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Enhancing corrosion resistance of reinforced concrete structures with hybrid fiber reinforced concrete

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ABSTRACT

Service loads well below the yield strength of steel reinforcing bars lead to cracking of reinforced concrete. This paper investigates whether the crack resistance of Hybrid Fiber Reinforced Concrete (HyFRC) reduces the corrosion rate of steel reinforcing bars in concrete after cyclic flexural loading. The reinforcing bars were extracted to examine their surface for corrosion and compare microcell and macrocell corrosion mass loss estimates against direct gravimetric measurements. A delay in corrosion initiation and lower active corrosion rates were observed in the HyFRC beam specimens when compared to reinforced specimens containing plain concrete matrices cycled at the same flexural load.

1. Introduction

The corrosion of steel reinforcements in concrete is one of the main causes of deterioration of concrete structures [1,2]. Reinforced concrete structures are often exposed to mechanical loading conditions which cause the plain concrete to crack at load levels well below the load that would induce yielding of the conventional steel reinforcement. Once a crack has formed it can reduce the overall strength and stiffness of the concrete structure in addition to allowing water and aggressive agents such as chlorides to permeate faster and further into the concrete, thereby accelerating the corrosion process and reducing the service life of reinforced concrete structures [3–5].

Historically, a significant amount of attention was given to designing for crack width based on exposure conditions [6]. It was postulated that limitations on the allowable crack width from mechanical loading could reduce corrosion rate. Various researchers have shown that the use of crack width variations above 0.1 mm as a means for corrosion resistant design is inadequate because the correlation between long term corrosion behavior and crack width is not very strong [7–9]. This being said, it is still prudent to differentiate between cracked and uncracked corrosion initiation times and rates in reinforced concrete.

Boulfiza et al. [10] used modeling to determine an effective permeability for cracked and uncracked concrete. Variations in crack width from 0.1 to 0.3 mm had little effect on permeability (relative differences on the order of 5×). In comparison, the effective permeability of cracked (0.1 mm) and the uncracked matrices showed a difference of 13 orders of magnitude with the uncracked matrix having the significantly lower permeability. From these results, it appears that Cl^- ingress through saturated concrete can be treated in a binary manner with extremely high rates of Cl^- intrusion occurring through well defined surface cracks and relatively negligible rates occurring through a dense matrix. Mohammed et al. [11] isolated microcell and macrocell corrosion behavior on cracked and uncracked segments of reinforced concrete beam elements. Their experiments found that corrosion initiated in cracked segments sooner and with higher corrosion rates than uncracked. Similar results were also described by others [12–14], where higher corrosion activity was observed within cracked areas than in uncracked areas.

If a concrete structure is to be constructed in a particularly corrosive environment, then a prudent approach would be to enhance the cracking resistance of the concrete matrix to prevent the ingress of chlorides. One possible solution for an enhanced degree of crack control is from the application of fiber reinforcement. Various researchers have explored the cracking characteristics of fiber reinforced composites with steel reinforcements [15,16], however, research that directly examines the effects of fiber reinforcement on corrosion rate is very limited. Polypropylene (PP) fibers at relatively low dosages ($V_f = 0.2\%$) in field cured specimens were ponded with seawater and investigated in [17]. Quicker times to active corrosion were observed in the specimens without the PP fibers, with the formation of cracks from plastic shrinkage during the first 24 h of curing blamed. Cracking in restrained shrinkage specimens with and without PP fibers was induced by [18,19]. Depending on the test series, corrosion was induced through carbonation or salt

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water ponding and in both cases lower average corrosion rates were measured in the fiber reinforced specimens.

Investigation on the effect of steel fiber reinforcement on corrosion has been carried out by [20,21]. A delay in active corrosion in steel fiber reinforced concrete beams compared to plain concrete beams was observed based on macrocell current density measurements [20]. In such cases, the extent to which corrosion rate differences are observed is strongly correlated with the resistance, afforded by fiber reinforcement, to induced cracking of the composite.

This paper explores the effect of a Hybrid Fiber Reinforced Concrete (HyFRC) composite on corrosion resistance. The HyFRC that is being utilized in this study was specifically designed to delay dominant crack formation up to strain levels exceeding the yield strain of conventional steel reinforcing bars in composite flexural beams [22], thus providing it with superior crack resistance in relation to plain concrete. Under load, the HyFRC material differentiates itself from conventional fiber reinforced composites by delaying dominant crack formation which would otherwise coincide with the cracking strength of the concrete matrix. Achieving such a delay at a relatively low fiber volume fraction is accomplished by controlling cracking on multiple scales using fibers of different sizes and aspect ratios. Microfibers are utilized to control the onset of microcracks and delay their coalescence into macrocracks and macrofibers are used to control the propagation and opening of macrocracks.

This paper explores whether use of HyFRC, due to its enhanced cracking resistance, is a viable approach to influencing the corrosion behavior of reinforced concrete elements when exposed to mechanically induced flexural loads. The paper provides a comparative analysis between the HyFRC and a plain concrete mix exposed to the same load demand to isolate the effect of HyFRC crack resistance on the time to corrosion initiation and subsequent propagation rates for embedded rebar in addition to a gravimetric comparison of reinforcing bar mass loss.

2. Experimental program

2.1. Materials

Table 1 summarizes the fiber characteristics used in this study. Fibers with different aspect ratios and material compositions were used. Polyvinyl alcohol (PVA) fibers were chosen to control microcracks. Two steel fibers with different aspect ratios, denoted as S1 and S2, were used to control macrocracks. The hooked ends of the steel fibers provide mechanical anchorage through which the fiber stiffness can be fully realized. The weight ratios of the HyFRC mix are given in Table 2 including the fiber volume percentages of the PVA and steel fibers. Coarse aggregates having a maximum size of 9.5 mm and fine aggregates with a fineness modulus of 3.2 were used in both the control and HyFRC mixture. Type II cement was used as the binder. The HyFRC consists of a total fiber volume fraction of 0.015. A plain concrete mixture was prepared with the same weight ratios minus the fiber reinforcement. Concrete curing consisted of an initial 7 days of wet curing followed by 21 days of dry curing. The conventional steel reinforcing rebar used for the reinforced beams was ASTM A615 Grade 60.

Table 2
Weight ratios of HyFRC mix.

Type	Cement[a]	Water	CA[b]	FA[c]	Fiber volume (%)		
					PVA	S1	S2
HyFRC	1.0	0.54	1.83	2.00	0.2	0.5	0.8

[a] ASTM C150 Type II.
[b] Coarse aggregate: pea gravel, 9.5 mm maximum aggregate size.
[c] Fine aggregate: fineness modulus = 3.2.

2.2. Flexural testing of reinforced HyFRC and control specimens

To examine the flexural performance of HyFRC and to investigate the impact of flexural load induced cracking on corrosion, six HyFRC and six plain concrete beam specimens (152 mm × 152 mm × 608 mm) reinforced with Gr. 60 steel reinforcing bars were cast. In addition, three HyFRC beam specimens of the same dimensions but without steel reinforcement were cast to confirm the deflection hardening behavior of the HyFRC mix. All specimens were tested under four point bending according to [23].

2.3. Preparation of beam specimens for corrosion testing

Prior to casting concrete, the rebar surface was prepared by sandblasting in order to remove the mill scale. One end of the rebar was drilled and tapped in order to provide electrical connection through a screw and ring terminal. Both ends of the rebar were painted with a layer of moisture sealant and then wrapped with electrical tape and covered with a polyolefin heat shrink tube. The ends of the polyolefin tube were pinched closed and covered with the moisture sealant in order to prevent the ingress of moisture.

After subjecting the specimens to a cyclic loading protocol representative of damage accrual experienced by reinforced concrete structures under mechanical service loads, corrosion of the steel reinforcing bar was induced by ponding a salt water solution. The proposed test method is very similar to that specified in [24] with the major exceptions being that the beam element dimensions have been modified, the concrete saturation was continually maintained and a supplemental potentiodynamic method was used for corrosion monitoring (to be discussed in the next section). Potentiodynamic is used in reference to the testing method utilizing a sweep of potential to determine resistance properties of the working electrode. The ponding dams were constructed out of 3.2 mm thick PVC and where adhered to the concrete surface with a cement caulk. Ponding was not cycled in the manner described by ASTM G109 [24], rather the salt solution was replaced on a weekly basis by vacuuming out the old solution and replacing it with new solution, the time to conduct this process on all six specimens was less than 1 h which would be representative of the maximum possible “dry” cycle. All beam surfaces not designated as an “exposed surface” were coated with a polymeric based sealant. The intent behind the sealing method was to increase the driving force behind the solution’s intrusion into the beam matrix. The exposed bottom surface provided the only evaporation sink, which would effectively pull the solution through the matrix and create a vertical moisture gradient.

Table 1
Fiber properties.

Designation	Material	Length (mm)	Diameter (mm)	Strength (MPa)	Stiffness (GPa)
PVA	PVA	8	0.04	1600	43
S1	Steel, hooked	30	0.55	1100	200
S2	Steel, hooked	60	0.75	1050	200