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Corrosion resistance of strain-hardening steel-fiber-reinforced cementitious composites

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ABSTRACT

This study investigated the corrosion resistance of strain-hardening steel-fiber-reinforced cementitious composites (SH-SFRCs) in a chloride environment. Two types of steel fibers, hooked and twisted, were added (2% by volume) to a high-strength mortar matrix (90 MPa). All the specimens were exposed to cyclic wetting in a 3.5% chloride solution followed by drying. The corrosion resistance of SH-SFRCs was then evaluated by measuring the direct tensile resistance after the chloride cycles. The strain capacity and toughness of all the SH-SFRCs decreased significantly after 105 chloride cycles, whereas a slight reduction was observed in their post-cracking strength. The corrosion resistance of SH-SFRCs after the chloride cycles was strongly dependent on the width of multiple microcracks when the SH-SFRCs were pre-cracked by tensioning until 0.1% tensile strain. The addition of calcium nitrite (CNI) was successful in improving the corrosion resistance of the pre-cracked SH-SFRCs in the chloride environment.

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1. Introduction

Concrete has been widely used in offshore structures such as concrete floating bridges, Condeep, Sea Tank, and C G Doris. Compared with steel offshore structures, current concrete offshore structures have demonstrated superior corrosion resistance in marine environments [1]. However, their service life is generally only between 20 and 50 years owing to chloride damage, impact, and fatigue loads from the aquatic settings. In particular, cracks resulting from the brittle nature of concrete accelerate the ingression of detrimental chloride [2,3]. Thus, to extend the service life of concrete offshore structures, it is important to increase the crack resistance of concrete by enhancing the ductility.

Various methods have been used to increase the crack resistance of offshore concrete structures, including the addition of steel lining or pre-stressing of the concrete. Existing concrete cracks could be repaired by injecting high-strength mortar, epoxy, or urethanes. Moreover, to extend the service life of concrete structures, self-healing concrete has been proposed and intensively investigated by many researchers [4–9]. All of these methods have their limitations, however. The additional steel lining significantly increases the construction cost for installation and corrosion protection. Even though pre-stressing concrete has been effective, it is still difficult to control shrinkage or temperature cracks prior to pre-stressing [4]. Finally, the current repair and crack self-healing methods mostly work on dormant cracks, but concrete offshore structures are continuously subjected to dynamic cyclic loads [5–9].

Our study proposes the use of strain-hardening steel-fiber-reinforced cement composites (SH-SFRCs) because of their very high crack resistance as well as high post-cracking tensile strength compared with normal concrete, as illustrated in Fig. 1 [10]. The very fine multiple microcracks of SH-SFRCs are expected to not only prevent the ingression of harmful substances such as chloride but also provide favorable conditions for crack self-healing [11–13]. SH-SFRCs are also expected to enhance the resistance of offshore structures under fatigue and impact loads owing to their high energy-absorption capacity [14–16]. However, offshore structures are frequently exposed to corrosive environments containing

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Abbreviations: ASTM, American Society for Testing and Materials; CNI, calcium nitrite; H, hooked (type of high-strength steel fiber); RILEM, Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures); SFRC, steel-fiber-reinforced concrete; SH-SFRC, strain-hardening steel-fiber-reinforced cementitious composite; T, twisted (type of high-strength steel fiber).

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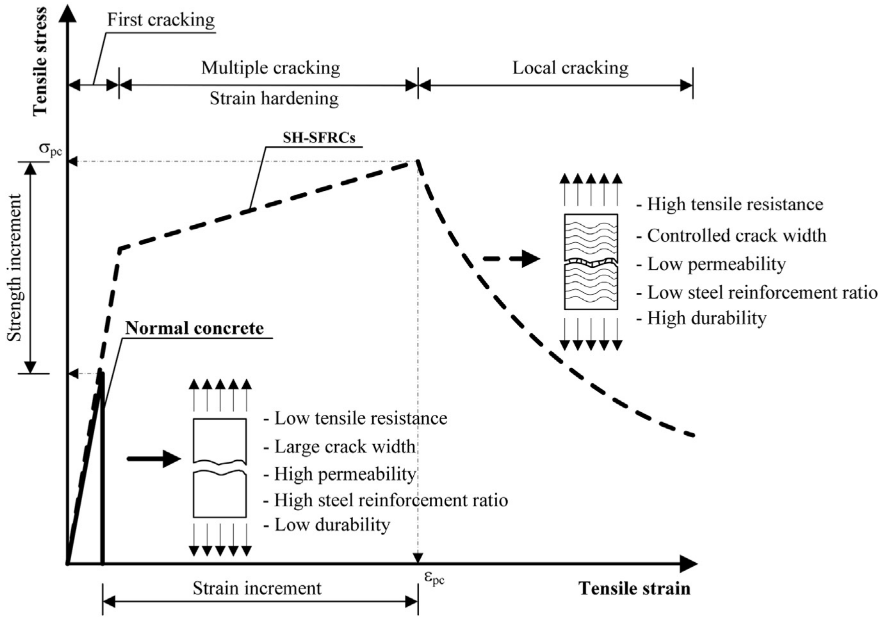

Fig. 1. Advantage of using SH-SFRCs in offshore structures [10].

chloride salts. As steel fibers used in SH-SFRCs in a chloride environment are vulnerable to corrosion, it is unclear whether the superior tensile resistance of SH-SFRCs with high energy-absorption capacity and tensile strength would persist in an environment with harsh chlorides. In addition, the proper approach to enhance the corrosion resistance of SH-SFRCs for marine applications is yet to be determined.

The aim of this research is to provide useful information on the resistance of SH-SFRCs against chloride corrosion for marine applications. The specific objectives are (1) to investigate the corrosion resistance of SH-SFRCs in a chloride environment, (2) to investigate the effect of crack width on the corrosion resistance of SH-SFRCs, and (3) to evaluate the effect of adding calcium nitrite (CNI) as a corrosion inhibitor on the corrosion resistance of SH-SFRCs.

2. Corrosion resistance of steel-fiber-reinforced concrete (SFRC)

Although SH-SFRC is one of the promising construction materials for marine applications owing to its strain-hardening behavior [10], very little research has been performed on the corrosion resistance of SH-SFRCs. There have been a few studies on the corrosion resistance of steel-fiber-reinforced concretes (SFRCs), a class of strain-softening composites [17–23]. Most of the earlier works evaluated the effect of steel-fiber corrosion on the mechanical resistance of SFRCs [17–19] and the effect of crack width on the corrosion resistance of SFRCs [20–23].

Kosa et al. investigated the effects of corrosion on the mechanical resistance of SFRCs during chloride cycles [17,18]. The flexural, tensile, compressive strength, and toughness of SFRCs decreased as the level of steel-fiber corrosion increased. They reported that the reduction in mechanical resistance was caused by the reduction in the steel fibers' cross-sectional area and the eventual fiber breakage even though the bond between the corroded fibers and the matrix could be enhanced for steel fibers with only slight corrosion. Mangat et al. explored the long-term performance of SFRCs in a marine environment [19]. They reported that the energy-absorption capacity of all SFRCs gradually decreased after 150 days in a marine shower. They also indicated that both low-carbon steel and corrosion-resistant fibers were severely corroded, whereas melt-extract fibers showed no evidence of corrosion when exposed to the same simulated marine environment.

Kosa et al. investigated the corrosion resistance of pre-cracked SFRCs in a chloride environment [20], and they proposed 0.15 mm as the limit to permissible crack widths of SFRCs. Mangat et al. recommended 0.2 mm and 0.15 mm as permissible crack widths for SFRCs with melt-extract and low-carbon fibers, respectively, for marine applications [21]. They also reported that pitting corrosion was initiated in low-carbon steel and melt-extract steel fibers bridging cracks when the widths of the cracks were greater than 0.24 and 0.94 mm, respectively. In addition, the energy-absorption capacity of pre-cracked SFRCs was even higher than that of non-cracked SFRCs when the initial crack widths were less than 0.2 mm. Nordstrom et al. showed that SFRCs with cracks narrower than 0.1 mm could be used even in a severe chloride environment because of the crack self-healing phenomenon in SFRCs [22]. Granju et al. reported that there was no corrosion in the steel fibers of SFRCs if the widths of the cracks were below 0.1 mm [23]; the flexural strength of SFRCs slightly increased since the light corrosion of steel fibers enhanced the interfacial friction between the fiber and the matrix. Moreover, rust, the product of steel-fiber corrosion, was not strong enough to generate any spalling of the concrete surrounding the steel fibers.

Although several researchers have investigated and reported the corrosion resistance of SFRCs, the corrosion resistance of SH-SFRCs, which show tensile-strain-hardening behavior unlike that of SFRCs, is yet to be fully understood. In particular, the effect of steel fibers' corrosion on the tensile resistance of SH-SFRCs should be clearly investigated before SH-SFRCs are used in marine infrastructures.

3. Experimental program

An experimental program was designed to investigate the corrosion resistance of SH-SFRCs in a chloride-rich environment. Eight series of specimens, divided into groups A and B, were

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