Bendable Concrete

Victor C. LI[1]

[1] University of Michigan, USA

Concrete is arguably the most important construction material. Since its early days, concrete has always been known as a material strong in compression, but tends to be brittle in tension. While the use of steel reinforcement has made concrete highly effective in large-scale constructed facilities, improvement in resiliency, durability, and sustainability of infrastructure can be further enhanced if concrete can be made ductile. Engineered Cementitious Composites (ECC, also known as Bendable Concrete) has been designed to overcome the brittleness of concrete. With a tensile ductility of 2-5% and a self-controlled tight crack width less than 100 µm, ECC enables high damage tolerance of structural members even under fully reversed shear loading and impact loading, and demonstrated unusual durability under a variety of environmental exposures. This article summaries some key properties of ECC and highlights selective recent applications in full-scale infrastructure.

Keywords: Concrete, innovation, ductile, ECC, infrastructure.

1. THE NEED FOR INNOVATION IN CONCRETE TECHNOLOGY

Since the introduction of concrete in the 1800's, it has become a ubiquitous material for almost all imaginable constructed facilities. These include transportation systems such as highway and airfield pavements, and shipping ports, building systems from single-family homes to the tallest buildings in the world, water systems from small irrigation channels to large dams, and energy systems from nuclear power containment buildings and cooling tower to ultra tall wind turbine towers. The impact of concrete as a construction material on our quality of life and on modern commerce has never been greater. Concrete is arguably the most important man-made engineering materials. It occupies the top position in terms of consumption amount amongst all engineering materials, at 12 billion tonnes or 2 tonnes per person on an annual basis.

Concrete technology has advanced in many significant ways over the last fifty years. The discovery of lowering porosity through the use of low water/cement ratio and the addition of microsilica led to the development of high strength concrete in the 1970-90's. This trend was aided by the availability of high range water reducing agents – chemical additives that maintain good workability despite reduced water content in the concrete mix. More recently, it is recognised that high strength alone is not adequate to maintaining the performance of concrete over its lifetime. Various efforts during 1990-2010 led to High Performance Concrete that embraced a broader definition of quality beyond strength, including durability by denser particle packing, and higher consistency in the quality of cast concrete by self-consolidation without depending on skilled manual vibration. In the last decade, there has been increasing focus on greening concrete through various processes, including the adoption of industrial waste streams into concrete mixes, and through recycling of used concrete as artificial aggregates. The reduction of energy requirement and carbon emission in the production of cement via improved cement kiln technology has also contributed to greening concrete. In summary, the advances in concrete with higher compressive strength, enhanced quality and durability, and reduced environmental impacts, have led to a variety of improvements in concrete infrastructure and the concrete industry.

Despite technological advances as highlighted above, today's concrete infrastructure continues to suffer from required repeated maintenance, and a lack of resiliency requires costly repair and even causes loss of human life after a major loading event. Cases in point are:

- Many countries including the US, Canada, Germany, Japan and Korea have annual expenditure outlays on infrastructure repair outstripping expenditures on new construction.
- Recent events such as 2005 US Katrina Hurricane, 2011 Japan Tohoku earthquake, and 2013 Philippine Typhoon Haiyan point to the susceptibility of infrastructure to natural forces.

In addition, there is increasing awareness that the built environment dominated by concrete infrastructure is often at odds with the natural environment in terms of life cycle energy and carbon footprints. Innovations are urgently needed to address these grand challenges that are adversely affecting the quality of life of urban communities.

The underpinning shortcoming of normal concrete is poor tensile load carrying capacity. Specifically, concrete has a fracture toughness less than 0.1% of that of steel. The propensity to cracking has significant implications on durability of concrete infrastructures under normal service conditions and on safety of infrastructures under severe loading. The brittle nature of concrete has never been successfully addressed in the past.

2. WHAT MAKES ECC UNIQUE?

Imagine a new concrete that has low embodied energy and has a negative carbon footprint, durable under a broad range of exposure environments and even repairs itself when damaged. Imagine that this concrete is also tolerant to damage thus minimising both infrastructure repair cost and recovery time after a major loading event. While such a concrete does not exist today, Engineered Cementitious Composites (ECC), also known as Bendable Concrete, has been designed to support civil infrastructure that are durable, resilient and sustainable.

ECC is a family of ductile concrete with a compressive strength ranging from 50 MPa to 200 MPa. The unique feature, however, is its tensile ductility, about 3-5% in tensile strain capacity as measured by direct tension in a loading machine and recorded by Linear Variable Differential Transofrmers (LVDTs) (Li, 2003). This is about 300 to 500 times the tensile strain capacity of normal concrete and fiber reinforced concrete (about 0.01%). Figure 1 shows a tensile stress-strain curve of ECC under direct unaxial tension test. ECC can be designed for a variety of functionalities, including self-consolidating (Kong *et al*, 2003), self-sensing (Lin *et al*, 2011), self-thermally adapting (Desai *et al*, 2014), and self-healing (Herbert and Li, 2013).

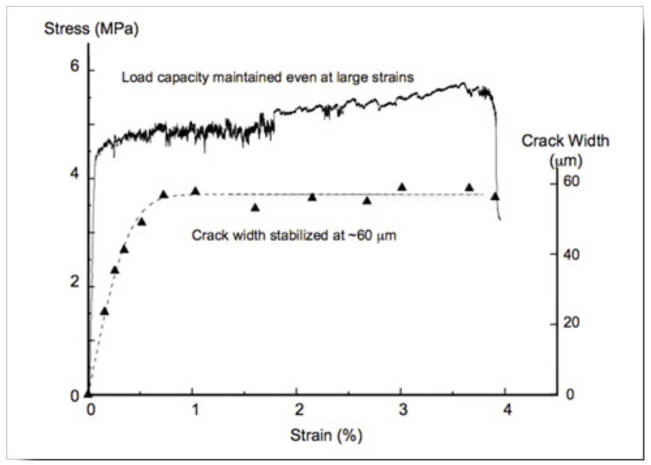


Figure 1 ECC has tensile ductility several hundred times that of normal concrete, and crack width self-controlled to less than 100 100 µm.

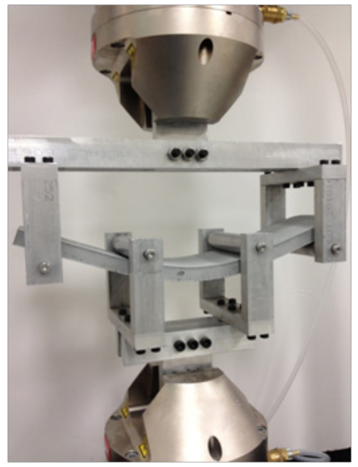


Figure 2 ECC flexes without brittle fracture

Most high strength concrete fails at a tensile strain of 0.01% to 0.2%, despite its high compressive strength. Textile concrete can have high tensile ductility. However, they are limited to certain types of precast applications. ECC has emerged as the most ductile concrete in full-scale cast-in-place applications. Figure 2 shows a slab of ECC under flexural load. The large deformability without succumbing to brittle fracture is evident.

The ductility of ECC also makes the material highly tolerant to impact loading. Substantially higher impact load resistance and energy absorption have been demonstrated (Maalej *et al*, 2005; Yang and Li, 2012). Figure 3 shows the contrast of response between a ECC slab and a common concrete reinforced with steel, when both are subjected to impact loading in a drop weight tower test.

Unlike high strength concrete, ECC has a design basis (Li, 1993) that does not aim at eliminating flaws, but rather controlling the size distribution of flaws so that controlled microcracking is allowed. These microcracks with tight crack width, typically less than 100 µm, contribute to the tensile ductility when overloaded, then subsequently undergo self-healing (Yang *et al*, 2011). The self-healing mechanism is an accelerated form of continued hydration and pozzolanic reaction. This damage management paradigm (as opposed to damage prevention) is akin to that of nature's nacre - the iridescent material on the inside of abalone shells. Similar to cement, nacre is made of brittle calcium carbonate platelets that slip over one another under load. The ductile deformation then undergoes self-healing to protect the soft-body of the abalone. In many ways, and particularly the deliberate introduction of a large amount of slip surfaces through microfibers with controlled bonding, ECC emulates the amazing features of nature's nacre.

1vcli@umich.edu Prof. Victor LI

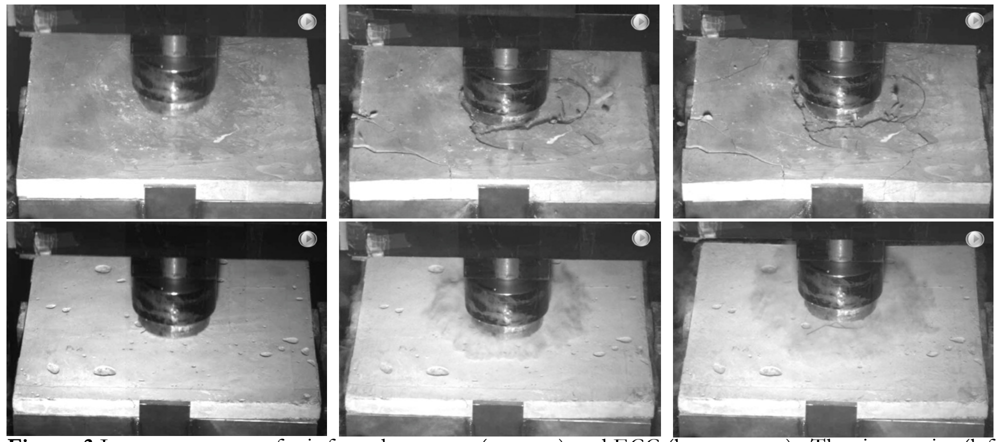
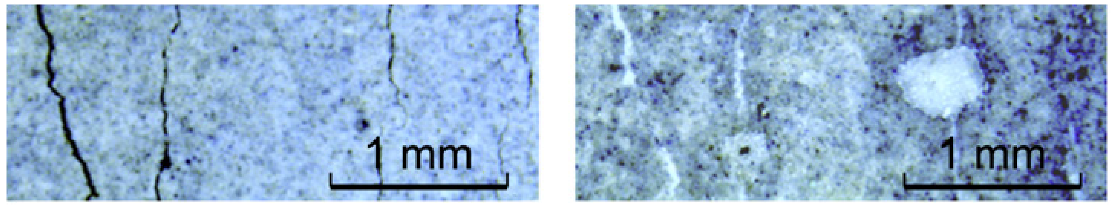


Figure 3 Impact response of reinforced concrete (top row) and ECC (bottom row). The time series (left to right) shows just before impact, at impact, and after rebound of impact tub on slab.



(a) (b)

Figure 4 ECC self-heals crack damage when exposed to water and air. (a) Before and (b) after healing

(a) (b)

Figure 5 (a) Spalled mortar specimen after 95 hours accelerated corrosion, and (b) ECC specimen after 350 hours accelerated corrosion.

ECC undergoes self-healing of crack damage requiring only the presence of air and water. Figure 4 shows an ECC specimen before and after healing.

The intrinsically tight crack width without depending on steel reinforcement contributes to enhanced durability of infrastructure even under an aggressive environment. For example, it has been shown that under chloride environment, the effective chloride diffusion coefficient of ECC remains substantially lower than that of normal concrete under the same load and chloride exposure (Sahmaran *et al*, 2007). The rate of corrosion of the reinforcing steel is also significantly lower under salt spraying and drying cycles (Miyazato and Hiraishi, 2005). Further in an accelerated corrosion test using an impressed current on the re-bar, cover spalling in ECC is fully suppressed (Sahmaran *et al*, 2008) (Figure 5).

Designing a ductile concrete by trial-and-error is next to impossible due to the infinite combination of fiber (type, length, diameter), matrix (toughness, flaw size and distribution) and interface (chemical and frictional bonds) parameters. A strong theoretical foundation had to be developed to guide the composite development process. Meeting this challenge led to the first ever micromechanical model of strain-hardening ductile concrete (Li and Leung, 1992; Li, 1993).

The second challenge was measurements of micromechanical parameters, including fiber/matrix interaction properties. New experimental methods in microfiber pullout test (Li *et al*, 1990; Katz and Li, 1992) had to be developed, and a number of hither-to unknown micromechanisms were identified, including slip-hardening processes and snubbing mechanisms of synthetic fibers as they debond and slide out of the matrix during matrix crack propagation.

The development of the theoretical design basis of ECC combined with experimental techniques to quantify micromechanical parameters was critical in the successful realisation of ductile ECC. Research on ECC requires background in concrete technology, material science, and mechanics of materials. Interdisciplinary research inspired by nature's nacre led to today's ECC technology.

3. BENEFITS AND IMPACTS TO THE CONSTRUCTION INDUSTRY

Over the last decade, ECC has emerged in full-scale civil infrastructures in the transportation, building, water and energy industry domains. ECC has been applied cast-in-place, as well as in precast structural elements. In cast-in-place applications, ECC with self-consolidation fresh property has been used. Both new structures and repair/retrofitted structures have benefited from the unique properties of ECC.

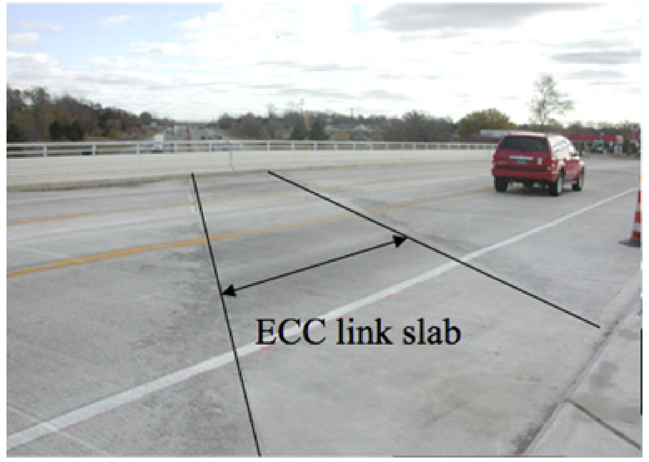


Figure 6 ECC link slab replaces conventional expansion joints to enhance the service life of bridge deck in the US.

Figure 6 shows a bridge deck with an ECC link slab (Lepech and Li, 2009) replacing a conventional expansion joint that typically requires frequent repairs. This application takes advantage of the large deformability of ECC to act like an expansion joint when the deck needs to lengthen and shorten due to temperature induced expansion and contraction. The computed tensile strain demand on this link slab was over 2%, a value no normal concrete, high strength or not, can withstand without brittle fracture. The ECC was batched in a ready-mix plant and transported to site by ready-mix trucks. Six truck loads of self-consolidating ECC (Figure 7) were deployed in this retrofit application. After ten years in use, this link-slab remains in a condition similar to when it was first installed, thus demonstrating its durability under traffic and severe weather conditions (freeze-thaw cycles in winter) in the state of Michigan.

Figure 7 Self-consolidating ECC enhances quality control in cast on-site projects

The ECC link slab provides an opportunity to study infrastructure sustainability when advanced construction material is introduced. Keoleian *et al* (2005) conducted a comparative life-cycle analysis of resource input and pollutant emissions between a bridge deck that utilises ECC link slab and a bridge deck with conventional expansion joints. They found that about 40% of total primary energy and carbon dioxide equivalent were saved due to the reduced maintenance frequency requirement and the associated impact on traffic patterns when ECC link-slab is used to replace conventional expansion joints (Figure 8). Simultaneously, the life cycle cost of the 60 years service life was found to be reduced by 37%.

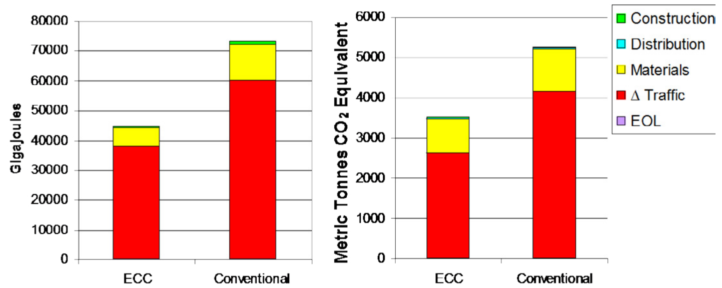
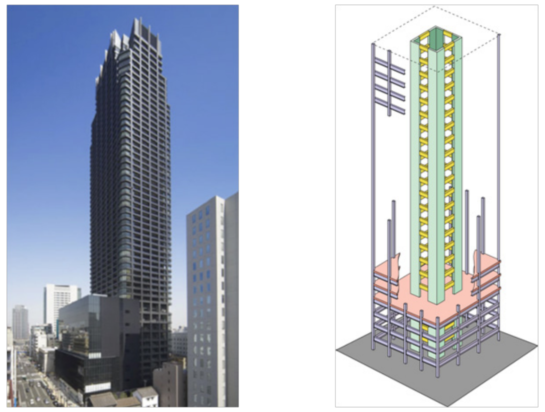


Figure 8 Life cycle (a) primary energy consumption and (b) CO2 equivalent for the ECC shows about 40% less than that of conventional bridge deck systems.



(a) (b)

Figure 9 ECC coupling beams were used to enhance seismic safety in the tallest R/C building in Japan. (a) the 60 story Kitahama Building in Osaka, Japan, and (b) Schematic showing four coupling beams (in yellow) on each floor levelcorrosion.

Figure 10 ECC coupling beams as seen during building construction

Figure 11 ECC dampers used to enhance seismic safety and durability of the Seisho By-Pass Viaduct in Japan.

Figure 9(a) shows the use of ECC in the tallest reinforced concrete (R/C) building in Japan – The 60-story Kitahama Building in Osaka, Japan. In this application, the ECC coupling beams serve to absorb energy during an earthquake (Kanda *et al*, 2011). The high tensile ductility of ECC enables a desirable hysteresis behaviour of the coupling beams under reversed shear loading. Extensive experiments demonstrated the damage tolerant response with load capacity remaining stable even at high drift angles. The coupling beams were precast in a precast yard, transported to the construction site, and dropped into location four pieces on each floor level, connecting to the core wall (Figure 9(b)). Figure 10 shows the coupling beams while the building was under construction.

ECC dampers were adopted to retrofit the Seisho By-Pass viaduct in Japan, to enhance its seismic safety. Over one thousand dampers were precast and installed. The viaduct retrofit dampers were designed to absorb energy during seismic loading, and remain durable in an aggressive chloride and water environment (Figure 11). In this application, both tensile ductility and tight crack width of ECC are critical to the performance of the retrofitted viaduct.

The field applications of ECC briefly highlighted above are motivated by the needs to reduce maintenance (as in bridge deck with ECC link slab), and to enhance safety under natural hazards (as for tall buildings with ECC coupling beams). In the case of the ECC dampers, both attributes become important and must be embodied in a single concrete. Two concrete materials, one ductile and the other durable, would not be effective. These applications are illustrative of the wide applicability of the new ductile concrete.

4. CONCLUSIONS

ECC represents a paradigm shift from damage prevention to damage control and management in concrete design. Instead of tight packing of ingredients as in high strength concrete, ECC emphasises synergistic load sharing among the composite components under overloading. The result is a new concrete with high tensile ductility, bendable under flexural load.

The invention of ECC enables structural engineers to provide a safer, more durable, and sustainable built environment for society. Safety can be greatly improved with ECC because it is damage tolerant when subjected to large loads such as earthquakes and impacts (e.g. blast loading). ECC improves durability through self-control of cracking that typically leads to deterioration of concrete and its reinforcement. Self-healing of ECC further aids in managing crack damage. Life cycle assessment modeling results confirmed that the adoption of ECC technology leads to a reduction of carbon and energy footprints of constructed facilities. ECC can contribute to the construction industry's ongoing worldwide efforts towards more sustainable and resilient infrastructure. In short, ECC represents an enabling technological innovation for enhancing harmony between the built and natural environment.

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