Engineered Cementitious Composites

Can Composites Be Accepted as Crack-Free Concrete?

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Because conventional concrete is brittle and tends to crack easily under mechanical and environmental loads, there are concerns with durability. During the past decade, the effort to modify the brittle nature of ordinary concrete has resulted in high-performance fiber-reinforced cementitious composites (HPFRCCs), which are characterized by tensile strain-hardening after first cracking. Engineered cementitious composites (ECCs), a special type of HPFRCC, represent a new concrete material that offers significant potential to reduce the durability problem of concrete structures. Unlike ordinary concrete and fiber-reinforced concrete materials, ECC strain-hardens after first cracking, as do ductile metals, and it demonstrates a strain capacity 300 to 500 times greater than normal concrete. Even at large imposed deformation, crack widths of ECC remain small, less than 80 μm. Apart from unique tensile properties, the relationship between crack characteristics and durability—including transport properties (permeability, absorption, and diffusion); frost resistance with and without deicing salts; performance in a hot and humid environment; performance in a high-alkaline environment, corrosion, and spall resistance; and self-healing of microcracks—is presented. Research results indicate that, because of intrinsic self-control tight crack width, robust self-healing performance, and high tensile strain capacity, many durability challenges confronting concrete can be overcome by using ECCs.

Concrete is the most widely used construction material in the world. With exponential growth of human population and industrialization, concrete is now used not only for buildings but also for highways, bridges, underground mass transit facilities, wastewater treatment systems, and marine structures. Modern structures are being exposed to more severe environmental and mechanical conditions than before, and the lack of durability is one of the most serious issues facing reinforced concrete infrastructures worldwide. One of the most severe concerns is the drastic decrease of durability associated with concrete cracking. Cracking is usually a result of various physical, chemical, and mechanical interactions between concrete and its environment, and it may occur at stages throughout the life of a structure. The formation of cracks, coupled with a lack of crack width control in brittle concrete, is primarily responsible for two damaging phenomena: reducing the strength and stiffness of the concrete structure, and accelerating the ingress of aggressive ions, leading to other types of concrete deterioration such as corrosion, alkali-silica reaction, and sulfate attack, and resulting in further cracking and disintegration. As a result, these cracks can dramatically reduce the long-term durability performance of concrete.

If durability and eventually sustainability are important goals, current construction practice and codes of recommended practice must undergo a paradigm shift to achieve concrete structures that have tight cracks or are "crack-free" in preference to high strength. While it is unrealistic to imagine the complete suppression of cracking in concrete, the ability to use robust self-healing functionality as an autogenous mechanism in areas with tight cracks may lead to the realization of such virtually crack-free concrete. 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 (*1*). Self-healing of cracks should be taken into account when specifying tolerable crack widths. Evardsen (*2*), and Reinhardt and Jooss (*3*) proposed that cracks of less than 100 μm can easily be closed by self-healing process.

During the past decade, concrete technology has been undergoing rapid development. The effort to modify the brittle behavior of plain cement materials, such as cement pastes, mortars, and concretes has resulted in modern concepts of high-performance fiber-reinforced cementitious composites (HPFRCC), which are characterized by tensile strain-hardening after first cracking and multiple microcracks with tight crack width. HPFRCCs with tensile strain in excess of 3% can now be routinely produced with ordinary cement, fly ash, and aggregates. This advance is due to the development in fiber, matrix, and composite processing technology, as well as better understanding of the fundamental micromechanics governing composite behavior, particularly the interaction among fiber, matrix, and interface properties (*4–7*). Engineered cementitious composites (ECCs) are a special type of ultra HPFRCC, containing a small amount of short random fibers, micromechanically designed at the University of Michigan to achieve high damage tolerance under severe loading and high durability under normal service conditions (*8–10*). It is a relatively new material, with a number of benefits, including high ductility under uniaxial tensile loading, and improved durability due to intrinsically tight crack width.

Through the use of ECCs, which display significantly higher ductility and more reliable crack width control than reinforced concrete does, durability problems resulting from cracking can be solved. Over the past 5 years, a significant amount of work has been carried out in investigating the relationship and interaction between ECC cracking and durability. After a brief introduction to ECC, some of these recent durability research results in ECC cracking and durability are synthesized in the following sections. The durability subjects

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include (*a*) ECC cracking and transport properties (permeability, absorption and diffusion); (*b*) corrosion and spall resistance; (*c*) frost resistance with and without deicing salts; (*d*) performance under a hot and humid environment; (*e*) performance under a high-alkaline environment; and (*f*) self-healing of microcracks in ECC.

ENGINEERED CEMENTITIOUS COMPOSITES

The most distinctive characteristic separating ECC from conventional concrete and fiber-reinforced concrete (FRC) is an ultimate tensile strain capacity between 3% to 5%, depending on the specific ECC mixture. This strain capacity is realized through the formation of many closely spaced microcracks, allowing for a strain capacity over 300 times that of normal concrete. These cracks, which carry increasing load after formation, allow the material to exhibit strain hardening, similar to many ductile metals.

While the components of ECC may be similar to FRC, the distinctive ECC characteristic of strain hardening through microcracking is achieved through micromechanical tailoring of the components (i.e., cement, sand, and fibers) (*8–11*), along with control of the interfacial properties between components. Fracture properties of the cementitious matrix are carefully controlled through mix proportions. Fiber properties, such as strength, modulus of elasticity, and aspect ratio have been customized for use in ECC. The interfacial properties between fiber and matrix have also been optimized in cooperation with the manufacturer for use in this material. Typical mix proportions of ECC using a polyvinyl-alcohol (PVA) fiber are given as follows:

- Cement, 1.00;
- Water, 0.58;
- Sand, 0.80;
- Fly ash, 1.20;
- HRWR, 0.013;
- Fiber (%), 2.00

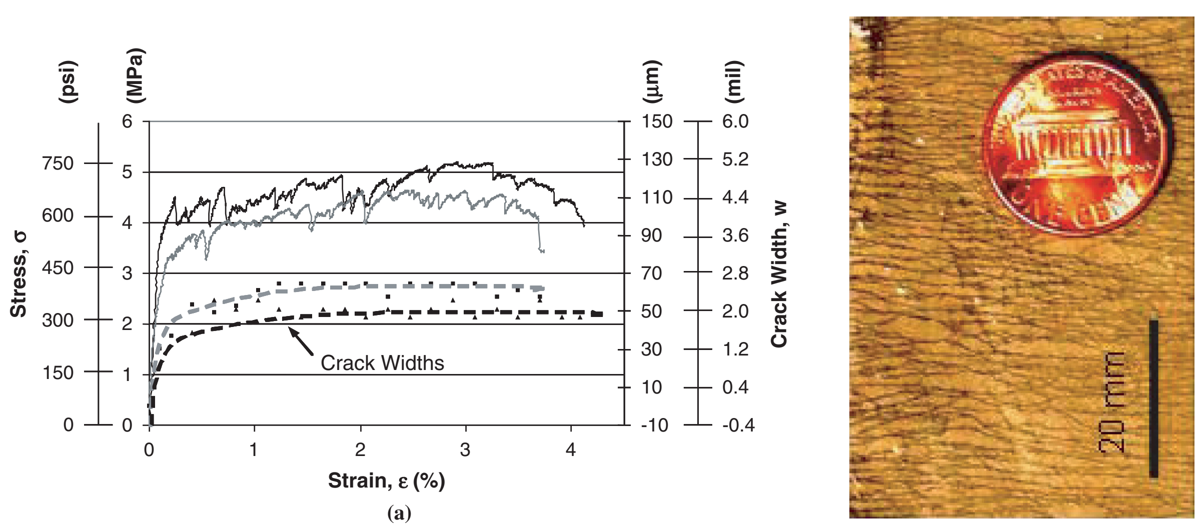
HRWR = high-range water reducer; all ingredient proportions by weight except for fiber.

While most HPFRCCs rely on a high fiber volume to achieve high performance, ECC uses relatively low amounts, typically 2% by volume, of short, discontinuous fiber. This low fiber volume, along with the common components, allows flexibility in construction execution. To date, ECC materials have been engineered for self-consolidation casting (*12*), extrusion (*13*), shotcreting (*14*), and conventional mixing in a gravity mixer or conventional mixing truck (*15*).

Figure 1 shows a typical uniaxial tensile stress–strain curve of ECC material containing 2% PVA fiber (*16*). The characteristic strain-hardening behavior after first cracking is accompanied by multiple microcracking. The crack width development during inelastic straining is also shown in Figure 1. Even at ultimate load, the crack width remains smaller than 80 μm. This tight crack width is self-controlled, and whether the composite is used in combination with conventional reinforcement or not, it is a material characteristic independent of rebar reinforcement ratio. Under severe bending load, an ECC beam deforms similarly to a ductile metal plate through plastic deformation with the development of multiple cracks with small crack spacing and tight crack widths (<0.1 mm) (Figure 2). Microcracks developed from the first cracking point and spread out in the midspan of the flexural beam. Bending failure in ECC occurred when the fiber bridging strength at one of the microcracks was reached, resulting in localized deformation at this section once the modulus of rupture is approached. In compression, ECC materials exhibit compressive strengths similar to those of high-strength concrete (e.g., greater than 60 MPa) (*15*).

TRANSPORT PROPERTIES OF CRACKED AND SOUND ENGINEERED CEMENTITIOUS COMPOSITE

Depending on the driving force, the transportation of liquids, gases, and ions through hardened concrete can occur mainly through three mechanisms: permeation, absorption, or diffusion. Each of these mechanisms, however, has the potential to be influenced by cracking because cracking provides a less resistant and thus preferential pathway for fluid to flow. For ECC with multiple cracks of self-limiting width, a better understanding of fluid and ion transport in cracked and



(a)

(b)

FIGURE 1 ECC materials: (*a*) typical tensile stress–strain curve and (*b*) crack width development.

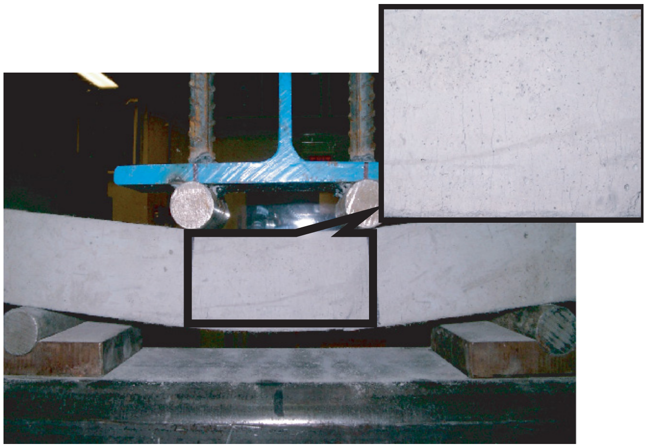


FIGURE 2 Response of ECC under flexural loading (inset shows close-up view of microcracks).

sound ECC is crucial to the development of criteria for predicting its service life.

Water Permeability

Typically, cracks increases the permeability, allowing water, oxygen, and chloride ions to easily penetrate and reach the reinforcing steel and accelerate the initiation of steel corrosion in concrete. The water permeability of concrete was shown to decrease by seven orders of magnitude as the crack width decreases from 550 µm to below 100 µm (*17*). ECC exhibits many tight cracks compared with fewer wide cracks with conventional FRCs. Tight cracks in ECC have been shown to drastically reduce the water permeability to a level similar to that of sound concrete (*18, 19*).

Chloride Diffusion

The penetration of chloride ions into concrete is considered to be the major cause of corrosion. Increased crack width can be related to higher chloride penetration rate in cement composites. Beams loaded to 20 kN indicated chloride penetration to a depth through the total 100-mm depth of the reinforced mortar specimen, while it was restricted to 30 mm in the reinforced ECC specimen (*20*). To determine the corrosion rate of ECC and mortar, macrocell and microcell corrosion rates were also 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/mortar beams, respectively (*20*).

Şahmaran et al. also conducted immersion and ponding tests on ECC and reinforced mortar specimens (*21*). From results of immersion tests, chloride penetration depth was found to be reduced in uncracked ECC specimens compared to that uncracked mortar. From ponding tests of precracked specimens under high imposed bending deformation, the effective chloride diffusion coefficient was found to be linearly proportional to the number of cracks in ECC, 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 with that of crack number. This study concludes that controlling crack width is significantly more important than controlling crack number for structural durability associated with chloride ion penetration.

Absorption

Transport of liquids in porous solids due to surface tension acting in capillaries is called water absorption. Absorption is related not only to the pore structure, crack density, and crack size, but also to the moisture state of the concrete. 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 dry or partially saturated condition, permeability and diffusion may not be the dominant transport processes in concrete materials, but capillary suction or absorption is (*22*).

The relationship between tight crack width and capillary suction indicated that the water absorption increase is fairly high as the number of cracks on the surface of the ECC specimens increases (*23*). Therefore, the sorptivity test shows that microcracked ECC specimens would be more vulnerable to attack than are virgin specimens. As the number of cracks along the specimen grows, the sorptivity of ECC increased exponentially. Even so, the sorptivity values of preloaded ECC specimens up to a strain representing 1.5% on the exposed tensile face is not particularly high when compared with that of normal concrete. Moreover, in the same study, the use of water repellent admixture in the production of ECC easily inhibited the sorptivity even for the mechanically preloaded ECC (Figure 3) (*23*).

CORROSION AND SPALL RESISTANCE

The spall resistance of ECC was investigated by pushing a tapered steel rod into a hole cast through an ECC slab, to simulate the expansive force generated by a corroding rebar (*20, 24*). Test results showed that ECC accommodated the simulated expansion by "plastic yielding" through the formation of radial microcracks, while concrete fractured in a brittle manner under the expansive force. Figure 4 shows the signature damage and failure modes in ECC and concrete slabs after testing. Even with identical material compressive strengths, a significantly higher load (30 kN) was sustained by the ECC slab as compared to the concrete slab (~7 kN). With a tensile ductility on the order of 3% to 5%, therefore, the results of these studies showed that ECC has significant antispalling ability compared with that of conventional concrete.

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 (*25*). By preserving low transport properties after cracking, and eliminating spalling through high ductility, ECC material reduces chloride intrusion to effectively protect reinforcement from corrosion (*20, 21, 26*). In accelerated corrosion tests, ECC did not exhibit the severe distress observed on conventional mortar specimens (Figure 5). Corrosion-related distress in mortar beams resulted in the reduction of the flexural strength, and such reduction was not observed in the ECC beams (*26*).

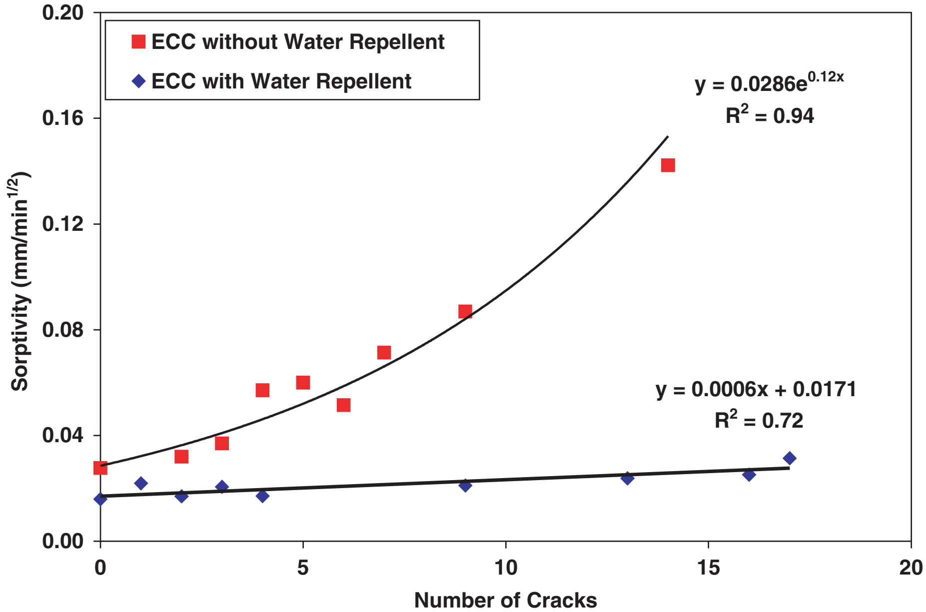


FIGURE 3 Sorptivity versus number of cracks for ECC mixtures.

FROST RESISTANCE WITH AND WITHOUT DEICING SALTS

Freeze–thaw testing in accordance with ASTM C666, Procedure A, was performed with companion series of ECC and normal concrete specimens (*27*). Non-air-entrained specimens were used as control since no air entrainment was added to the ECC mixtures. In addition to typical dynamic modulus testing of prism specimens outlined in ASTM C666, Procedure A, a series of ECC tensile specimens was subjected to freeze–thaw cycles. Results of the tensile tests were compared with those with reference samples of identical age cured in water at 22°C. These tests allowed the effect of freeze–thaw exposure on the composite strain capacity to be evaluated. Testing of ECC and concrete prisms was conducted concurrently over 14 weeks. After 5 weeks (110 cycles), the concrete specimens had severely deteriorated, requiring removal from the freeze–thaw machine. However, all ECC specimens survived the test duration of 300 cycles with no degradation of dynamic modulus or surface. This performance results in a durability factor of 10 for concrete compared with 100 for ECC, as computed according to ASTM C666, Procedure A.

(a)

(b)

FIGURE 4 Failure modes of (*a*) concrete and (*b*) ECC.

(a) (b)

FIGURE 5 ECC and mortar specimens after accelerated corrosion test: (*a*) ECC cylindrical specimen after 350 h of accelerated corrosion and (*b*) mortar cylindrical specimen after 95 h of accelerated corrosion.

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%, well above the capacity needed for most applications. The observed superior frost durability of ECC over conventional concrete is due to the increase of larger pore volume, and intrinsically high tensile ductility and strength due to the presence of micro-PVA fibers (*28*).

The limited field performance of non-air-entrained ECC also indicates that it has a superior freezing and thawing resistance (*27, 29, 30*). As one of the first field applications of ECC in the United States, a concrete bridge deck patch was completed in cooperation with the Michigan Department of Transportation (MDOT) in 2002. A complete summary of this work has been outlined by Li and Lepech (*30*). During this work, one section of a deteriorated bridge deck was repaired with ECC while the remaining portion was repaired with a commercial concrete patching material commonly used by MDOT. This repair scenario allowed for a unique ECC–concrete comparison subjected to identical environmental and traffic loads. The concrete repair material used was a prepackaged, commercially available repair concrete. The repaired bridge deck experienced more than five complete Michigan winter cycles of freezing and thawing, in addition to live loads before reconstruction was carried out. During these years, the ECC patch repair survived the combined environmental and live loading environment with minor microcracking limited to less than 50 μm. In contrast, the concrete repair portion developed localized cracks in excess of 3.5 mm wide and required re-repair in 2005 (Figure 6).

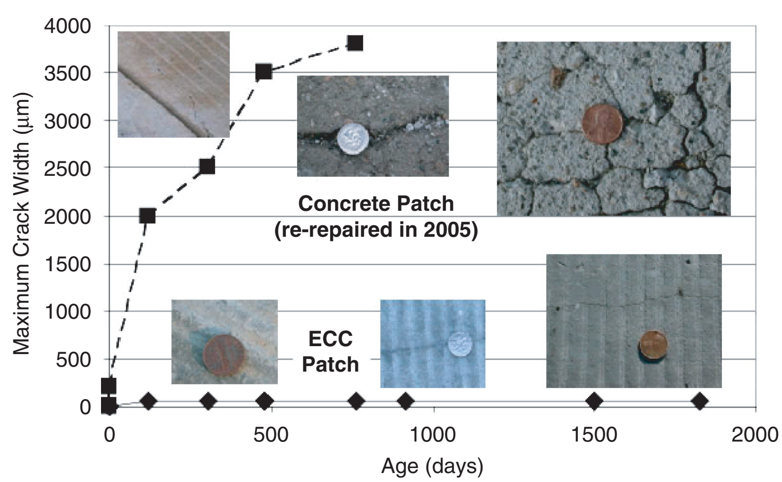


FIGURE 6 Development of crack width over time in ECC and concrete patch.

Due to the high volume fly ash content, it is also important to test the performance of ECC exposed to freezing and thawing cycles in the presence of deicing salt. Salt scaling resistance of non-air-entrained sound (uncracked) and mechanically preloaded (cracked) ECC specimens was evaluated by Şahmaran and Li in accordance with ASTM C672 (*31*). Non-air-entrained mortar specimens with and without fly ash were also tested as control specimens. After 50 freeze–thaw cycles in the presence of deicing 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 C672. This level of durability holds true even for ECC specimens preloaded to high deformation levels and exhibiting extensive microcracking. In comparison, the control 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 deicing salt.

In a separate test, both preloaded (cracked) and sound ECC coupon specimens were exposed to freeze–thaw cycles in the presence of deicing salts for 25 and 50 cycles, to evaluate the residual tensile strength and the ductility of reloaded ECC specimens (*31*). The reloaded specimens showed negligible loss of ductility, and they retained the multiple microcracking behavior and tensile strain capacity of more than 3%. It was also discovered that microcracks due to mechanical loading healed 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 microcracked, remains durable despite exposure to freezing freeze–thaw cycles in the presence of deicing salts.

DURABILITY UNDER EXTREMELY HOT AND ALKALINE ENVIRONMENT

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. Hot water immersion was performed on individual fibers, single fibers embedded in ECC matrix, and composite ECC material specimens (*32*). After 26 weeks in hot water immersion at 60°C, 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 more than 250 times that of normal concrete.

Another environment that could affect the microstructure and composite properties of ECC is a high-alkaline environment. Since ECC has high contents of high-volume fly ash, alkali-silica reaction of ECC is expected to be satisfactory and results of ASTM C1260 test do show no damaging expansion (*33*). Even though no deleterious expansion has been observed due to alkali silica reaction, alkalis penetrating through microcracks or even the uncracked matrix may affect the mechanical performance (*33*). ECC coupon specimens were first preloaded under uniaxial tension to strain levels, and then exposed to an alkaline environment up to 3 months at 38°C and reloaded up to failure. The reloaded specimens showed slight loss of ductility and tensile strength, but they retained the multiple microcracking behavior and tensile strain capacity of more than 2% (about more than 200 times that of normal concrete and normal FRC).

SELF-HEALING OF MICROCRACKS IN ENGINEERED CEMENTITIOUS COMPOSITE

The relatively low permeation and diffusion, as well as high residual mechanical stiffness and strength of cracked ECC specimens, is due not only to the tight crack width but also to the presence of self-healing of the microcracks. The self-healing of cracks becomes prominent when crack width is small. In a recent study conducted by Yang et al., it was found that the crack widths within cement-based materials must be controlled to below 150 μm, preferably below 50 μm, to engage noticeable robust self-healing behavior (*34*). The chemical makeup and physical properties of ECC—self-controlled tight crack width, and high tensile ductility, in particular—make self-healing prevail in a variety of environmental conditions. Those conditions include wetting and drying cycles, conditioning temperature, water permeation, chloride submersion, and freezing and thawing exposure in the presence of deicing salts, even when the composite is deliberately damaged by tensioning to a strain of several percent (*19, 21, 31, 33–36*). Self-healing related to mechanical and transport properties recovery of predamaged (by preloading in tension to create multiple microcracks) composite takes place automatically at cracked locations, without external intervention. This observation is also supported by an environmental scanning electron microscope observation of ECC across a healed crack (Figure 7). The establishment of self-healing in ECC looks to improve the long-term ductility and durability of ECC after damage, and to establish a much more durable civil engineering material subjected to various environmental conditions.

CONCLUSION

ECCs have benefits including high tensile ductility and very tight crack width (generally less than 80 μm) under applied loads. In regard to transport properties, these reduced, finely distributed microcracks can provide good resistance to transport of water or aggressive substances, or both, from the environment even under extensive straining. 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 with or lower than that in normal sound concrete without any cracks. Apart from the slight reductions in ultimate tensile strain and strength capacities, 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 deicing salts, continuous sodium hydroxide at 38°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 before exposure. Moreover, self-healing in regard to mechanical and transport properties recovery of predamaged (by precracking) ECC is revealed in a variety of environmental exposure, include wetting and drying cycles, conditioning temperature, water permeation, and chloride submersion. As a result of the observations reported in this paper, ECC can be accepted as a virtually crack-free concrete, and it is expected to aid in extending the service life of concrete structures exposed to severe environments.

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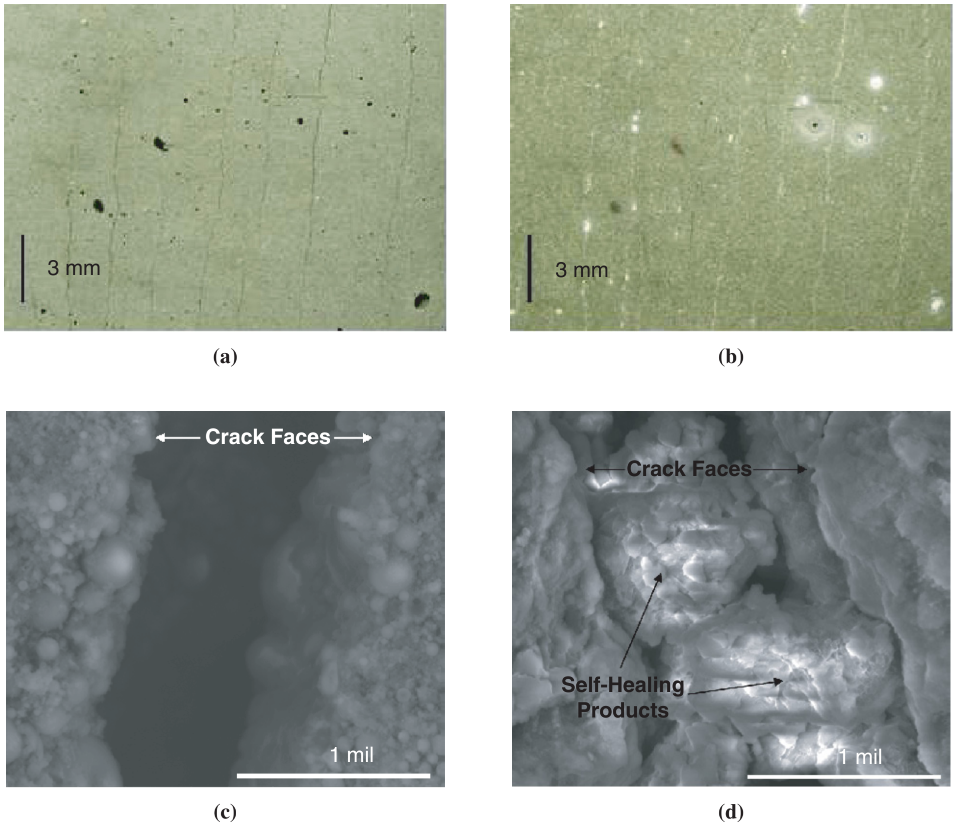

FIGURE 7 Images indicating self-healing product formation in ECC: (*a*) appearance of ECC permeability specimens before permeability testing, (*b*) appearance of ECC permeability specimens after permeability testing, (*c*) ECC crack faces before permeability testing, and (*d*) autogenous self-healing crystalline formations in ECC crack after permeability testing (*30*).

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