High Performance Fiber Reinforced Cement Composites (HPFRCC5)
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EFFECT OF CRACKING AND HEALING ON DURABILITY OF ENGINEERED CEMENTITIOUS COMPOSITES UNDER MARINE ENVIRONMENT

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ABSTRACT

Engineered Cementitious Composites (ECC) offer significant potential for durable civil infrastructures under marine environment, due to its high tensile strain capacity of more than 3%, and controlled micro-crack width of less than 60 μm. An experimental study was designed to investigate the durability of ECC material with regard to cracking and healing under combined mechanical loading and environmental loading conditions. ECC coupon specimens were firstly preloaded under uniaxial tension to different strain levels, and then exposed to a chloride environment for 1, 2 and 3 months and subsequently reloaded up to failure. The reloaded specimens retained multiple micro-cracking behavior and tensile strain capacity of more than 3%, although the average crack width increases from 40 μm to 100 μm and the tensile strength was reduced by 10%. The test results indicated strong evidence of self-healing of the micro-cracked ECC material, which can still carry considerable tensile stress and strain. The phenomenon of self-healing effectively closes the microcracks. These results confirmed that ECC, both uncracked and micro-cracked, remain durable despite exposure to a severe marine environment.

1. INTRODUCTION

Cracking is usually a result of various physical and chemical interactions between concrete and its environment, and it may occur at different stages throughout the life of a structure. The durability of concrete structures is commonly affected by the presence of cracks. Cracks can reduce the strength and stiffness of the concrete structure and accelerate the ingress of aggressive ions, leading to other types of concrete deterioration and resulting in further cracking and disintegration [1]. Concrete shrinkage, thermal deformations, chemical reactions, poor construction practices and mechanical loads are some of the causes of cracks in concrete [2]. A summary of maximum allowable crack widths in various codes and specifications by technical committees for design of reinforced concrete structures in marine exposure is shown in Figure 1. As seen from Figure 1, the most stringent requirements are specified by JSCE and ACI 224.

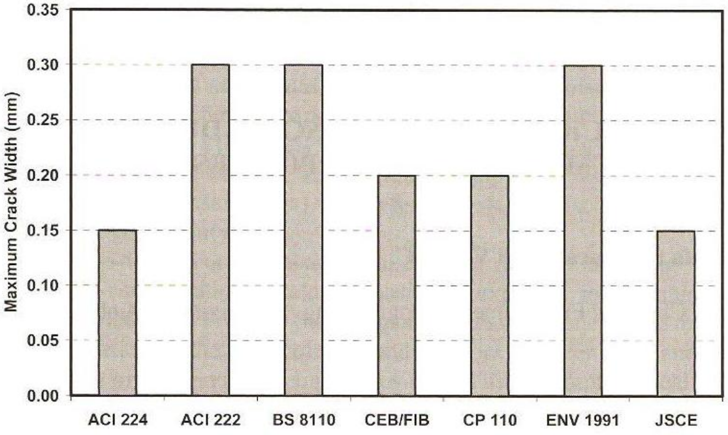


Figure 1: Comparison of allowable crack widths: Marine exposure [2-8]

Self healing is generally attributed to the hydration of previously unhydrated cementitious material, calcite formation, expansion of the concrete in the crack flanks, crystallization, closing of cracks by solid matter in the water and closing of the cracks by spalling of loose concrete particles resulting from cracking [9]. Self healing of cracks should also be taken into account when specifying tolerable crack widths. Evardsen [10], and Reinhardt and Jooss [11] proposed that cracks of less than 0.1 mm can easily be closed by self healing process.

Despite extensive research, reliable crack width control using steel reinforcements in concrete structures remains difficult to be realized in practice. Recently, a new high performance cementitious composite has been developed by Li and co-workers [12] called Engineered Cementitious Composites (ECC). ECC is a high performance fiber reinforced cementitious composite with substantial benefit in both high ductility and improved durability due to tight crack width. By employing micromechanics-based material design, maximum ductility in excess of 3% under uniaxial tensile loading can be attained, and ECC changes the cracking behavior from a single crack with large crack width to multiple microcracks. Even at large imposed deformation, crack widths of ECC remain nearly constant, less than 70 μm, while the number of cracks increases. Figure 2 shows a typical uniaxial tensile stress-strain curve of an ECC containing 2% PVA fiber. The characteristic strain-hardening after first cracking is accompanied by multiple micro-cracking. The crack width development during inelastic straining is also shown in Figure 2. Even at ultimate load, the crack width remains on the order of 50 μm to 70 μm. Under marine environment, ECC's tight crack width can greatly reduce the chloride penetration rate, and its tensile ductility helps prevent spalling resulting from the expansion of the corroding reinforcement.

Little research has been conducted on the long term durability of ECC in the cracked and uncracked state, and self healing of fine cracks under marine environment. In this study, an experimental program was designed to investigate the durability of ECC material under combined mechanical loading and environmental loading conditions. ECC coupon specimens were preloaded under uniaxial tension to the strain of 0.5%, 1.0% and 1.5%, to simulate different strain levels applied to an in-service structure. The pre-applied strain can be a combination of strain due to vehicle load, prestressing load, shrinkage, thermal load, etc. Later on, the specimens were exposed to a chloride environment with the chloride concentration of 3% for 1, 2 and 3 months and subsequently reloaded up to failure. The effect of autogenous healing was assessed by measuring the retained stiffness, ultimate tensile strength and tensile strain capacity of ECC.

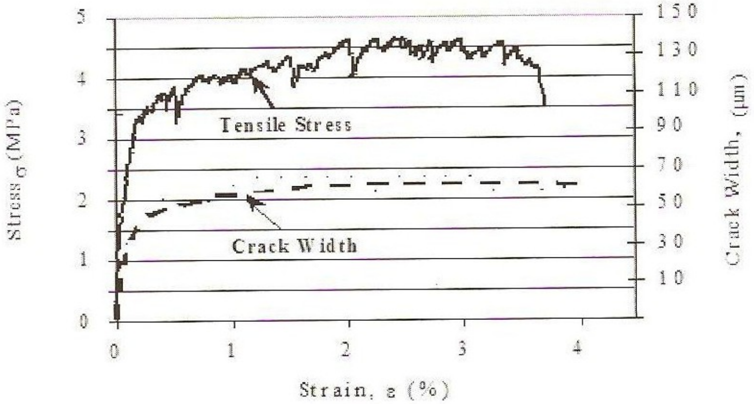


Figure 2: Uniaxial tensile stress-strain curve and crack development of ECC

2. EXPERIMENTAL PROGRAM

2.1 Mixture Proportions

The mix proportions for ECC are summarized in Table 1. The materials used were ordinary Portland cement, silica sand passing 200 μm sieve with average grain size 110 μm, Class-F fly ash, high range water reducer (HRWR), poly-vinyl-alcohol (PVA) fiber and water. A special poly-vinyl-alcohol (PVA) fiber designed particularly for ECC applications is used at 2% (by volume) in this ECC mixture. This fiber has a length of 8 mm, a diameter of 39 μm, and a nominal tensile strength of 1620 MPa. The density of the PVA fiber is 1300 kg/m^3.

ECC mixture was prepared in a standard mortar mixer. The mixing sequence is as follows: the cement, fly ash, sand and water were first mixed, and then the HRWR was slowly added while mixing continued, and finally the fiber was incorporated. From ECC mixture, 152.4 × 76.2 × 12.7 mm^3 coupon specimens were prepared for the direct uniaxial tensile test. The fresh ECC was then covered with plastic sheets and demoulded after 24 h. The specimens were cured in plastic bag at 95 ± 5% RH, 23 ± 2 ^{0}C for 6 days. The specimens were then left to cure in laboratory air, under uncontrolled conditions of humidity and temperature until the age of 28 days for testing. The direct tensile cracks were introduced in the coupon specimens as described in the next section. After pre-cracking, these specimens were stored in sodium chloride solution. For control study, some specimens without precracking were cured in laboratory air and then exposed to sodium chloride solution.

Table 1. Mixture properties of ECC by weight

	ECC (M45)
FA/C	1.2
W/CM*	0.27
Water (W), kg/m^3	331
Cement (C), kg/m^3	570
Fly ash (FA), kg/m^3	684
Sand (S), kg/m^3	455
Fiber (PVA), kg/m^3	26
High range water reducer (HRWR), kg/m^3	5.1

* CM: Cementitious materials (PC+FA)

2.2 Pre-Cracking and Uniaxial Tensile Testing

After 28 days of curing, the coupon specimens were pre-loaded to 0.5, 1.0 and 1.5% direct tensile strain to achieve various amounts of microcracking before exposure to sodium chloride solution. Before testing, aluminum plates were glued to both ends of the coupon specimen to facilitate gripping. Tests were conducted on an MTS machine with 25 kN capacity under displacement control at a rate of 0.005 mm/s. Typical stress-strain curves of the preloaded specimens are shown in Figure 3.

The pre-cracked ECC specimens were then continuously immersed in a 3% NaCl solution at room temperature, together with some uncracked specimens without preloading, for 30, 60 and 90 days. Subsequently direct tensile measurements on these specimens were conducted and stress-strain curves were recorded. In the case of uncracked specimens, average strain capacity and ultimate strength of ECC are an average of four specimens. In the case of pre-cracked specimens, average strain capacity and ultimate strength of ECC are calculated from a minimum of four and maximum of six specimens. The sodium chloride solution was replaced with a fresh solution every month.

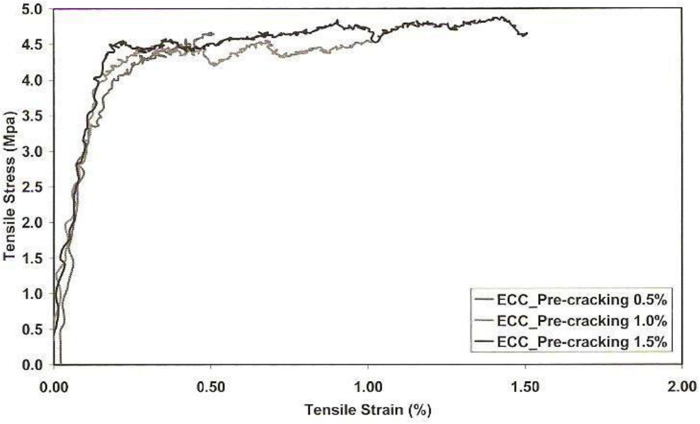


Figure 3: Typical pre-cracking tensile stress-strain curves of ECC

3. EXPERIMENTAL RESULTS AND DISCUSSION

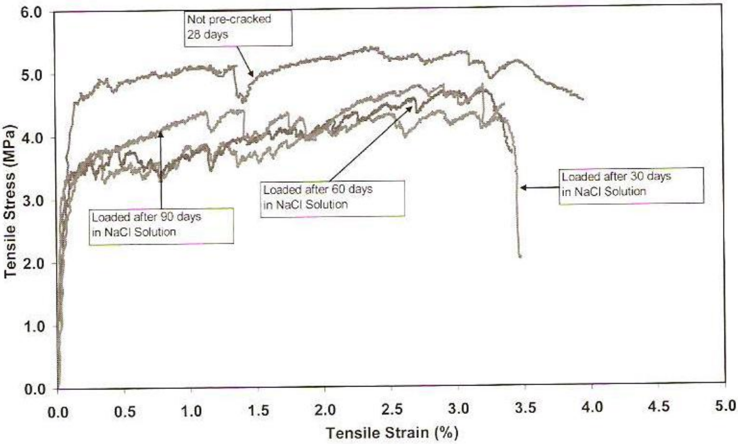
Table 2 summarized the tensile strain capacity, tensile strength, and crack width of ECC with various preloaded strain value, and NaCl exposure conditions. Typical tensile stress-strain curves obtained for specimens before and after exposure to NaCl solution are shown in Figure 4. For the uncracked specimens, exposure to NaCl appears to reduce the cracking strength and ultimate strength by about 10%. However, the tensile strain capacity does not appear to be affected. For the pre-cracked specimens, exposure to NaCl appears to be similarly affected, such that the influence of pre-cracking even up to 1.5% does not exacerbate the deterioration.

Table 2. Tensile Properties of ECC under different NaCl exposure conditions

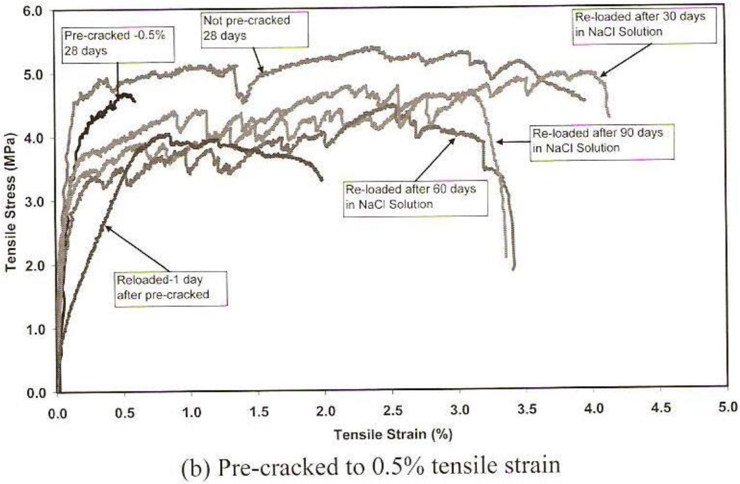
Curing Condition	Pre-loaded Strain (%)	Tensile Strain Capacity (%)	Ultimate tensile strength (MPa)	Average crack width (μm)
28 days air + 30 days air or NaCl	0.0 (Air curing)	2.86 ± 0.58	4.81 ± 0.64	~ 45
	0.0 (3% NaCl)	2.79 ± 0.54	4.34 ± 0.62	~ 100
	0.5 (3% NaCl)	3.85 ± 0.61	4.59 ± 0.29	~ 100
	1.0 (3% NaCl)	2.66 ± 0.66	3.85 ± 0.09	~ 100
	1.5 (3% NaCl)	2.48 ± 0.94	3.87 ± 0.73	~ 100
28 days air + 60 days air or NaCl	0.0 (Air curing)	2.51±0.19	4.75 ± 0.32	~ 35
	0.0 (3% NaCl)	2.37±0.50	4.25 ± 0.47	~ 100
	0.5 (3% NaCl)	3.16±0.26	4.05 ± 0.47	~ 100
	1.0 (3% NaCl)	3.28± 0.42	4.18 ± 0.22	~ 100
	1.5 (3% NaCl)	2.97± 0.69	4.07 ± 0.47	~ 80
28 days air + 90 days air or NaCl	0.0 (Air curing)	2.51±0.19	4.75 ± 0.32	~ 35
	0.0 (3% NaCl)	2.37±0.50	4.25 ± 0.47	~ 100
	0.5 (3% NaCl)	3.16±0.26	4.05 ± 0.47	~ 100
	1.0 (3% NaCl)	3.28± 0.42	4.18 ± 0.22	~ 100
	1.5 (3% NaCl)	2.97± 0.69	4.07 ± 0.47	~ 80

Figure 4 shows also the tensile properties of ECC specimens that had been pre-cracked to 0.5, 1.0% and 1.5% strain levels, then unloaded, and reloaded 1 day after pre-cracked. Thus these specimens had no time to undergo any crack healing which is found in specimens exposed to NaCl solution. As expected, there is a remarkable difference in initial stiffness between virgin specimen and pre-cracked specimen under direct tension. This is due to re-opening of cracks within pre-cracked specimens during reloading [13]. The opening of these cracks offers very little resistance to load, as the crack simply opens to its previous crack width before fiber bridging is re-engaged. Once fiber bridging is re-engaged, however, the load capacity resumes, and further tensile straining of the intact material can take place.

By comparing the initial material stiffness of reloaded ECC specimens exposed to NaCl solution in Figure 4, it can be observed that a significant recovery of mechanical stiffness has been achieved. This suggests that between the time of inducing pre-cracking and the time of testing, after exposure to NaCl solution, healing of the micro-cracks has occurred in the ECC specimens. This can be attributed primarily to the high cementitious material content and relatively low water to binder ratio within the ECC mixture. As a result of the formation of micro-cracks due to mechanical loading, unhydrated cementitious particles are easily exposed to the sodium chloride solution during the immersion period, which leads to development of further hydration processes. Finally micro-cracks under conditions of a damp environment were closed by newly formed products. These investigations indicated that the formation of re-hydration products in micro-cracks is possible. In ECC, the re-healing process is especially aided by the innately tight crack width.



(a) Not pre-cracked



(b) Pre-cracked to 0.5% tensile strain

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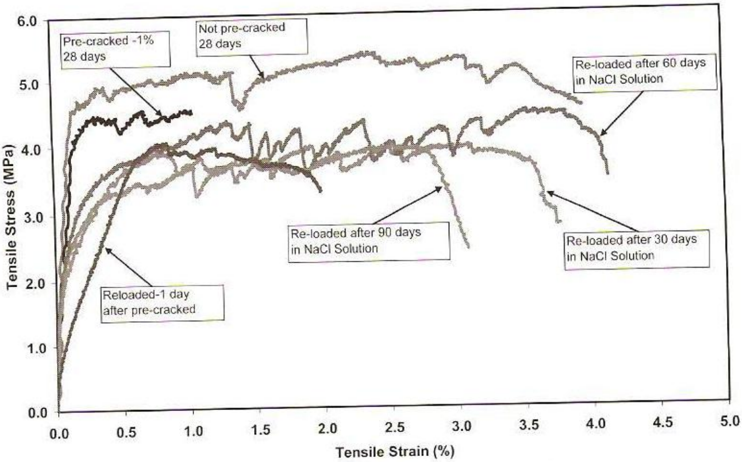
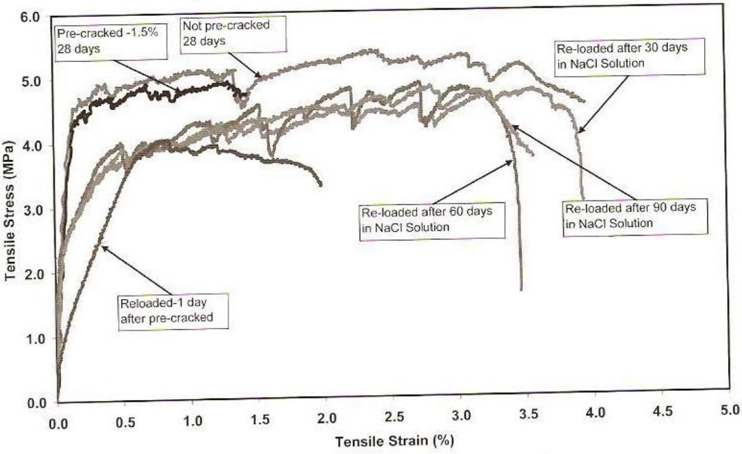


(c) Pre-cracked to 1.0% tensile strain



(d) Pre-cracked to 1.5% tensile strain

Figure 4: Tensile stress-tensile strain curves of ECC specimens before and after exposed to 3% NaCl solution

The average ultimate tensile strength values are shown in Figure 5. Compared to control specimens cured in laboratory air, the test results indicate that the specimens (pre-cracked and uncracked) stored in sodium chloride solution show a 10% reduction in ultimate tensile strength for all exposure ages; this may be attributed to the effects of leaching of calcium hydroxide from the specimens. Water not saturated with calcium hydroxide (high-calcium hydrated lime) may affect test results due to leaching of lime from the test specimens [14]. However, more experimental studies on a micro-mechanical scale are necessary to understand the reasons of the reduction in the ultimate tensile strength and increased crack width.

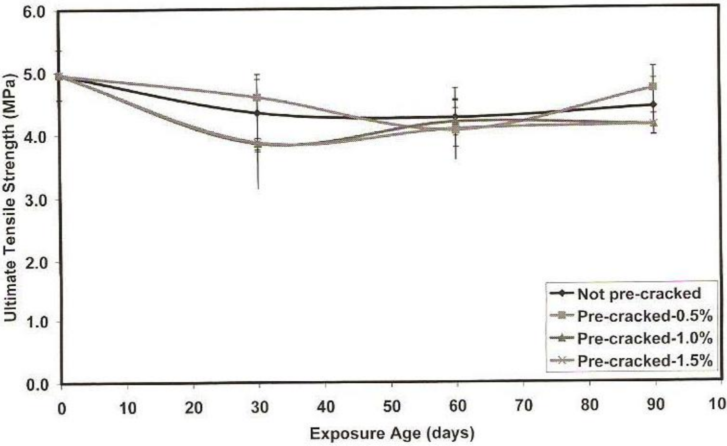


Figure 5: Influence of sodium chloride solution and mechanical loading on ECC ultimate tensile strength

Figure 6 shows the average of tensile strain capacity of ECC specimens stored in NaCl solution. The tensile strain capacity reported for these specimens does not include the residual strain from the pre-cracking load. By neglecting this residual strain, the large variability in material relaxation during unloading is avoided, and a conservative estimation for ultimate strain capacity of the material is presented. The tensile strain capacity of uncracked and pre-cracked ECC specimens exposed to NaCl solution averaged between 2.4% and 3.8%. This value is higher than or similar to that of air cured specimens (averaging 2.5% to 2.8%).

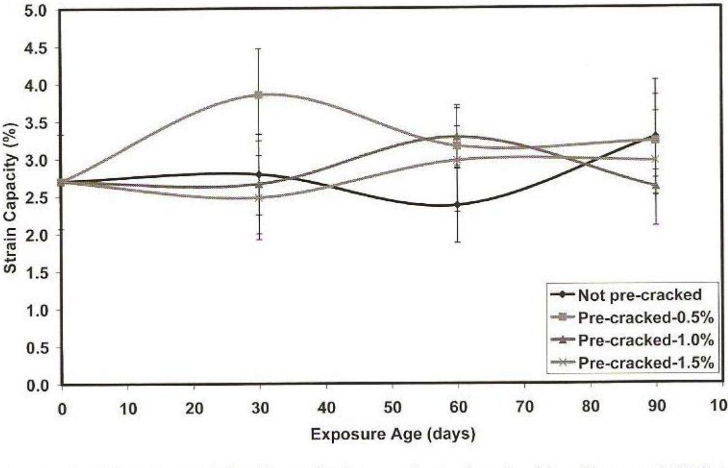
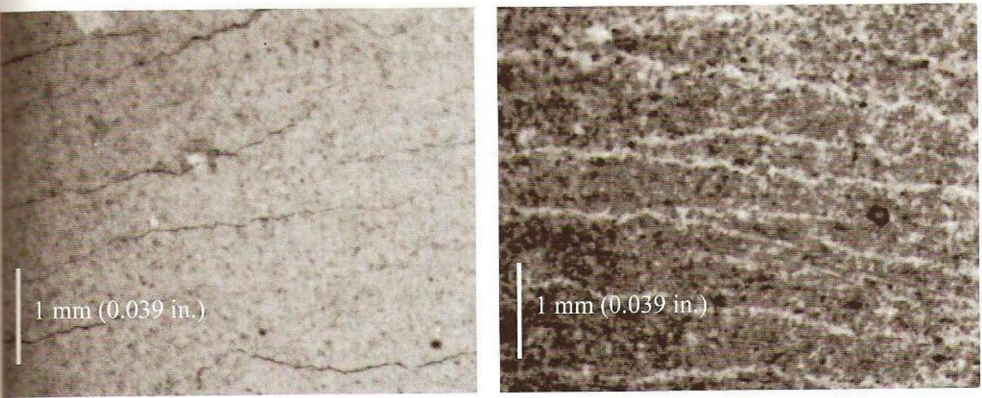


Figure 6: Influence of sodium chloride solution and mechanical loading on ECC tensile strain capacity

In the case of pre-cracked specimens exposed to NaCl solution, a distinct white deposit was visible, which formed a continuous dense layer over the crack surface (Figure 7). The deposits were most probably caused by efflorescence due to the leaching of calcium hydroxide into cracks [15]. It has also been suggested that in marine environment this effect may arrest chloride transportation by healing of cracks. From the present study, healing of micro-cracks of ECC under NaCl solution is evident from the mechanical properties discussed before. The mechanical properties indicate that micro-cracks of ECC exposed to NaCl solution healed almost completely. This can be attributed primarily to the high cementitious material content and relatively low water to binder ratio within the ECC mixture. The continued hydration of unhydrated cementitious material cause the self-healing of the crack and then may also reduce the ingress of aggressive ions.



(a) ECC cracks before NaCl exposure (b) ECC cracks after NaCl exposure

Figure 7: Self healing products in ECC microcracks before and after salt ponding test

4. CONCLUSION

Specimens pre-loaded up to 1.5% strain capacity showed almost complete recovery of stiffness when re-loaded in direct tensile tests even after periods of only one month in NaCl solution exposure. Preloaded ECC specimens with microcracks at 45 μm crack width induced by mechanical loading and then exposed to sodium chloride solution almost fully recovered their tensile strain. However, both pre-cracked and uncracked ECC specimens exposed to NaCl solution lost more than 10% of their ultimate tensile strength due to the leaching of calcium hydroxide under sodium chloride solution for all exposure ages. Furthermore, the crack width increased to around 100 μm compared with 45 μm in air curing condition. This phenomenon suggests possible change in the fiber/matrix interface bond properties. Microcracks of ECC specimen that were subjected to sodium chloride solution appear completely sealed as a result of self-healing. Hence, it is expected that transport properties recover to their original values before microcracking occurs.

The results presented in this study provide a preliminary database for the durability of cracked and uncracked ECC under combined mechanical loading and marine environmental loading conditions. For a complete understanding of durability of ECC in marine environment, it will be necessary to conduct further research on a micro-mechanical scale to investigate changes of ECC matrix toughness and fiber/matrix interface properties.

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