Engineered Cementitious Composites

Victor C. Li
The University of Michigan, Ann Arbor, USA

Abstract

This paper overviews Engineered Cementitious Composites (ECC) as an emerging construction material. Emphasis is placed on the accumulated knowledge on durability, safety, and sustainability of reinforced ECC (R/ECC) structures, recognizing that the concrete of the future must meet these characteristics. In light of recent and future full-scale field applications of ECC, the limited studies on long-term performance of ECC are also summarized.

Keywords: composite, fiber, ductility, durability, sustainability, safety, design, infrastructure.

Victor Li
University of Michigan
Rm 2326, GGB Building
Department of Civil and Environmental Engineering
Ann Arbor, MI 48109-2125
USA

Email: vcli@umich.edu
Tel: 734-764-3364

1.0 Introduction: The Demands on Future Concrete

Concrete is ubiquitous. Annually, more than one ton per capita of concrete is cast for infrastructure construction worldwide. By many measures, concrete is an excellent construction material. However, the mechanical properties and functional characteristics of concrete will have to be improved, in some ways drastically, and these improvements are already emerging in limited forms. These advancements are needed to address deficiencies in concrete infrastructure, currently facing three major challenges:

Brittle failure under severe loading: Infrastructures are subjected to severe natural loadings such as earthquakes, which see no national boundaries. In some cases, serious damages have occurred to infrastructures including buildings, roadways and bridges. While not all economic losses are due to concrete structural damage, the estimated economic impact is big: $100 billion [1] for the 1995 Kobe earthquake in Japan and $20 billion [2] for the 1994 Northridge earthquake in the US. FEMA [2] estimates losses from a future earthquake in the US to approach $200 billion. Infrastructure failure can often be traced to brittle fracture of concrete, e.g. bond splitting, cover spalling, and core crushing resulting in subsequent collapse of bridge piers or columns in soft first stories in buildings. Severe loading is not limited to natural events only, but extends to deliberate acts of terrorism. The World Trade Center bombing in New York City in 1993, the Alfred P. Murrah Federal Building bombing in Oklahoma City in 1996, and the most recent terrorist attack on the World Trade Center in 2001, are examples of terrorist acts on building structures. Commonly observed failure modes such cracking, spalling, and fragmentation under impact or blast loading have been correlated with the inadequate tensile behavior of concrete [3].

Deterioration under normal service loading: Deteriorating infrastructure is a threat to the economic well-being of many countries. Most recently, the American Society of Civil Engineers issued a “Report Card” for American infrastructure [4]. The averaged grade was a D, with a total estimated investment need of $1.6 trillion over the next five years for repair and retrofit. The corresponding cost has been placed at $2 trillion dollars for Asia’s infrastructure. In Europe, Japan, Korea, Thailand and the US, the annual outlay for repair has or will soon exceed that for new construction. Although deterioration is not as dramatic as collapse of infrastructure, the magnitude of this problem in terms of dollar cost dwarfs those associated with failure due to severe loading. A major cause of lack of durability of reinforced concrete structure may be traced to cracking of concrete which may lead to steel reinforcement corrosion and other problems.

Lack of sustainability of R/C structures: The sustainability of R/C infrastructure has come into question in recent years. Globally, the huge flow of material driven by concrete production causes significant societal and environmental impacts. The production of one ton of cement, for example, requires 1.7 tons of raw materials and generates 1 ton of carbon dioxide (CO_2). Cement production accounts for 5% of all global anthropogenic CO_2 emissions [5] and significant levels of SO_2, NO_x, particulate matter and other airborne pollutants [6,7]. Developing countries undergoing rapid economic development require infrastructure expansion; however the intense negative interaction between the built and natural environment is increasingly a global concern. The lack of infrastructure durability as highlighted above only worsens the situation. Repeated repairs of R/C infrastructure are decidedly unsustainable.

The infrastructure challenges suggest that future concrete must have the following characteristics:

- Highly ductile – with ability to “yield” like a metal when overloaded, even under severe impact load or large imposed deformation, thus providing infrastructure safety

- Highly durable – with ability to withstand mechanical and environmental loads under normal service conditions, thus providing service life significantly higher than current infrastructure,
- Highly sustainable – minimize natural resource use and pollution emission, during the full life cycle (material production, construction and use, end of life demolition) of an infrastructure, thus ensuring harmonious interaction between the built and the natural environment.

2.0 Engineered Cementitious Composite (ECC)

ECC is a fiber reinforced cement based composite material [8, 9, 10] systematically engineered to achieve high ductility under tensile and shear loading. By employing micromechanics-based material design [8-11], maximum ductility in excess of 3% under uniaxial tensile loading can be attained with only 2% fiber content by volume. This moderate amount of short discontinuous fibers allows flexibility in construction execution, including self-consolidation casting [12] and shot-creting [13]. Structural products have been manufactured by extrusion of ECC [14]. Recent research indicates that ECC holds promise in enhancing the safety, durability, and sustainability of infrastructure.

Figure 1 shows a typical uniaxial tensile stress-strain curve of a 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. Even at ultimate load (5% strain), the crack width remains at about 60 μm, and even lower at strain below 1%. 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. In contrast, normal concrete and fiber reinforced concrete rely on steel reinforcement for crack width control. The tight crack width of ECC is important to the serviceability of ECC structures as the tensile ductility is to the structural safety at ultimate limit state.

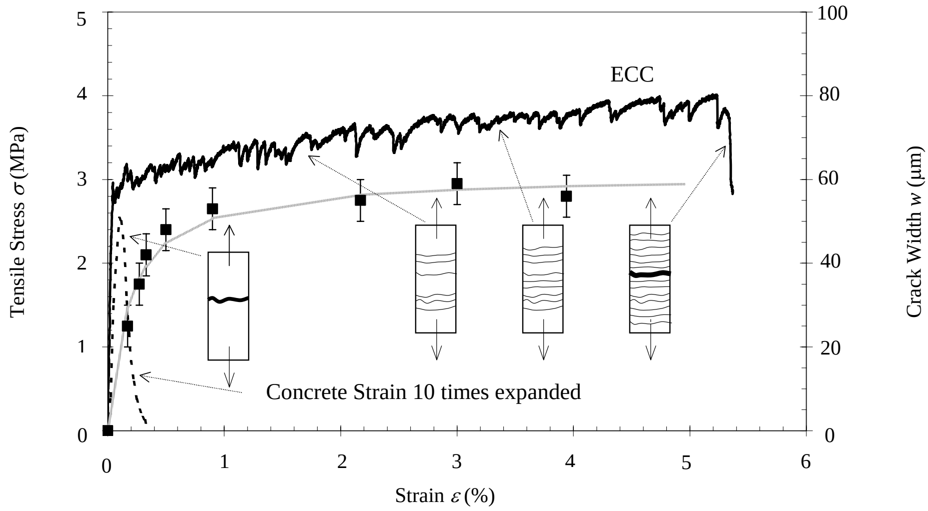


Figure 1: Typical tensile stress-strain curve and crack width development of ECC.

2.1 Safety

A major driver of next generation infrastructure resistant to seismic loading is performance-based earthquake engineering. Its implementation (e.g. PEER [15]) eases the adoption of new high performance material such as ECC. In addition to collapse resistance, Billington [16] in reviewing this subject suggested that the use of ECC could lead to highly damage tolerant structures with limited residual crack widths such that post-earthquake repair costs could be minimized.

A large amount of experimental data on damage tolerant behavior of R/ECC structures is available. Structural elements tested under fully reversed cyclic loading include beam [17, 18], column [19], beam-column connections [20], infill walls [18, 21], frames [22], bridge pier [23], coupling beams [24] and damping elements [25], amongst others. These studies, which used ECC or adapted versions of ECC, demonstrate superior seismic resistant response as well as minimum post-earthquake repair need. Specifically, R/ECC exhibits ductile shear response, high-energy absorption behavior, stable hysteretic loops even at large drifts, and structural integrity. These characteristics are exhibited in Fig. 2, which clearly demonstrates the high damage tolerance of the cyclically loaded flexural element [26]. The test results also illustrate the potential reduction or elimination of steel stirrups by taking advantage of the shear ductility of ECC. The favorable characteristics of R/ECC are a direct result of the tensile ductility of ECC, which promotes compatible deformation between ECC and the reinforcement even up to steel yielding [27]. The tensile ductility in ECC also translates into shear ductility since the material undergoes diagonal tensile multiple cracking when subjected to shear [28].

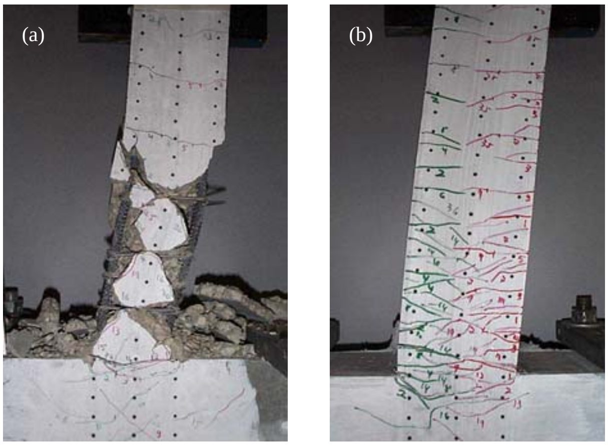


Figure 2: Damage behavior of (a) R/C and (b) R/ECC without stirrups, shown at 10% drift after reverse cyclic loading.

Fragmentation resistance of ECC under impact load has been confirmed experimentally. For example, Maalej et al [29] demonstrated experimentally that ECC panels subjected to high velocity projectiles showed increased shatter resistance with damage reduction due to scabbing and spalling, as well as high energy absorption associated with distributed microcracking.

2.2 Durability

The cause of infrastructure deterioration, under combined environmental and mechanical loads, is complex. In bridges and roadways, deterioration often begins with cracking due to thermal movements or restrained drying or autogenous shrinkage cracking [30, 31]. These cracks are exacerbated by fatigue loading due to moving traffic [32, 33]. Compromise of the transport properties of cracked cover concrete allows the penetration of chlorides and other aggressive agents through the cover to the depth of the steel reinforcement. Subsequent corrosion in the rebar may create expansive forces that eventually lead to spalling of the brittle concrete cover.

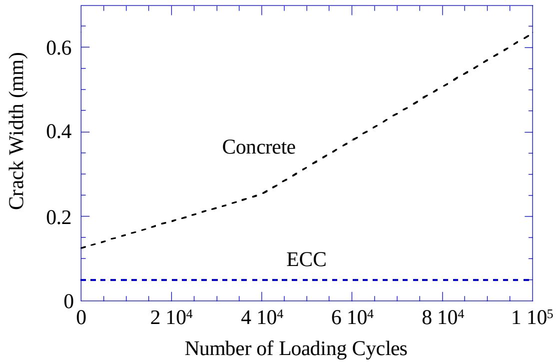


Figure 3: Crack width evolution of link slab specimens during fatigue test.

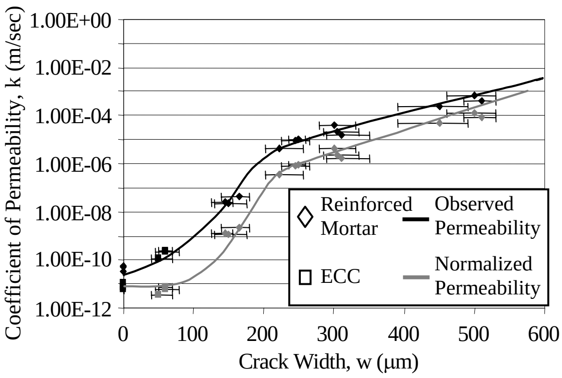


Figure 4: Coefficient of permeability versus crack width for ECC and reinforced mortar series pre-strained to 1.5% in uniaxial tension. Grey symbols indicate data normalized by number of cracks.

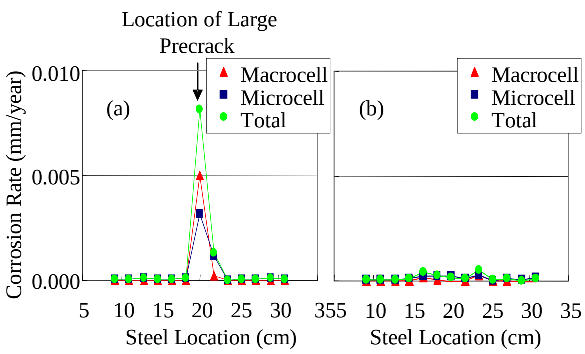


Figure 5: Microcell and macrocell corrosion rate measured for (a) R/C, and (b) R/ECC along the reinforcement bar length (adapted from [39]).

The infrastructure deterioration process outlined above suggests two specific deficiencies of concrete. The low tensile strain capacity of concrete (0.01%) makes it readily susceptible to cracking, with attendant crack width that must be controlled by steel reinforcement. Still, crack width of mm dimension is common [31]. The need for steel reinforcement to control crack width in concrete and the tendency to corrode due to penetration of aggressive agents through cracks represent a contradiction underlying the current infrastructure deterioration dilemma. The other deficiency of concrete is its tendency to fracture in a brittle manner, which is responsible for concrete cover spalling.

Recent experiments provide supporting evidence that the characteristics of ECC can intervene in the deterioration process described above. Under restrained drying shrinkage, ECC shows cracks of width limited to about 30 μm [34]. Particularly noteworthy is that this crack width is independent of the dimensions of the structure [35], which is not the case in normal concrete. Furthermore, fatigue loading does not seem to increase the crack width. Figure 3 shows the crack width development of a concrete and an ECC link-slab [36] under fatigue loading. After 100,000 cycles, the crack width in the concrete link-slab increases to over 0.6 mm, while the crack width in the ECC link-slab remains close to 50 μm.

The transport properties of the concrete cover determine the time needed for the penetration of aggressive agents to reach the steel reinforcements. Transport mechanisms include permeation, diffusion and capillary suction. It is known that the permeability of cracked concrete scales with the third power of crack width [e.g.37], and that a crack with width below 100 μm (50 μm for gas permeability) tends to behave like sound concrete [38]. Permeability tests conducted on specimens pre-strained to 1.5% in tension (with crack width at 60 μm) confirm that ECC loaded to the strain-hardening stage during service would behave similar to sound concrete (Fig. 4, [39]). Preloaded R/ECC and R/C beams exposed to chloride accelerated environment [40] revealed diffusion governed chloride penetration depth of 0-20 mm and 80-100 mm in the R/ECC and the R/C beams respectively. 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 (Fig. 5). Capillary transport may be a concern for ECC since the crack width is so small. A recent study [41], however, showed that capillary suction in ECC could be controlled by a hydrophobic agent.

Spall resistance of ECC was investigated [39,42] by pushing a tapered steel rod into a hole in an ECC slab in order to simulate the expansive force generated by a corroding rebar. The test results showed that ECC accommodated the expansion by a "plastic yielding" process involving radial microcracks, while concrete fractured under the expansive force. Figure 6 shows the signature damage and failure modes in ECC and concrete slabs after testing. Significantly higher force (30 kN) was sustained by the ECC slab compared to the load capacity of the concrete slab (~7 kN). From the above discussion it is clear that the major stages of infrastructure deterioration, including restrained shrinkage cracking, fatigue crack width widening, compromise in transport properties in cover concrete, rapid penetration of aggressive agents through the cover reaching the reinforcement, and steel corrosion and cover spalling, can each be alleviated or even eliminated when concrete is replaced by ECC. ECC offers tensile ductility and tight crack width control which should result in higher infrastructure durability.

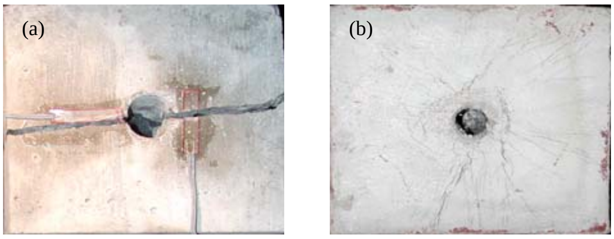


Figure 6: Failure modes of (a) concrete, and (b) ECC

2.3 Sustainability

Infrastructure sustainability accounts for both the greenness of the construction material as well as the economic, social and environmental costs associated with the various stages of the life cycle of the infrastructure. Current studies of green construction materials seldom consider the life-cycle costs. When life-cycle costs are considered, typically only the economic dimension and only the agency cost are accounted for, leaving out important user cost and externality considerations.

The development of green ECC [43, 44] for sustainable infrastructure requires a more complete life cycle framework integrating the three dimensions of social, environmental and economic considerations. Such a model [45, 46] is being constructed at the University of Michigan, based on an interdisciplinary approach drawing from civil and materials engineering, environmental economics, industrial ecology, public health, and geological sciences. A preliminary version of this integrated life cycle assessment and cost model was applied to two alternative R/C bridge deck designs: one with conventional mechanical expansion joints, and the other with ECC link slabs. Life cycle energy, greenhouse gas emissions, agency costs for construction and rehabilitation, and social costs including construction-related user delay costs and environmental pollutant damage costs are quantified for each system over a 60-year bridge service life. Results show that the ECC link slab system has a 37% economic cost advantage over the conventional system, consumes 40% less total primary energy, and produces 39% less carbon dioxide. Figure 7 shows the model outputs on primary energy consumption and global warming potential for the two bridge deck designs, for different stages of their life cycles. These results show the dominance of the use phase on the total life cycle cost and burden. In addition, while the cost of ECC is assumed to be about three times that of normal concrete on a per unit weight basis, the life cycle material cost is lower due to the smaller amount of material needed when repair frequency decreases.

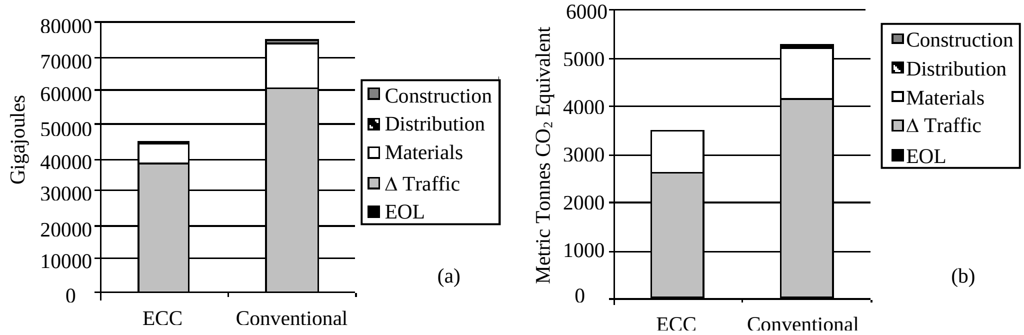


Figure 7: Total (a) primary energy consumption, and b) global warming potential, by life cycle stages for two designs of bridge decks [45].

The above findings which quantitatively establish the advantage of deploying ECC infrastructure rest on a yet to be substantiated assumption – that the ECC link-slab design has a service life twice as long as the conventional one. However, given the known information on the durability of R/ECC as summarized in the previous section of this paper and the available long term performance data described in the following, this assumption on service life appears not unreasonable. Further research along these lines is needed.

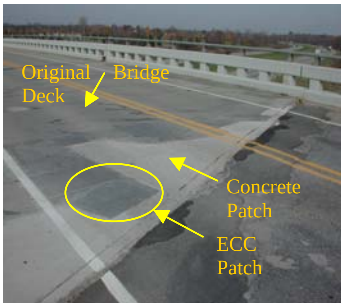
3.0 Applications and Long Term Performance of ECC

Figure 8: The Mihara bridge (Hokkaido, Japan) uses a steel/ECC composite deck (Courtesy, T. Kanda).

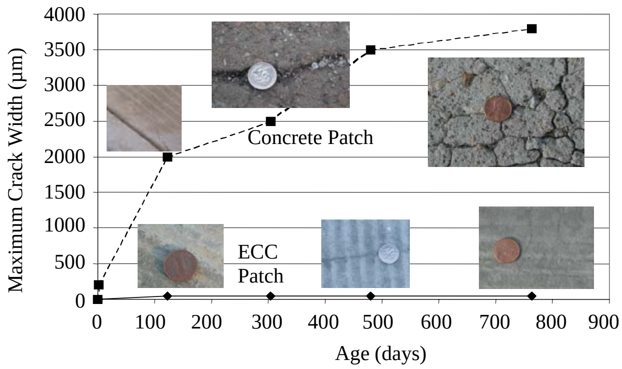
The full-scale use of ECC is expanding. A summary of field applications can be found in [47]. Field applications include composite steel/ECC deck for a cable-stayed bridge in Hokkaido, Japan, repair of the Mitaka Dam in the Hiroshima-Prefecture in 2003 [48], and an impending bridge deck retrofit with ECC link-slabs [36] in Michigan, in the US in 2005.

Figure 8 shows the newly constructed Mihara Bridge [49]. This cable-stayed bridge, expected to open to traffic in April, 2005, has a thin composite ECC/steel deck. The tensile ductility and tight crack width control of ECC are features that contribute to a 40% reduction in weight and an expected service life of 100 years. A significant reduction in cost was also reported.

The long-term performance of ECC has not been fully examined under field conditions. However, at least two studies support the contention that ECC performs well under actual field conditions. One study [50] involves the use of ECC for repair of a concrete gravity earth-retaining wall (18m in width and 5m in height) that has been damaged by alkali-silica reaction (ASR) cracking. The decision to use ECC for the 50-70 mm thick repair was based on the need to prevent reflective cracking from the substrate concrete to the repair layer, anticipated had normal concrete been used in this repair. Since repair in April, 2003, this wall has been continuously monitored. Ten months after the repair, the microcrack width in the ECC repair layer remained below 50 μm, while the maximum crack width in the premix cement mortar used as a control was 0.2mm.



(a)



(b)

Figure 9: (a) Patch repair on a bridge deck. (b) Crack width development in concrete patch and ECC patch over time.

Another long-term performance check is afforded by a small ECC patch repair (Fig. 9a, [51]) placed on the deck of the Curtis Road bridge over M-14 in Michigan in Oct., 2002. This patch was placed one day after the surrounding repair concrete was placed. As of this writing, the ECC patch and surrounding concrete have experienced almost three full winter freeze-thaw cycles. This bridge is traveled by heavily loaded 11-axle trucks. Figure 9b shows the monitored maximum crack width as a function of age. It reveals that the crack width in the ECC patch remains almost at a constantly low level, around 50 μm, while the maximum crack width in the surrounding concrete is significantly higher at the same age. The last data point at 780 days after repair indicates a maximum crack width of 3.8 mm in the concrete.

4.0 Conclusions

It is tempting to ask what type of concrete is needed for next generation infrastructure that are safe, durable and sustainable. Will structures be damage tolerant to even severe earthquakes or blast loading? Is infrastructure service life of more than 150 years attainable, with minimum maintainence? Will infrastructure of tomorrow be sustainable and built in harmony with the natural environment? It may be difficult to meet these challenges with current brittle concrete, no matter what the compressive strength is. Materials like ECC, with its ultra ductility and tight crack width control, however, show characteristics that may meet the demands of next generation infrastructure. A large amount of research remains to be conducted to fill the knowledge gaps of this relatively new construction material. However, ECC has already emerged from the laboratory into full-scale field applications. These applications will provide useful feedback into the re-design of ECC to meet specialized requirements for different applications. The micromechanics based materials engineering of ECC will aid substantially in further tailoring of this material, as is already happening in green ECC design for sustainability and in light-weight ECC [52] for applications where dead-load needs to be minimized. The recent applications also generate extremely important structural design knowledge. The activities of technical committees working towards code language, such as RILEM TC-HFC, will further aid in the realization of next generation infrastructure by adopting materials like ECC.

5.0 Acknowledgements

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