Bendable Composites

Ductile Concrete for Structures

By Victor C. Li

Concrete is brittle. *Through proper reinforcement with ductile steel, however, design and construction of reinforced concrete (R/C) structures has become commonplace. Today, R/C represents a highly successful form of civil infrastructure. Yet R/C infrastructure systems continue to experience increasing challenges in safety under severe loading, and durability under combined mechanical and climatic loading. Concerns for harmonious co-existence between the built and the natural environment have been on the rise. There has long been a desire to create highly damage tolerant yet economic structures that require minimum maintenance, and with minimum environmental impacts.*

To achieve enhanced safety, a variety of approaches have been attempted, with varying degrees of success. Examples include special reinforcement detailing, steel jacketing, addition of structural damping devices, etc. It appears, however, that given the brittle nature of concrete, the most direct and effective approach to creating damage tolerant structures would be to embed intrinsic tensile ductility into concrete. If concrete behaves like steel in tension (highly ductile), while retaining all other advantages (e.g. extreme compressive strength), concrete structures with enhanced serviceability and safety can be readily realized.

For years, material researchers have attempted to make concrete ductile. Successes have been achieved, involving fiber reinforcement in almost all cases. However, these early attempts have the limitations that either the amount of fiber required is excessive or the fibers must be continuous and aligned. These requirements lead to composites that are expensive and impossible to produce by conventional construction equipment, thus limiting the feasibility of early versions of high performance fiber reinforced concrete materials in full-scale structures.

Engineered Cementitious Composites (ECC, also known as "Bendable Concrete"), developed in the last decade, may contribute to safer, more durable, and sustainable concrete infrastructure that is cost-effective and constructed with conventional construction equipment. With two percent by volume of short fibers, ECC has been prepared in ready-mix plants and transported to construction sites using conventional ready-mix trucks. The mix can be placed with-out the need for vibration due to its self-consolidating characteristics. The moderately low fiber content has also made shotcreting ECC viable. Furthermore, the most expensive component of the composite, fibers, is minimized resulting in ECC that is more acceptable to the highly cost sensitive construction industry.

ECC is ductile. Under flexure, normal concrete fractures in a brittle manner (*Figure 1a*). In contrast, very high curvature can be achieved for ECC (*Figure 1b*) at increasingly higher loads, much like a ductile metal plate yielding. Extensive inelastic deformation in ECC is achieved via multiple micro-cracks, with widths limited below 60μm (about half the diameter of a human hair). This inelastic deformation, although different from dislocation movement, is analogous to plastic yielding in ductile metals such that the material undergoes distributed damage throughout the yield zone. The tensile strain capacity of ECC can reach 3-5%, compared to 0.01% for normal concrete. Structural designers have found the damage tolerance and inherent tight crack width control of ECC attractive in recent full-scale structural applications. The compressive strength of ECC is similar to that of normal to high strength concrete.

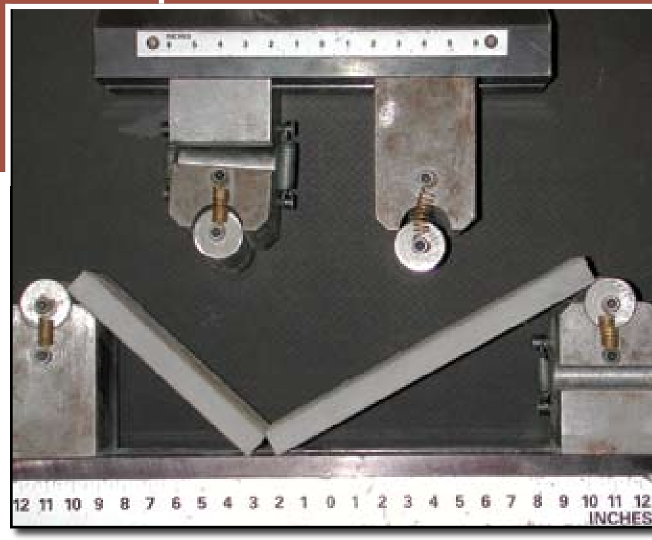

Figure 1a: Response under flexural loading - brittle fracture of concrete

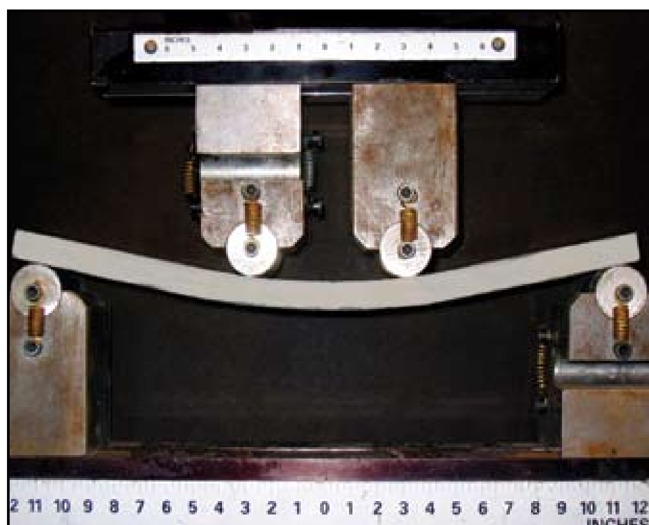

Figure 1b: Response under flexural loading - ductile deformation in ECC

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Structural Applications of ECC

Earthquake resistant structures

Extensive research has been carried out on steel reinforced ECC (R/ECC) structural elements including beams, columns, connections, and frames under simulated seismic loading. These experiments confirm significant improvements in damage tolerance, suppressing many of the commonly observed failure modes in R/C such as cover spalling and bond splitting. Additionally, the amount of steel shear reinforcement can be drastically reduced since ECC remains highly ductile in shear.

As an example, a self-centering R/ECC frame was studied. Self-centering is achieved through self-restoring forces exerted by highly elastic FRP rebar used in the frame columns to attain zero residual drift after a seismic event. Ductile ECC protects the FRP rebar from premature rupturing, as is often observed with the use of FPR reinforced concrete. High energy absorption is provided by the extended hinge zone in the beams, which are reinforced with conventional steel rebar. The compatible deformation between ECC and steel allows a longer segment of the steel rebar to yield, even when both materials have undergone extensive inelastic deformation. No shear reinforcement is used in the columns. The self-centering ability and damage tolerance characteristics of this frame enhance collapse resistance while reducing the cost of post-earthquake repair.

R/ECC was recently adopted in the coupling beams of two high-rise R/C residential buildings (27-story Glorio Roppongi High Rise in central Tokyo and the 41-story Nabeaure Tower in Yokohama) under construction by Kajima Corporation in Japan. The precast ECC coupling beams connect the core walls on each floor, and reportedly provide high vibration damping and energy absorption during an earthquake. The new material technology enables structural engineers to achieve a more efficient building design and reduce construction cost. *Figure 2* shows an illustration of the Nabeaure Tower in Yokohama to be completed in early 2007.

Figure 2a: Nabeaure Tower in Yokohama

Durable and Sustainable Infrastructure

Recent research has generated a wealth of knowledge on the enhanced durability of structures when applying ECC. Freeze-thaw exposure, accelerated weather exposure, fatigue, and wheel load abrasion and wear tests, all indicate high ECC material durability. Self-controlled tight crack widths reduce transport of water and corrosives through the cover, and significantly delay corrosion of reinforcing steel. Furthermore, the ductility of ECC minimizes the potential for cover spalling, as observed in tests simulating expansion of rebar in ECC. This experimental data, combined with the potential elimination of steel reinforcement intended for crack width control in conventional R/C, makes ECC an attractive alternative to normal concrete for extending structural service life.

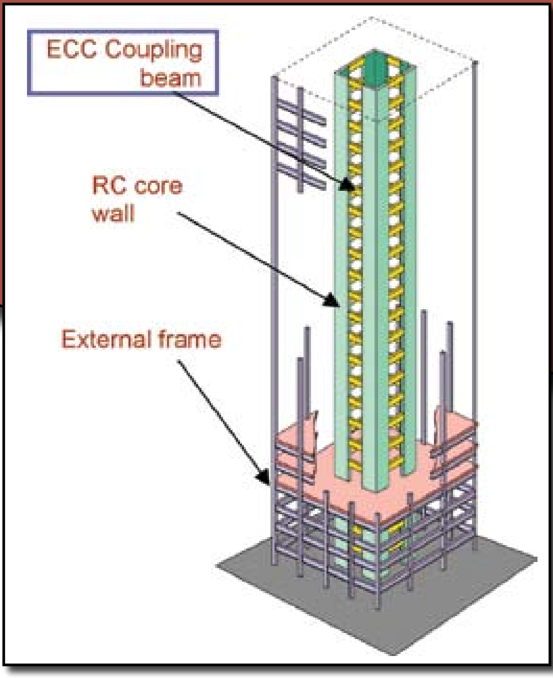


Figure 2b: Illustration of Hybrid Multi-Tower showing the ECC coupling beams

In the fall 2005, an ECC link-slab was constructed for demonstration by the Michigan Department of Transportation on a bridge in southeastern Michigan. This ECC link-slab replaced a conventional bridge deck expansion joint that had high maintenance costs associated with debris-induced joint jamming and cracking of adjacent slabs. The tensile ductility of ECC was exploited to accommodate imposed deformation from adjacent spans due to temperature variation, live load and drying shrinkage, while maintaining tight crack widths for enhanced bridge deck durability. This first large-scale demonstration project (*Figure 3*) in the US confirms the ability of ECC mixing and casting using commercial concrete ready-mix facilities and equipment. As indicated by the contractors, the self-consolidating nature of ECC makes it easy to apply in the field.

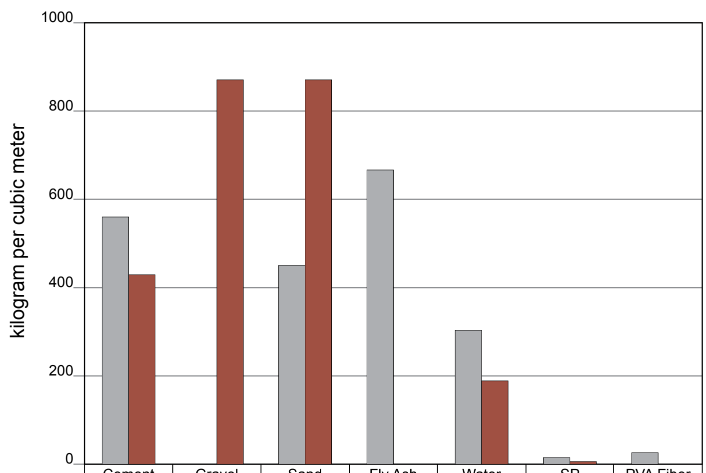
The ECC link-slab project also served as a case study of infrastructure sustainability. ECC extends the service life of the link-slab by slowing the deterioration rate associated with steel reinforcement

Figure 3a: Completed ECC Link-Slab (Phase 1) on the Grove Street Bridge in Ypsilanti, Michigan

Figure 3b: Grove Street Bridge opened to traffic

corrosion. The required maintenance interval of the overall bridge deck, made continuous with the installation of the link-slab, is also extended. Comprehensive life cycle analysis quantifies roughly 40% reductions in terms of primary energy usage and CO_2 emissions (responsible for global warming) when ECC was used to replace conventional expansion joints on this concrete bridge deck. In economic terms, the total life cycle cost savings (user, agency and environmental) is 16% over the sixty-year service life.

Apart from new construction, ECC has also been applied to a number of structural repair cases. As an example, an alkali-silicate reaction (ASR) damaged earth retaining wall in Gifu, Japan, was repaired with a 50-70 mm overlay of ECC in 2003. Twenty-four months after the repair, only microcracks less than 0.12 mm wide can be found in the ECC covering layer, whereas cracks of 0.3 mm are present in the adjacent normal repair mortar layer due to continued ASR expansion in the underlying concrete. Similar findings related to excellent crack width control in ECC were reported for a 2002 patch repair on a concrete bridge deck in southeastern Michigan. After more than 3 winter's worth of freeze-thaw cycles and traffic loads, the ECC patch revealed cracks with maximum width less than 0.05 mm, compared to cracks over 3 mm wide in the adjacent concrete patch placed simultaneously with the ECC patch. These studies suggest that ECC can be a durable structural repair material.



	Cement	Gravel	Sand	Fly Ash	Water	SP	PVA Fiber
ECC M45	561	0	449	673	327	14.00	25.99
Concrete	432	864	864	0	192	4.30	0.00

Figure 4: A Mix-Design of ECC and regular concrete (adapted from MLTAP, 2005)

The Making of ECC

ECC is made with ingredients typically found in concrete, including cement, sand, fly ash, and superplasticizer. However, no coarse aggregates are employed, and no air entrainment is necessary. Instead, micro-fibers are added. The type, size and amount of all ingredients and their mixing sequence are carefully controlled, so that the resulting composite maintains self-consolidating characteristics during casting and ductile behavior after hardening. An example ECC mix design is given in *Figure 4*, which also includes a normal concrete mix design for comparison. *Figure 5* shows self-consolidating casting from a ready-mix truck for the bridge link-slab project mentioned above.

The components in an ECC mix design have been tailored using a body of knowledge (broadly known as micromechanics) on how the fiber, mortar matrix and the interface between them interact under mechanical loading. As a result, brittle fracture failure is eliminated. Instead, multiple microcracks form when the composite material is overloaded beyond the elastic state (pseudo-yielding), and the propagating microcracks maintain very tight crack width in accordance with the tailored nature of the bridging fibers. The whole inelastic deformation process of ECC can be likened to the "give" built into the human skeleton due to the presence of muscles and ligaments. A human skeleton with only bones would be significantly more brittle.

The design of ECC is analogous to the design of a well-engineered structure that employs knowledge of load carrying behavior of structural elements such as beams, columns and connections, as well as the interactions between these elements. In ECC, the design of the composite with fiber, matrix and interface is at much smaller length scales, but conceptually equivalent.

Summary

ECC is an ultra-ductile fiber reinforced cementitious material that embodies a micromechanics-based design concept. The tensile ductility and self-controlled tight crack width characteristics are conducive to enhancing structural safety under severe loading, and durability under normal service loading. The design concept allows ECC to be optimized for cost-sensitive large volume structural applications using normal construction equipment. Recent full-scale construction of bridge and building structures provide valuable experience in the adoption of this new material for civil infrastructures. The rapid advancement of this material from basic research in the laboratory to field applications around the world is a result of close collaboration between academia and industry. The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) has already set up a technical committee, designated TC HFC, to prepare code-ready language for future structural design codes that embody strain-hardening materials like ECC.

The cost of ECC is currently about three times that of normal concrete per cubic yard. However, a number of commercial projects in Japan and Australia have already demonstrated that initial construction cost savings can be achieved when ECC is used, through smaller structural member size, reduced or eliminated steel reinforcement, elimination of other structural protective systems, and/or faster construction offered by the unique fresh and hardened properties of ECC.

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When long term cost and environmental impacts are accounted for, as suggested by the life cycle cost/impact analyses for the ECC bridge deck highlighted above, the advantages offered by ECC over conventional concrete become even more compelling.

ECC is a field-ready ductile concrete that has the potential to significantly contribute to enhancing infrastructure safety, durability and sustainability.▪

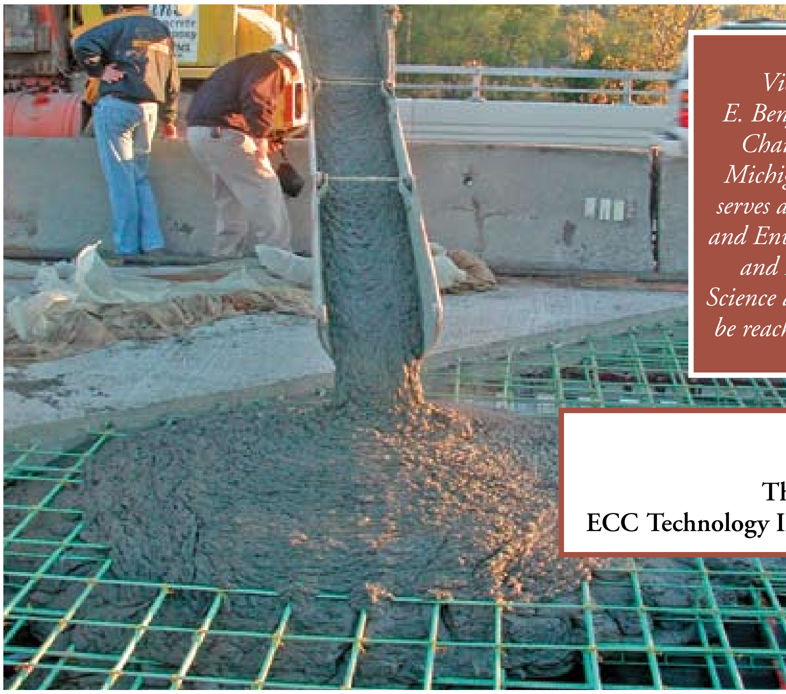

Figure 5: Self-consolidating casting of ECC

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A short course on Bendable Concrete will be offered by the inventor at the University of Michigan late this summer. Targeted audience includes engineers and entrepreneurs. For further information, please visit http://ace-mrl.engin.umich.edu.

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Additional Reading

The ACE-MRL, http://ace-mrl.engin.umich.edu
ECC Technology International Network, http://www.engineeredcomposites.com/

An extensive list of references is included in the on-line version of this article. Visit www.structuremag.org.

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