reinforcement were fabricated with geometry provided in Fig. 1 in which each bar was placed to have a 25 mm clear cover distance to the nearest top/bottom concrete face with chlorides introduced by ponding of 3.5 weight percent NaCl solution (being an average ocean salinity) on the top face of each beam. The influence of moisture transport to the reinforcing bar locations from the side faces of concrete was restricted by the distance of horizontal cover, in excess of 60 mm, and a coating of concrete sealant on all surfaces other than the reservoir and the bottom face. Electrical connection between top and bottom steel bars was provided by an external connection of wires (not shown) allowing for the development of a macrocell corrosion circuit in a manner similar to ASTM G109. Concurrently, the polarization resistance (following ASTM G59) of the top reinforcing bar (9.5 mm diameter) was regularly monitored to track the development of a microcell corrosion circuit. Both macrocell corrosion current densities (i_{galv}) and microcell corrosion current densities (i_{corr}), as determined by the Stern–Geary Equation, are presented as normalized by the exposed surface area of the working electrode (9.5 mm diameter bar). For the duration of corrosion testing, samples were stored in a temperature and relative humidity controlled chamber set to provide a 50 °C and 50% relative humidity environment. Chloride introduction by means of 3.5 weight percent NaCl ponding was sustained for the first year of sample monitoring after which the existing ponding liquid was allowed to evaporate and a further year of corrosion activity was dictated by the storage conditioning to simulate extended wet and dry seasons.

In addition to pure corrosion-induced damage experimentation a supplementary experimental parameter of load controlled mechanically-induced damage was introduced by exposing a subset of samples to a five cycle loading/unloading four point bending test to simulate service loading under a considered application as a continuous bridge approach slab. A magnitude of 32 kN was applied to an inverted beam during which the "top" face (relative to subsequent ponding) of the beam underwent tension strains in excess of the tensile strain capacity of conventional concrete. The pre-damaged state, with associated crack openings, was recorded by imaging on a flatbed scanner from which corrosion-induced crack growth/development could later be established.

3. Results

Reinforced beam response to be subjected to unidirectional cyclic mechanical preloading at an amplitude of 32 kN differed greatly

Table 1
Concrete mix proportions (kg/m^3).

	Portland cement	Class F fly ash	Water	Fine aggregate	Coarse aggregate	PVA fiber	Steel fiber
Reference[1]	397	131	237	1006	497	–	–
SC-HyFRC[1]	397	131	237	1044	418	2.6	102

[1] Chemical admixtures, superplasticizer and viscosity modifying admixture, added to achieve flowable behavior.