Engineered Cementitious Composites: An Innovative Concrete for Durable Structure

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ABSTRACT

This paper reviews recent research on the durability properties of Engineered Cementitious Composites (ECC), a special type of high-performance fiber reinforced cementitious composites designed with micromechanical principles, under various environmental and mechanical loads. The durability subjects include (a) ECC cracking and transport properties (permeability, absorption and diffusion), (b) corrosion resistance (c) freeze–thaw and salt scaling resistance, (d) performance under hot and humid environment, and (e) performance under high alkaline environment. The research results indicate that due to intrinsic self-control tight crack width and high tensile strain capacity, many durability challenges confronting concrete can be overcome by using ECC. The enhanced performances of ECC under mechanical and environmental loads are expected to contribute substantially to improving civil infrastructure sustainability by reducing the amount of repair and maintenance during the service life of the structure.

INTRODUCTION

Concrete is the most widely used construction material in the world. Even though it was designed for mainly carrying compressive loads, concrete in real field condition is also subjected to tensile stresses due to structural loading, shrinkage (if the shrinkage is restrained), chemical attack and thermal deformations. The tensile strength of concrete is only about 10% of its compressive strength, and brittle concrete cracks when subjected to tensile stresses. The main causes of durability problems of concrete structures (reinforcement steel corrosion, sulfate and acid attacks, alkali silica reaction, and freeze-thaw damage) are mainly related to the penetration of harmful substances such as chloride, alkalies, acids, sulfates, carbon dioxide into hardened concrete, and cracks in concrete provide quick paths for intrusion of these harmful substances and seriously affect the durability and service life of concrete structures. Therefore, durability is vitally important for all concrete structures, and it can be associated with the brittle nature of concrete.

In recent years, the effort to modify the brittle nature of ordinary concrete has resulted in modern concepts of ultra high performance fiber reinforced cementitious composites, which are characterized by tensile strain-hardening after first cracking. Depending on its composition, its tensile strain capacity can be up to several hundred times that of normal and fiber reinforced concrete. Engineered Cementitious Composites (ECC), designed to strain harden in tension based on micromechanical principles, allows optimization of the composite for high performance represented by extreme ductility while minimizing the amount of reinforcing fibers, typically less than 2% by volume [Li, 1998; Li, 2003; Li, *et al.*, 2001]. Unlike other concrete materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity up to 500 times greater than normal concrete (Figure 1). Along with tensile ductility, the unique crack development within ECC is critical to its durability. Different from ordinary concrete and most fiber reinforced concretes, ECC exhibits self-controlled crack widths under increasing load. Even at large imposed deformation, crack widths of ECC remain small, less than 60 μm (Figure 1). In contrast, it is well known that reliable crack width control using steel reinforcement is difficult to achieve in concrete structures. With intrinsically tight crack width and high tensile ductility, ECC represents a new concrete material that offers a significant potential to naturally resolving the durability problem of concrete structures. A typical mix design of ECC using poly-vinyl-alcohol (PVA) fiber reinforcements is given in Table 1.

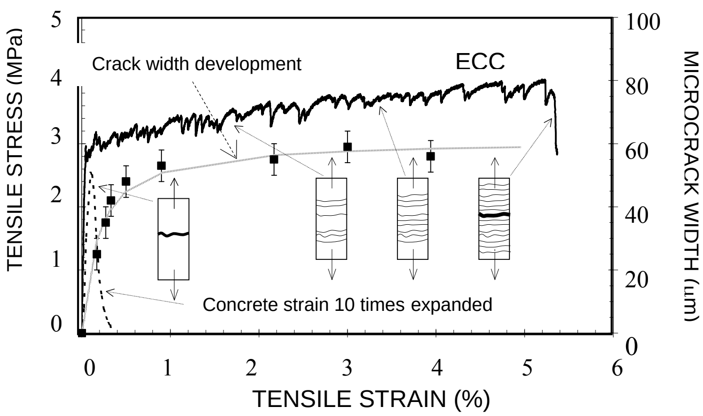


FIGURE 1 - TYPICAL TENSILE STRESS-STRAIN CURVE AND CRACK WIDTH DEVELOPMENT OF ECC

Material	Proportion
Cement	1.00
Water	0.54
Fly ash	1.20
Sand	0.54
Fiber (vol), %	2.00
Superplasticizer	0.013

TABLE 1 - **TYPICAL MIX DESIGN OF ECC MATERIAL**

In recent years, increasing research has been conducted on durability of ECC materials. This paper provides an overview of the recent investigations in ECC cracking and durability at the University of Michigan. The subjects include (a) ECC cracking and transport properties (permeability, absorption and diffusion), (b) corrosion resistance (c) freeze–thaw and salt scaling resistance, (d) performance under hot and humid environment, and (e) performance under high alkaline environment.

TRANSPORT PROPERTIES

Depending on the driving force, the transportations of liquids, gases and ions through hardened concrete can occur chiefly through three different mechanisms; permeation, absorption, or diffusion. Depending upon the conditions, transport of liquids, gases and ions may be driven by one or a combination of these three mechanisms. The main driving force behind permeation is the presence of a pressure gradient. Permeation is very important for concrete structures under water such as offshore structures or fluid retaining structures such as water tanks. Absorption, driven by capillary pore suction, is the predominant transport process when unsaturated concrete is exposed to liquids. Diffusion is the most commonly studied transport process of ions, such as chloride, which accelerates the initiation of steel corrosion in concrete. When the saturated concrete is exposed to a chloride solution, a chloride concentration gradient is created between the concrete element surface and the pore solution. In this case, diffusion will be the predominant driving mechanism of chloride transport.

Permeability

Typically, the formation of cracks increases the transport properties of concrete, allowing water, oxygen and chloride ions to easily penetrate and reach the reinforcing steel and accelerate the initiation of steel corrosion in concrete. Lepech and Li studied the water permeability of mechanically loaded ECC and reinforced mortar [Lepech and Li, 2005]. In that study, both ECC and reinforced mortar specimens were tensioned to identical 1.5% deformation, resulting in a variety of crack widths and number of cracks among the various specimens. The ECC specimens revealed microcracks less than 60 μm regardless of the imposed deformation level, and the cracked specimens exhibited nearly the same water permeability as sound concrete (Figure 2). In contrast, cracks larger than 150 μm were easily produced in the reinforced mortar specimens under the identical imposed uniaxial deformation. The larger crack widths resulted in significant increase in water permeability of the reinforced mortar, despite the smaller number of cracks. Further, when normalized by number of cracks within the specimen, the comparable permeability of cracked ECC with sound material becomes even more apparent (Figure 2).

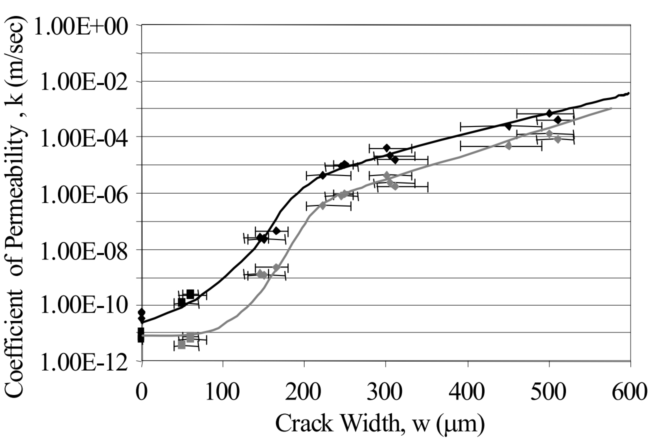


FIGURE 2 - PERMEABILITY OF CRACKED AND UNCRACKED ECC (SQUARE SYMBOLS) AND REINFORCED MORTAR SPECIMENS (DIAMOND SYMBOLS). GREY DATA POINTS ARE PERMEABILITY VALUES NORMALIZED BY NUMBER OF CRACKS IN THE SPECIMENS

Diffusion

The corrosion of steel in concrete is one of the major problems with respect to the durability of reinforced concrete structures, and the penetration of chloride ions into concrete is considered to be the major cause of corrosion. Miyazato and Hiraishi was probably the first to show that the penetration depth of chloride ions into ECC cover was substantially lower than that in concrete cover, using R/C and R/ECC beams preloaded to the same level of flexural deflection and subjected to identical accelerated chloride exposure [Miyazato and Hiraishi, 2005]. In addition, a relation between flexural deformation levels and the effective chloride diffusion coefficient of ECC and reinforced mortar was examined by Şahmaran et al [2007]. The effective chloride diffusion was computed based on measured chloride ion concentration profiles fitted to Crank's solution to Fick's 2nd Law. Under high imposed bending deformation, the preloaded ECC beam specimens revealed multiple microcracks width (CW) less than 50 μm and an effective diffusion coefficient significantly lower than that of the similarly preloaded reinforced mortar beam because of the tight crack width control in ECC (Figure 3). In contrast, cracks larger than 150 μm were easily produced in reinforced mortar specimens under the same imposed deformation, producing significant increase in the effective diffusion coefficient. The effective diffusion coefficient of ECC was found to be linearly proportional to the number of cracks, whereas the effective diffusion coefficient of reinforced mortar is proportional to the square of the crack width. Therefore, the effect of crack width on chloride transport was more pronounced when compared to that of crack number. In addition, tensile performances of ECC cracked and uncracked specimens under marine environment were investigated by Li et al [2007]. Apart from the slight reductions in ultimate tensile strain and strength capacities and higher residual crack width, the test results largely confirm the durability performance of ECC material under accelerated aging, even in cases where the material experiences mechanical loading that deforms it into the strain-hardening stage prior to exposure. Healing of micro-cracks induced by the preload is evident from the recovery of elastic stiffness of the exposed pre-cracked specimens on reloading.

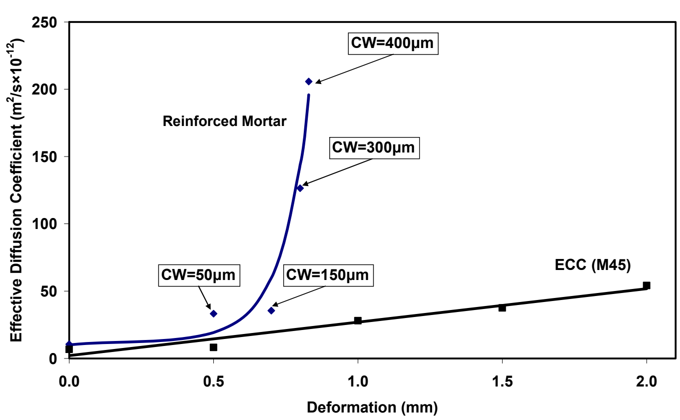


FIGURE 3 - DIFFUSION COEFFICIENT VERSUS PRE-LOADING DEFORMATION LEVEL FOR ECC AND MORTAR

Absorption

Since concrete structures in exposed conditions are generally subjected to the drying actions of wind and sun, they are rarely fully saturated when in service. Under this condition, therefore, permeability and diffusion may not be the dominant transport processes in concrete materials. Under dry or partially saturated conditions, the movement of water into concrete is controlled by capillary suction forces existing in the evacuated capillary cavities within the matrix [Martys and Ferraris, 1997]. As mentioned above, cracking in ECC is fundamentally different from that which occurs in concrete or reinforced concrete. One of the concerns of ECC is its crack pattern of closely spaced cracks with tight crack width in relation to capillary suction. This concern is addressed directly in the study conducted by Şahmaran and Li [2008-a] by measuring the sorptivity and absorption properties of pre-cracked ECC material. After various numbers of microcracks were introduced by mechanical loading, water absorption and sorptivity tests were performed to develop an understanding of how microcracks accelerated the deterioration process. Figure 4 shows the relationship between the sorptivity (mm/min$^{1/2}$) over six hours and the number of cracks, for ECC specimens. Corresponding values for virgin ECC specimens (data points with zero number of cracks) are also included in this plot. As seen from the figure, the presence of micro-cracking in ECC significantly alters the transport properties measured as a function of the number of micro-cracks. The water absorption increase is fairly high as the number of cracks on the surface of the ECC specimens increases. Therefore, the sorptivity test shows that micro-cracked ECC specimens would be more vulnerable to attack than virgin specimens. As the number of cracks along the specimen grows, the sorptivity of ECC increased exponentially. Even so, the sorptivity values of pre-loaded ECC specimens up to a strain representing 1.5% on the exposed tensile face is not particularly high when compared to that of normal concrete, probably due to higher amount of cementitious materials, lower water-cementitious materials ratio, high fly ash content and the absence of coarse aggregate. Moreover, in the same study, Şahmaran and Li [2008-a] also studied the absorption rate in cracked ECC, and found that the use of water repellent admixture in the production of ECC could easily inhibit the sorptivity even for the mechanically pre-loaded ECC (Figure 4).

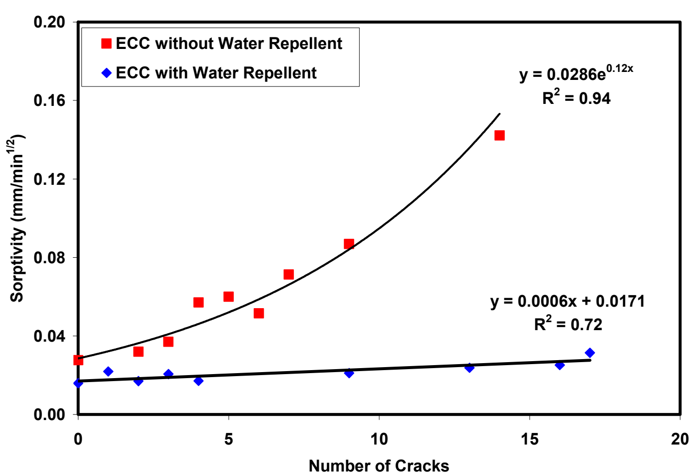


FIGURE 4 - SORPTIVITY VERSUS NUMBER OF CRACK FOR ECC MIXTURES

The reason for the relatively low permeation and diffusion cracked ECC specimens are not only due to the tight crack width but also the presence of self-healing of the microcracks. The self-healing of cracks becomes prominent when crack width is small. Based on experimental results, Evardsen, and Reinhardt and Jooss proposed that cracks with width below 0.10 mm can be closed by a self-healing process [Evardsen, 1999; Reinhardt and Joss, 2003]. In the case of precracked ECC specimens exposed to water or salt solution or under wet and dry cycles, micro-cracks in ECC were found to close due to self-healing, thus slowing further water intake, reducing the rate of water absorption and diffusion [Lepech and Li, 2005; Şahmaran *et al.*, 2007]. For example, an environmental scanning electron microscope (ESEM) observation of the fractured surface of ECC across a healed crack after exposed to salt solution is shown in Figure 5. The ESEM observations show that most of the products seen in the cracks were newly formed calcium-silicate-hydrate (C-S-H) gels, which are the basic cementing compound produced by the normal hydration reaction. This can be attributed primarily to the large fly ash content and relatively low water to binder ratio within the ECC mixture. The continued pozzolanic activity of fly ash is responsible for the self-healing of the crack which further reduces the ingress of the chloride ions.

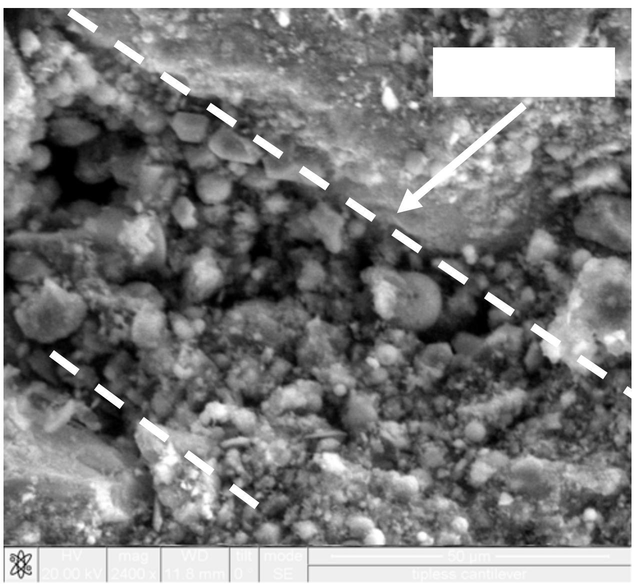


FIGURE 5 - ESEM MICROGRAPH OF REHYDRATION PRODUCTS IN A SELF-HEALED CRACK AFTER EXPOSURE TO SALT SOLUTION [Şahmaran *et al.*, 2007]

CORROSION RESISTANCE

Reinforcing steel bars embedded in concrete are usually well protected against corrosion by the high alkalinity of pore water because the steel surface is passivated in the presence of oxygen. However, reinforcing steel bars in concrete structures are depassivated when the chloride concentration reaches threshold levels on the rebar surface, or when the pH of the concrete cover drops below critical levels due to carbonation [Tuutti, 1982]. Some of the most commonly used protection methods for new constructions against steel reinforcement corrosion include high quality (low water to cement (W/C) ratio and good consolidation) concrete, increased concrete cover thickness, and use of epoxy coated steel reinforcing bars. Generally, low W/C ratio and good consolidation contribute to the reduction in permeability. A higher cover thickness is supposed to provide better physical protection because the concrete acts as a barrier which delays access of chloride ions, carbon dioxide and moisture to the steel reinforcement. However, as a result of restrained shrinkage, thermal deformations, chemical reactions, poor construction practices and mechanical loads, concrete unavoidably cracks and, over time, chlorides, carbon dioxide and moisture can penetrate even high quality concrete or concrete with good cover thickness [ACI 224R, 2001]. In addition, a larger cover thickness is known to lead to a greater crack width. Further, epoxy coatings on the surface of steel reinforcing bars are sometimes damaged during handling, or become brittle and delaminate from the steel reinforcing bars under high chloride concentrations, so that the reliability of epoxy coating for steel protection has been called into question [FHWA, 1992; Saques *et al.*, 1994; Manning, 1996]. Consequently, corrosion of reinforcement occurs which could lead to cover spalling and steel diameter reduction, and potentially diminishing of load capacity of the reinforced concrete member. At the root of this steel corrosion problem is the brittle nature of concrete materials. The brittleness of concrete inherently results in cracks that allow corrosives to penetrate the cover, and fail to resist the expansive force once corrosion starts.

With intrinsically tight crack width and high tensile ductility, ECC offers a significant potential to naturally resolving the corrosion related durability problem of reinforced concrete (R/C) structures. Concerned with the large number of microcracks within ECC in comparison to concrete, the rate of corrosion of reinforcing steel within an ECC matrix has been investigated and compared to R/C system [Miyazato and Hiraishi, 2005]. Preloaded R/ECC and R/C beams were exposed to a chloride environment to accelerate the corrosion process. To determine the corrosion rate of ECC and concrete, macrocell and microcell corrosion rates were separately determined. The total (macro and micro cell) corrosion rate was measured to be less than 0.0004 mm/year but exceeded 0.008 mm/year in the steel reinforcement in the R/ECC and R/C beams respectively (Figure 6).

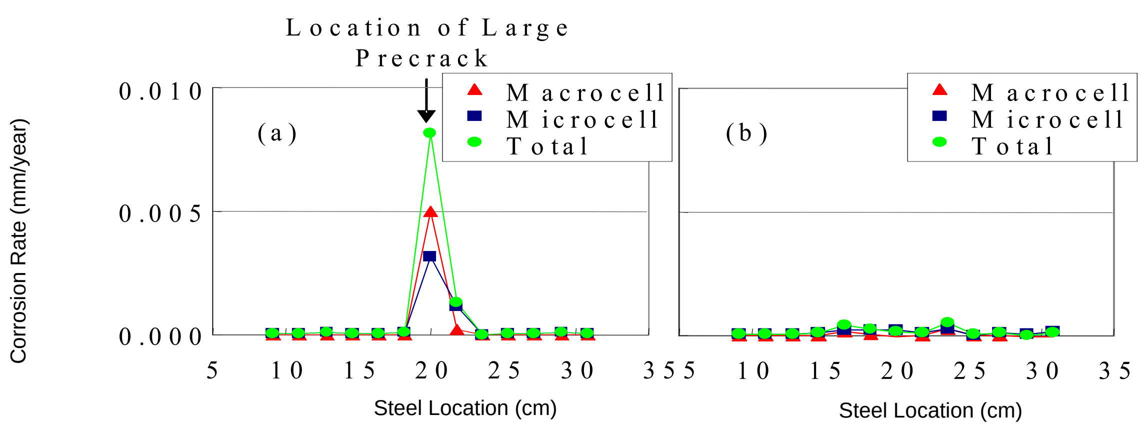


FIGURE 6 - MICROCELL AND MACROCELL CORROSION RATE MEASURED FOR (A) R/C, AND (B) R/ECC ALONG THE REINFORCEMENT BAR LENGTH [Miyazato and Hiraishi, 2005]

In another study, Şahmaran *et al.* (2008) investigated the cracking behavior and residual flexural load capacities of reinforced ECC (R/ECC) specimens and R/mortar specimens, which have equal compressive strength to the ECC. During accelerated corrosion test at constant applied voltage [Şahmaran et al., 2008], corrosion-induced crack width of the mortar specimens were found to increase with time as corrosion activity progressed. Larger crack widths up to 2.00 mm were observed at higher levels of corrosion (Figure 7). Moreover, corrosion of reinforced mortar beam specimens resulted in a marked reduction in stiffness and flexural load capacity. After 25 hours accelerated corrosion exposure, the flexural load reduced to about 34 % of the flexural capacity of the control mortar beam. On the other hand, crack widths (~ 0.1 mm) of ECC remained nearly constant with time as corrosion activity progresses, while the number of cracks on the surface of the ECC specimens increased. The results of this study also showed that ECC has significant anti-spalling ability compared with conventional mortar (Figure 7). In contrast to mortar specimens, the ECC beam specimens after 50 hours accelerated corrosion exposure retained almost 100% of the flexural capacity of the control specimens. Beyond 50 hours, the flexural capacity decreases, but retained over 45% that of the control specimens even after 300 hours of accelerated corrosion exposure.

(a) (b)

(c) (d)

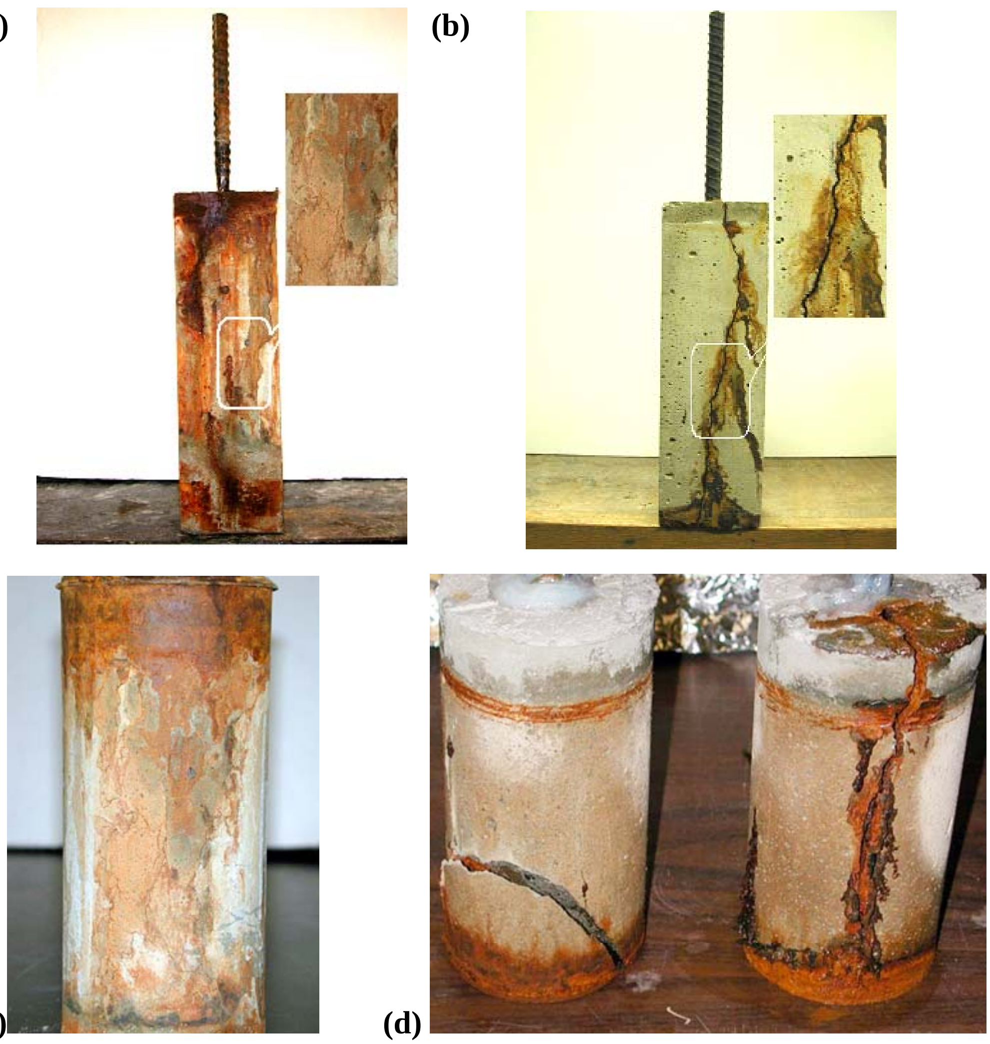
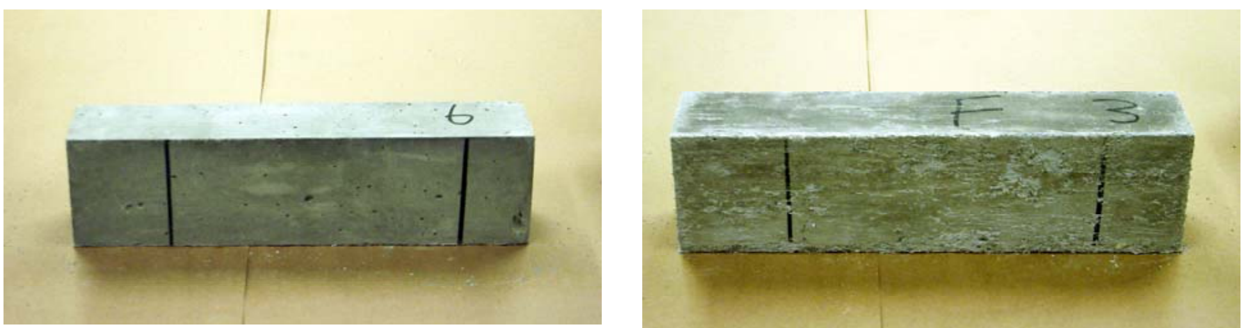


FIGURE 7 - ECC AND MORTAR SPECIMENS AFTER ACCELERATED CORROSION TEST: (A) ECC PRISMATIC SPECIMEN AFTER 300 HOURS ACCELERATED CORROSION, (B) MORTAR PRISMATIC SPECIMEN AFTER 75 HOURS ACCELERATED CORROSION, (C) ECC CYLINDRICAL SPECIMEN AFTER 350 HOURS ACCELERATED CORROSION, (D) MORTAR CYLINDRICAL SPECIMEN AFTER 95 HOURS ACCELERATED CORROSION [Şahmaran *et al.*, 2008]

FREEZE THAW AND SALT SCALING RESISTANCE

It is well known that the cyclical freeze-thaw cycles and the use of de-icing salts during winter are two of the major causes of rapid degradation in concrete pavements, bridge decks, parking structures, and similar structures. ECC used for this kind of structures must be resistant to cyclical freezing and thawing, and the effects of de-icing agents. It is known that a proper air-void system is generally needed in normal concrete to avoid internal cracking due to freeze-thaw cycles and scaling due to freezing in the presence of deicer salts.

Durability of non-air-entrained ECC specimens was tested by exposure to cycles of freezing thawing testing, in accordance with ASTM C666A [Li *et al.*, 2003]. Non-air-entrained concrete specimens were also tested as reference specimens. Non-air-entrained specimens were used as control since no air entrainment was added to the ECC mixtures. After 110 cycles, the concrete specimens had severely deteriorated, requiring removal from the freeze-thaw machine, as mandated by the testing standard. However, all ECC specimens survived the test duration of 300 cycles with no degradation of dynamic modulus. Figure 8 shows the typical surface condition of the after 300 freeze-thaw cycles and fog room cured prismatic ECC specimens. This performance results in a durability factor of 10 for concrete compared to 100 for ECC, as computed according to ASTM C666A. In uniaxial tension tests performed on wet cured and freeze-thaw exposed ECC tensile coupons at the same age, no significant drop in strain capacity was experienced after 300 cycles. Both wet cured and freeze thaw specimens exhibited a strain capacity of roughly 3%.



(a) fog room curing (b) after 300 freeze-thaw cycles

FIGURE 8 - ECC SPECIMEN SURFACE APPEARANCE AFTER (A) NORMAL CURING AND (B) FREEZE-THAW CYCLES

Numerous laboratory test data in accordance with ASTM C 672 have indicated that air entrained concretes incorporating high volume fly ash often perform unsatisfactorily when exposed to freezing and thawing cycles in the presence of de-icing salts. For the production of ECC, as much as two-thirds of the portland cement is substituted by fly ash. Due to the high volume fly ash content, it is important to test the performance of ECC exposed to freezing and thawing cycles in the presence of de-icing salt. Salt scaling resistance of non-air-entrained sound (uncracked) and mechanically pre-loaded (cracked) ECC specimens was evaluated by Şahmaran and Li in accordance with ASTM C672 [Şahmaran and Li, 2007-b]. Non-air-entrained mortar specimens with and without fly ash were also tested as reference specimens. After 50 freeze-thaw cycles in the presence of de-icing salt, the surface condition visual rating and total mass of the scaling residue for ECC specimens, even those with high volume fly ash content, remain within acceptable limits of ASTM C 672 (Figure 9). This level of durability holds true even for

ECC specimens pre-loaded to high deformation levels and exhibiting extensive microcracking. In comparison, reference mortar specimens under identical testing conditions deteriorated severely. Moreover, the replacement of fly ash with cement in mortar further exacerbated deterioration due to freezing and thawing cycles in the presence of de-icing salt. In a separate test, both pre-loaded (cracked) and sound ECC coupon specimens were exposed to freeze-thaw cycles in the presence of de-icing salts for 25 and 50 cycles to compare residual tensile strength and ductility of reloaded ECC specimens. The reloaded specimens showed negligible loss of ductility, and retained the multiple micro-cracking behavior and tensile strain capacity of more than 3%. It was also discovered that micro-cracks due to mechanical loading will heal sufficiently under freezing and thawing cycles in the presence of salt solutions, restoring them to nearly the original stiffness. These results confirm that ECC, both sound and micro-cracked, remains durable despite exposure to freezing freeze-thaw cycles in the presence of de-icing salts.

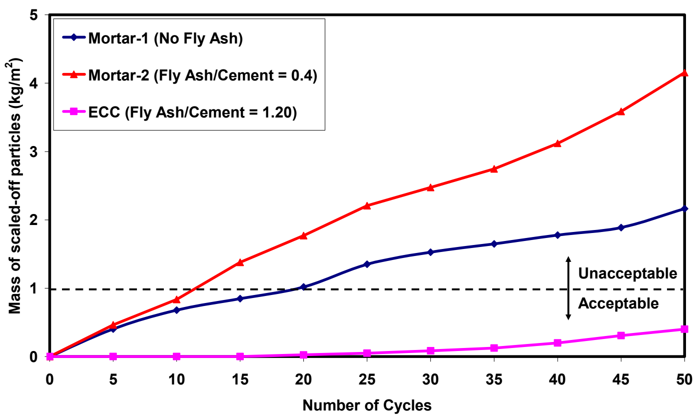


FIGURE 9 - MASS OF SCALED-OFF PARTICLES VERSUS NUMBER OF FREEZE THAW CYCLES FOR VIRGIN MORTAR AND VIRGIN ECC PRISMS IN PRESENCE OF DE-ICING SALTS

DURABILITY UNDER EXTREMELY HOT AND HUMID ENVIRONMENTS

In contrast to freeze thaw tests which are designed to simulate temperature changes in winter conditions, hot water immersion tests were conducted to simulate the long term effects of hot and humid environments. To examine the effects of environmental exposure, hot water immersion was performed on individual fibers, single fibers embedded in ECC matrix, and composite ECC material specimens [Li *et al.*, 2004]. Specimens for both individual fiber pull-out and composite ECC material were cured for 28 days at room temperature prior to immersion in hot water at 60 ºC for up to 26 weeks. After 26 weeks in hot water immersion, little change was seen in fiber properties such as fiber strength, fiber elastic modulus, and elongation. The tensile strain capacity of the ECC dropped from 4.5% at early age to 2.75% after 26 weeks of hot water immersion. While accelerated hot weather testing does result in lower strain capacity of ECC, the 2.75% strain capacity exhibited after 26 weeks remains over 250 times that of normal concrete.

DURABILITY UNDER HIGHLY ALKALINE ENVIRONMENTS

Another environment that could affect the microstructure and composite properties of ECC is a high alkaline environment. In addition to high alkaline matrix pore water solution, ECC can come into contact with alkaline media through interaction with a variety of alkaline chemicals, soil (or solutions diffusing through soil) and sea water. Even though no deleterious expansion has been expected due to alkali silica reaction because of the high volume fly ash (HVFA) content, small sand particle size and micro-fibers in ECC [Şahmaran and Li, 2008-b], durability of HVFA-ECC must be evaluated under high alkaline environments. Alkalis will penetrate through micro-cracks or even the uncracked matrix that could lead to modifications in the material microstructure and hence changes in the composite properties.

Şahmaran and Li investigated the durability of ECC under high alkaline environment [Şahmaran and Li, 2008-b]. The performance of ECC under high alkaline medium was tested according to ASTM C1260. The length change of the ECC bars was measured up to 30 days. Figure 10 shows expansive behavior of the ECC. The classification ranges given from the ASTM C 1260 are illustrated graphically in Figure 10 by horizontal gridlines. The results obtained from accelerated mortar bar test indicated that ECC did not show any expansion at the end of 30 days soaking period probably due to non-reactive silica sand. However, even if reactive silica sand and alkalis are present in ECC, it cannot be expected to develop deleterious expansion due to ASR because of the high volume fly ash content, small sand particle size and micro-fibers in ECC.

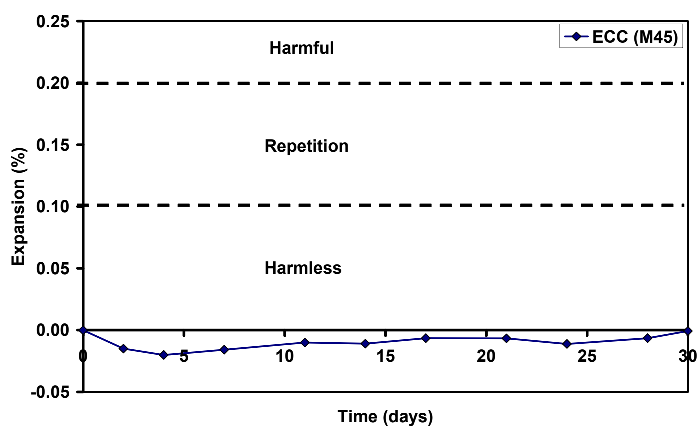


FIGURE 10 - EXPANSION TIME HISTORIES FOR ECC (ASTM C1260-94) [Şahmaran and Li, 2008-b]

In the same study, Şahmaran and Li evaluated the mechanical performance of both virgin and mechanically-loaded ECC under high alkaline environments [Şahmaran and Li, 2008-b]. ECC coupon specimens were firstly pre-loaded under uniaxial tension to different strain levels, and then exposed to an alkaline environment up to 3 months at 38 ^{o}C and reloaded up to failure. The reloaded specimens showed slight loss of ductility and tensile strength, but retained the multiple micro-cracking behavior and tensile strain capacity of more than 2% (about more than 200 times that of normal concrete and normal fiber reinforced concrete). The test results indicated strong evidence of self-healing of the micro-cracked ECC material, which can still carry considerable tensile stress and strain and restore nearly the original stiffness. This observation is also supported by an environmental scanning electron microscope (ESEM) observation of the fractured surface of ECC across a healed crack. The phenomenon of self-healing effectively closes the microcracks even after one month sodium hydroxide solution exposure period (Figure 11).

FIGURE 11 - ESEM MICROGRAPH OF REHYDRATION PRODUCTS IN A SELF-HEALED CRACK AFTER 30-DAY SODIUM HYDROXIDE SOLUTION EXPOSURE PERIOD [Şahmaran and Li, 2008-b]

CONCLUSION

In terms of transport properties, micro-cracks induced by mechanical pre-loading increase the permeability, the chloride transport and the sorptivity values of ECC. However, the risk of water transport by permeability and capillary suction, and chloride transport by diffusion in ECC, cracked or uncracked, is found to be comparable or lower with that in normal sound concrete without any cracks. Apart from the slight reductions in ultimate tensile strain and strength capacities and higher residual crack width, the results found in the studies summarized in this paper largely confirm the durability performance of ECC material under accelerated aging (exposure to freeze-thaw cycles with and without de-icing salts, continuous sodium hydroxide at 38 ^{o}C and sodium chloride solutions at room temperature (marine environment), and hot and humid environment) even in cases where the material experiences mechanical loading that deforms it into the strain-hardening stage prior to exposure. Healing of micro-cracks induced by the preload is evident from the microstructural studies and recovery of elastic stiffness of the exposed pre-cracked specimens on reloading.

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