

Durability Assessment of Reinforced-SHCC Structures During Initiation and Propagation Phases of Corrosion

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ABSTRACT

The fundamental reason behind the corrosion-related deteriorations in reinforced concrete structures is the brittleness of conventional concrete, which makes the unreinforced cover prone to cracking under small tensile stresses. Unlike conventional concrete, Strain-Hardening Cementitious Composite (SHCC) has been shown to mitigate the corrosion-related damage, primarily in the propagation phase of corrosion, due to small crack widths typically limited under 100 μm . This paper summarizes important findings from an extensive study, which evaluated the corrosion protection offered by SHCC during both the initiation and the propagation phases of corrosion, and compared its effectiveness to that of conventional concrete. The experimental investigations led to the development of a novel method for identifying the critical chloride concentration (C_{crit}) that is vital for determining the time-to-corrosion initiation. The novel method and additional investigations on the performance of reinforced-SHCC specimens during accelerated corrosion tests (propagation phase) provide a clearer assessment of the durability of cement-based composite structures.

Keywords: reinforced concrete, strain-hardening cementitious composite, engineered cementitious composite, corrosion, critical chloride content, chloride diffusion, macro-cell current, accelerated corrosion test, passive film

INTRODUCTION

Concrete is the world's most widely used construction material; however, reinforced concrete (RC) structures often suffer from chloride-induced steel corrosion ¹. According to the National

Association of Corrosion Engineers (NACE International), more than 10% of the nation's bridges in the United States (US) are structurally deficient or functionally obsolete due to corrosion. The annual maintenance cost of corrosion-damaged concrete bridges alone is estimated at \$8 billion². Every year, a significant amount of resource consumption, CO₂ emissions, and environmental hazards are caused by the maintenance and repair activities associated with corrosion-damaged RC infrastructure.

In RC structural members, the steel reinforcement is protected from corrosion by a passive oxide layer that forms on the rebar surface due to the high alkalinity of the concrete pore solution. However, this passive layer breaks down when a critical content (C_{crit}) of chloride ions (Cl⁻) diffuses through the concrete cover and accumulates at the rebar surface³. According to the classical Tuutti's model, the time needed for this process to occur is called the *time-to-corrosion initiation*, which is a function of chloride diffusivity of the concrete cover, chloride concentration at the concrete surface, and thickness of the cover⁴. Thus, the corrosion protection provided by the passive layer is lost at the end of the initiation phase, which is followed by the propagation phase of corrosion, where corrosion continues in the presence of water and oxygen at a faster rate [5]. During the propagation phase, corrosion products, which normally occupy 3-6 times the volume of the original steel removed due to corrosion⁵, cause tensile stress and cracking in the surrounding concrete. Throughout the propagation phase, fracture toughness (or tensile strength) and tensile ductility of the concrete cover determine the time between the start of corrosion propagation and the appearance of crack(s) at the outer surface of the concrete cover.

Existing methods to determine C_{crit} apply a salt solution with high chloride concentration, which is ponded on RC specimens and the corrosion activity of the embedded rebar is monitored using electrochemical techniques⁶. As soon as the corrosion activity exceeds a certain threshold (corrosion initiation⁷), the concrete around the embedded rebar is sampled and analyzed to determine the chloride content, which is assumed equal to the C_{crit} . The accuracy of this approach is limited by the resolution of the electrochemical technique, the threshold for indicating corrosion initiation, and the sampling interval. Different electrochemical techniques have different resolutions for measuring the corrosion activity⁸, and in some techniques, the resolution is not sufficient (signal/noise ratio is low) to distinguish between passive and active states of corrosion at a small pit on the rebar surface^{9,10}. Secondly, the threshold used for distinguishing passive and active states of corrosion for a new material is not known a priori^{6,11}. Researchers have often used their experience with other similar materials to distinguish between active and passive states of corrosion. Thirdly, the sampling intervals for measuring corrosion activity are of the order of several days (if not weeks or months), and the overall experiment can last for several months or years¹² depending on the diffusivity and thickness of the concrete cover and concentration of the salt solution. For these reasons, the likelihood of missing the instant of corrosion initiation is high, and due to continued diffusion, the C_{crit} values determined using the existing methods are different (typically greater) from the true C_{crit} . As a result, the C_{crit} values reported in the literature vary over a large range¹³.

Modern concrete materials such as strain-hardening cementitious composites (SHCCs) offer improved protection against chloride penetration due to their low diffusivity and limited crack widths (or openings)^{14,15}. The SHCCs are a class of ultra-ductile fiber-reinforced cementitious composites with tensile strain capacity typically greater than 1%¹⁶. An SHCC absorbs damage through multiple micro-cracking with crack widths typically limited to less than 100 μm. This behavior is in contrast to the brittle behavior of conventional concrete with unrestricted crack openings that often exceed several millimeters. The small crack width of an SHCC is particularly useful for limiting chloride, water, and oxygen ingress post-cracking¹⁷. The majority of the existing studies have examined the performance of SHCC in the corrosion *propagation* stage using

accelerated corrosion methods. Even at the saturated micro-cracking stage, an SHCC has a corrosion resistance comparable to that of an undamaged concrete of similar compressive strength¹⁸⁻²². There have only been a few studies on the corrosion *initiation* stage in reinforced SHCC²³⁻²⁵, and the majority of these studies have focused on the determination of effective diffusion coefficient (D_{eff}) of SHCC^{26, 27}. However, the C_{crit} of SHCC was often assumed equal to that of concrete with similar compressive strength or chemical composition. Due to the absence of coarse aggregates and the prevalence of fly ash, SHCC has a lower porosity, and therefore, lower D_{eff} compared to concrete. Although fly ash reduces the porosity and permeability of cementitious materials²⁸, its use in large amounts also reduces the pH of the pore solution due to the pozzolanic reaction^{29, 30}, which negatively impacts the stability of the passive film on the surface of reinforcement. The reduction in the pH of the pore solution might also decrease the chloride binding capacity of a cementitious material^{31, 32}, which is also detrimental for the passive layer. Thus, there is a need to determine the C_{crit} for SHCC and other modern concretes with high contents of supplementary cementitious materials, as their microstructure and chemistries are substantially different from conventional concrete.

The objective of this research is to investigate the corrosion protection offered by SHCC during both the initiation and the propagation phases of corrosion. The behavior of reinforced-SHCC specimens during the propagation phase of corrosion is compared to that of conventional RC specimens. The investigation of corrosion initiation in this study led to the development of a novel experimental method for determining C_{crit} , which addresses some of the challenges of the existing techniques. The proposed method is extended from an existing procedure, and it is based on the correlation between chloride contents at the rebar-concrete interfaces and average depths of the corrosion pits on the surface of the rebars.

DETAILS OF EXPERIMENTS

This section briefly describes the procedure used for making *beam* and *cylindrical* specimens. We used seventeen reinforced-SHCC beams to investigate corrosion initiation and six cylinders, three each for concrete and SHCC, to investigate the propagation phase of corrosion. The mixture proportions of SHCC used in this study are given in Table 1. The water-to-binder (binder = cement + fly ash) ratio of the SHCC mixture was 0.38. Further details regarding the fresh and hardened properties of SHCC and concrete used in this study can be found in the literature^{23, 24}.

Table 1
SHCC mixture proportions and ingredient properties

	Cement Type-I	Fly ash Class-F	Sand F-75	Water	HRWRA ¹	VMA ²	PVA Fibers
Proportions (by weight)	1.0	1.2	0.82	0.84	0.01	0.024	0.053
Mass-to-volume ratio (volume-to-volume ratio) ³	454.6 (kg/m ³)	545.5 (kg/m ³)	572.8 (kg/m ³)	380.0 (L/m ³)	2.08 (L/m ³)	5.97 (L/m ³)	20.0 (L/m ³)
Particle size range	5-50 (μm)	5-50 (μm)	70-300 (μm)	-	-	-	-
Specific gravity	3.2	2.4	2.6	1.0	1.2	1.005	1.3

¹ HRWRA = High-range water-reducing admixture

² VMA = Viscosity modifying admixture

³ Ratio of the mass (or volume) of each ingredient to the total volume of the mix

Beam specimens

Seventeen identical reinforced-SHCC beams, with dimensions of 280 mm × 152 mm × 114 mm (length × height × width), were prepared according to ASTM G109³³. The procedure for preparing the beams, including rebar (US #6, ASTM A615 Grade 60 - without coating) and mold preparations, are described in Fakhri et al.²⁴. Figure 1 (a) shows one of the finished reinforced SHCC beams.

Electrochemical techniques for detecting corrosion initiation

The effectiveness of different electrochemical techniques to detect corrosion activity, and the initiation of corrosion, varies. In this paper, the results for two electrochemical techniques (macro-cell current, and Tafel test) are presented and used to monitor the corrosion activity and to identify the initiation of corrosion. We also performed linear polarization resistance (LPR) and half-cell potential measurements to further monitor the corrosion activity. The results for these additional measurements are described in Fakhri²³. The macro-cell current was measured at the end of each wetting/drying cycle (every two weeks) according to the procedure described in ASTM G109³³. A high impedance digital multimeter with an accuracy of 1 μ V was used to measure the voltage across a resistor (100 Ω) connecting the top and bottom rebars as shown in Figure 2 (a). In this setup, the initiation of corrosion causes electrons to flow from the top rebar (anode) to the bottom rebars (cathode) through the resistor, forming a macro-cell²³. In this study, Tafel tests were performed only at the end of the observation period for each beam specimen (after detection of corrosion initiation), using a potentiostat. After conducting the Tafel tests, the SHCC beam specimens were sectioned²⁴ to determine chloride content at the rebar-SHCC interface using an automated titrator, following the procedure described in ASTM C1152³⁴.

Cylindrical specimens

Six single-rebar specimens, three each for concrete and SHCC, were prepared for this study. A single-rebar specimen is a cylindrical specimen of size 76 mm (diameter) × 152 mm (height) with a centrally embedded rebar of diameter 19 mm (US #6, ASTM A615 Grade 60 - without coating) and length of 203 mm as shown in Figure 1 (b). Single-rebar specimens made with concrete were named C1, C2, and C3, and those made with SHCC were named S1, S2, and S3. The procedure for preparing the cylindrical specimens is described in Fakhri²³.

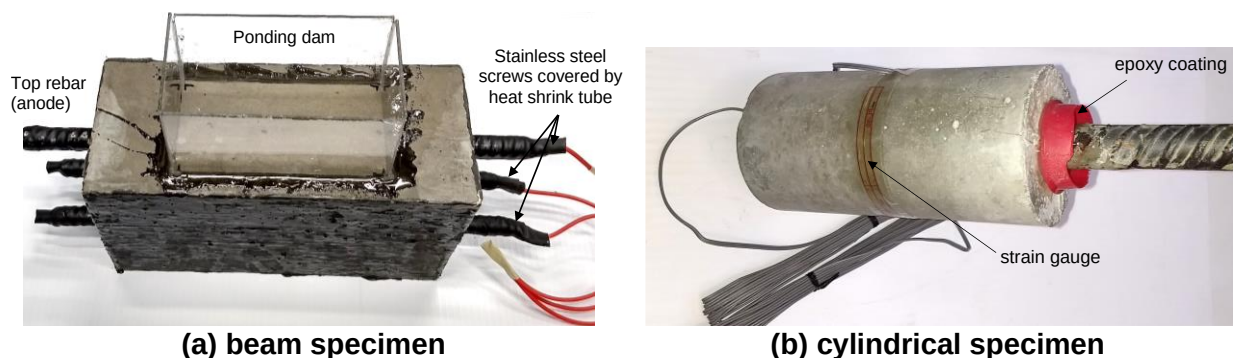


Figure 1: Finished specimens.

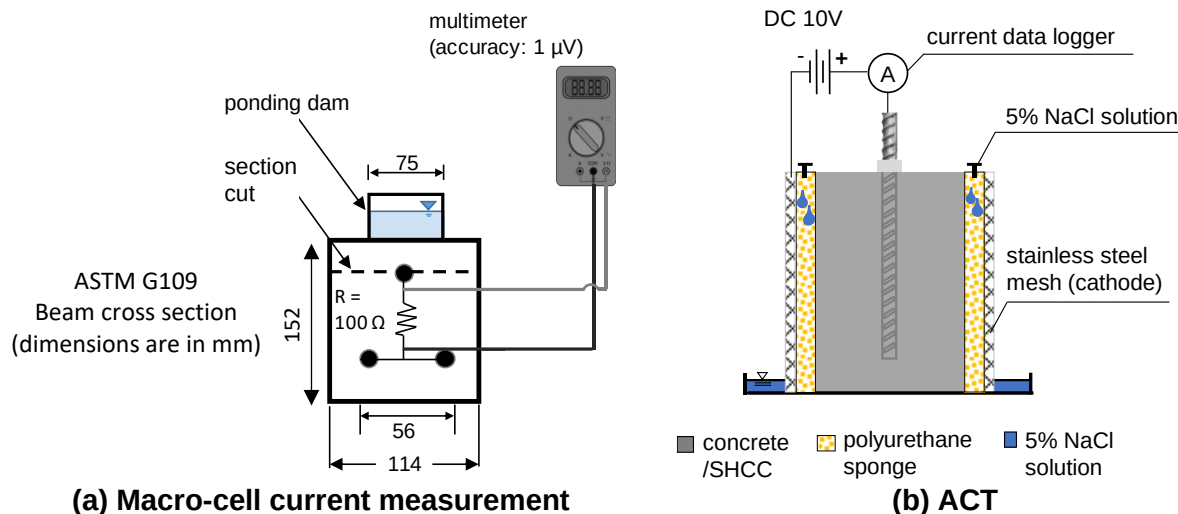


Figure 2: Test setups.

Accelerated Corrosion Test (ACT)

For the rapid simulation of corrosion (in propagation phase), potentiostatic accelerated macro-cell corrosion experiments with alternate wetting and drying cycles were performed on cylindrical specimens, using the experimental arrangement shown in Figure 2 (b). Instead of the common practice of partially submerging the specimens in a salt solution, exposure to chloride ions was provided through polyurethane sponges soaked in a salt solution, wrapped around the cylindrical specimens. A potential of 10 V was applied to all the specimens by connecting the positive terminal of the DC power supply to the rebars (anode) and the negative terminal to the stainless-steel mesh (cathode). Further details regarding the ACT can be found in Fakhri ²³.

RESULTS AND DISCUSSIONS

Initiation phase of corrosion

Macro-cell current and Tafel tests

The variations of macro-cell current with time for all the SHCC specimens are shown in Figure 3 (a). In this plot, the current-time curves of four randomly selected beams are shown in color for enhancing the readability, and the remaining thirteen curves are shown using gray color. The macro-cell current was almost zero as long as the top rebar embedded in the SHCC beam remained in the passive state. Corrosion initiation was marked by a significant increase in the macro-cell current. In this study, the macro-cell current of 1 μA was considered as the threshold for determining corrosion initiation in the SHCC beam specimens. However, in some specimens (for example, the specimen B4 shown in blue in Figure 3 (a)), the macro-cell current decreased after once exceeding 1 μA . Therefore, the specimens were sectioned after achieving two successively increasing macro-cell current readings greater than 1 μA to ensure the corrosion initiation. Based on the above condition, the days-to-sectioning (DTS, when last macro-cell current observation was made) of the SHCC beams ranged from 133 days to 238 days since the first exposure to the salt solution. Table 2 lists the DTS for various specimens.