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The Next Wave of Innovation

ADVANCED MATERIALS COUNCIL

Advanced materials are building-and infrastructure-related materials that exhibit high-performance attributes but have not reached widespread application in the commercial marketplace.
High-performance attributes include enhanced security, safety, resiliency, energy conservation, environmental sustainability, durability, cost effectiveness, functionality, productivity and maintainability.

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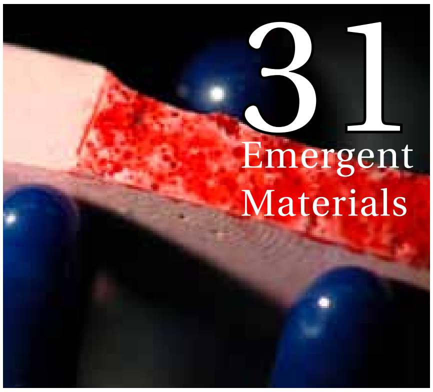

Messages:

On the cover:

The challenge facing researchers will be to develop advanced materials that will protect buildings from natural and manmade disasters while allowing designers to meet aesthetic, energy performance and sustainability goals.

High-Ductility Concrete for Resilient Infrastructures

Earthquakes, fires and blasts are known for their enormous capability to destroy everything in their path. Could a new type of concrete hold the answer to lessening the damage?

By Victor C. Li, University of Michigan

CIVIL INFRASTRUCTURE, INCLUDING buildings, bridges, roadways, tunnels, dams and airfield pavements, may be subjected to multi-hazards such as earthquakes, fires, storm surges, winds, projectiles and blast loading. Protection from catastrophic failures of infrastructure due to such extreme loadings cannot be assured despite many decades of research in structural design and materials development. This is illustrated by events such as the 1995 Alfred Murrah Federal Building bombing, the 1994 Northridge Earthquake in California, and the 2005 Hurricane Katrina in the Gulf of Mexico.

Within the concrete technology community, the development of increasingly high-strength (compressive) concrete over the last several decades has given hope for stronger structures. However, there is also increasing recognition that when a certain level of compressive strength is reached, the failure of a structure or structural element will be dominated by brittle fracture in tension. This recognition has led to an expansion of materials property development towards tensile ductility in recent years (see, e.g. Fischer and Li, 2006). This new focus of research and development may provide a rational basis to support the construction of new infrastructure and the rehabilitation of existing infrastructure for enhanced, robust resiliency against multi-hazards.

This article introduces Engineered Cementitious Composite (ECC), which has its microstructure designed from the ground up for tensile ductility. As a result, the material shows high damage tolerance under a variety of loading conditions. After a brief summary of the micromechanics-based design approach behind ECC, highlights of its tensile properties and some recent field applications of this emerging material are reviewed. The article concludes with brief comments on the future development of smart functional ECCs.

DESIGN APPROACH AND PROPERTIES OF ECC

The design approach behind ultra-ductile ECC is significantly different from that behind ultra high-strength concrete. The most fundamental principle of designing ultra high-strength concrete is the tight packing of particles, leaving as little void as possible in the hardened composite. This approach results in a delay of cracks growing out from material defects and extends the strength and stiffness of the concrete. This delay in crack initiation is a result of both smaller defect sizes and higher intrinsic matrix toughness, in accordance with fracture mechanics.

However, once a crack grows, its propagation is unstable and results in a high composite brittleness. The addition of fibers reduces this brittleness, making the material usable in a structural member.

One of the pioneers of this ultra high-strength design approach is Dr. Hans Henrik Bache at Aalborg Portland Group, in Denmark in the 1980s. The result was a fiber-reinforced, high-strength concrete known as Densit, with compressive strength reaching 120 mega pascals (MPa) (Bache, 1981). Since then, a number of derivatives of this class of concrete material have been developed and commercialized. These include Ductal, developed by LaFarge in France (Richard and Cheyrezy, 1995), and Cor-tuf, developed by the U.S. Army Engineer Research and Development Center (ERDC) (Neeley and Walley, 1995). These later developments have been further aided by the availability of particle-packing models, ultra-fine particles and strong chemical dispersants, and a specialized curing regime, whereby compressive strengths in excess of 200 MPa and tensile strength in excess of 10 MPa have been reported. Even with fiber reinforcement, however, this class of material shows tension-softening responses when tested under uniaxial tensile loading, with a strain capacity no more than 0.2 percent.

As pointed out earlier, high-strength concrete performs well under pure compression loading. However, many structures experience flexural and shear loading that invariably introduces tensile stresses into the material. In dynamic loading, compressive stress waves traveling through the thickness of a concrete element and approaching a free surface would reflect back as a tensile wave that results in high-velocity debris ejected on the back side of the structure (Forquin and Erzar, 2009). No amount of steel reinforcement can prevent this type of failure mode involving concrete spalling and fragmentation, since the reinforcement always requires a concrete cover.

Even on the direct impact side, the materials adjacent to the crater under a penetrating object often develop tensile radial cracks (Cargile et al, 2002). Again, this suggests the presence of high local tensile stress. Concrete structural elements subjected to fire often spall due to a combination of differential thermal stress and internal pressure generation by vaporization of capillary pore water. The resulting tensile stresses eventually lead to brittle fractures of the surface concrete, enabling direct contact between next line reinforcing steel and flames, and reducing the time it takes for steel to soften and structurally collapse.

In order to withstand tensile stresses and prevent brittle fractures, a high composite material toughness is preferred. If the fracture failure mode is fully suppressed by the material's tensile ductility (for example, if the material can be made to undergo plastic yielding deformation without localized fracture), the phenomena highlighted earlier can be avoided. As a result, the structure experiences high damage tolerance. This forms the design philosophy behind ECC that results in the development of a fundamentally ductile concrete.

ECC is designed based on the micromechanics of crack initiation, fiber bridging and steady-state crack propagation (Maalej and Li, 1994; Lin and Li, 1997; Li et al, 2002) in a brittle matrix reinforced with randomly distributed short fibers. By deliberately allowing cracks to form at a tensile stress just below the fiber-bridging capacity (for example, before fiber bridging capacity is exhausted via fiber pull-out or rupture), and by controlling the crack width through the crack-propagation mode (flat crack versus Griffith-type crack), ECC has the ability to undergo non-catastrophic damage in the form of multiple crack formation while maintaining tensile load-bearing capacity.

Analogous to ductile metal where strain hardening is accompanied by dislocation damage to the material, ECC undergoes tensile strain-hardening accompanied by the formation of multiple microcracks. Macroscopically, the brittle fracture mode of normal concrete is turned into a "plastic yielding"-like mode in ECC. To control when microcracks should be allowed to initiate and whether the flat crack propagation mode dominates over the Griffith crack mode, micromechanical parameters of the fiber, matrix and the fiber/matrix interface in the composite must be properly tuned. Guided by the micro-fracture and fiber-bridging models, the optimized micromechanical parameters are then translated into specific combinations of fiber, matrix and interface characteristics. In this manner, the design goal of ECC is targeted at tensile strain-hardening with ductility of several percent (several hundred times that of normal concrete). Compressive strength is retained but ensured not to violate the tensile strain-hardening criteria.

FIGURE 1 shows the tensile stress-strain relationship of a typical ECC material obtained from a uniaxial tension coupon test. FIGURE 2 shows the compressive strength development curve of an ECC. In this example, the tensile ductility and the compressive strength are 3 to 4 percent and 70 MPa at 28 days (Wang and Li, 2007). A very high strength version of ECC (with the compressive strength reaching over 160 MPa) has recently been developed at the University of Michigan in collaboration with the ERDC.

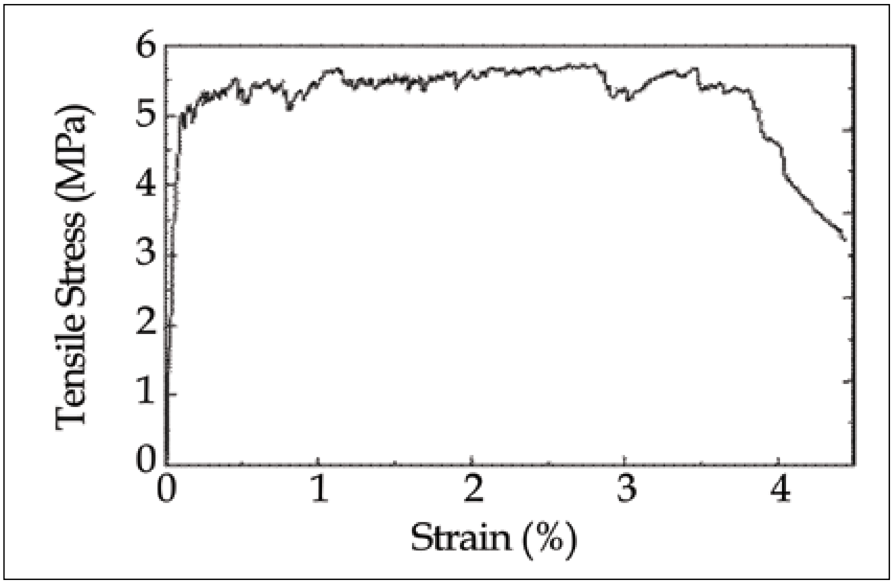

Figure 1. The typical tensile stress-strain curve of ECC . Image courtesy of Wang and Li, 2007.

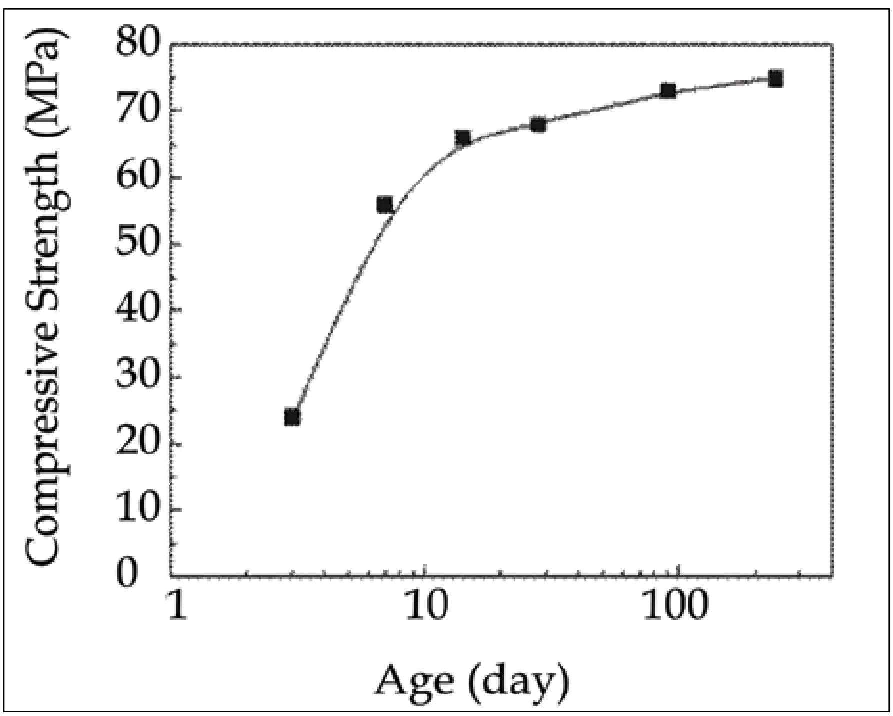

Figure 2. The typical compressive strength development curve of ECC. Image courtesy of Wang and Li, 2007.

FIGURE 3 shows the bending behavior of ECC under a flexural load. When loaded to beyond the elastic range, the material flexes rather than fractures, hence the nickname "bendable concrete."

The availability of a micromechanics-based model allows highly versatile tailoring of ECC for a variety of desirable fresh and hardened concrete characteristics, in addition to strength and ductility. For example, self-compacting ECC (Kong et al, 2003) and sprayable ECC (Kim et al, 2003) have been developed. In addition, lightweight ECC (Wang and Li, 2003) with density below 1 g/cc, and high-early-strength ECC (Wang and Li, 2006) with compressive strength reaching 21MPa at 4 hours have also been developed. These various versions of ECC have been designed to meet specific performance requirements in different applications. ECC is a family of fiber-reinforced ductile cement-based composite materials designed on a micromechanical basis.

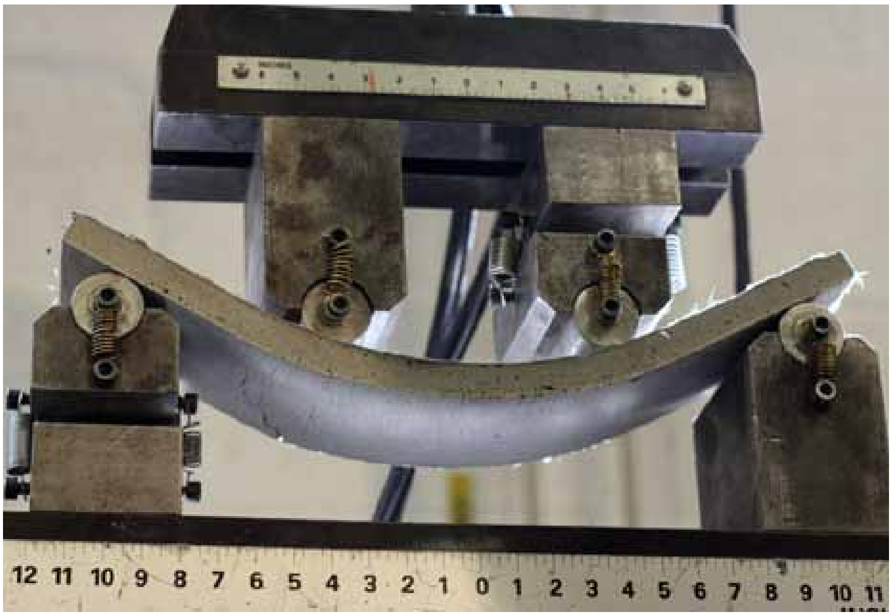

Figure 3. This image shows the extreme flexing capabilities of ECC under a large bending load. Image courtesy of UM News Services.

Figure 4. Sprayable ECC applied to irrigation channel repair. Image courtesy of LFL & Associates, 2008.

APPLICATIONS OF ECC

ECC is used in water and energy infrastructure as well as in the building and transportation industrial sectors. Apart from cost-saving considerations, the driving force behind the applications of ECC includes enhanced safety (Li, 1993), durability (Lepech and Li, 2006; Sahmaran and Li, 2010) and environmental sustainability (Lepech et al, 2008).

Sprayable ECC was applied to the rehabilitation of irrigation channels in the western United States (FIGURE 4). In this application, the damage tolerance of ECC was used to combat the perennial freeze-thaw failure of normal concrete channels. ECC has been demonstrated to be resistant to freeze-thaw cycles with or without the presence of de-icing salts (Lepech and Li, 2006; Sahmaran and Li, 2007). Other applications of ECC in water infrastructure include the surface repair of an eroded dam in Hiroshima, Japan (Kojima et al, 2004). In this application, the water-tightness of ECC was exploited.

ECC was used as a surface protection coating (FIGURE 5) for pipelines used in the oil/gas industry. Damage resistance, improved durability and flexibility were cited as the rationale behind its use in this application (Lepech et al, 2010). Other potential applications of ECC being considered in energy infrastructure include its adoption in the foundation and the towers of offshore wind turbines.

ECC was used in the form of coupling beams (FIGURE 6) in the core of tall buildings (Maruta et al, 2005). These coupling beams provide high energy-absorption capabilities under reverse-cyclic-shear loading during seismic events. These coupling beams were precast offsite and installed onsite by casting the core wall around the beams from floor to floor. Other potential building/housing infrastructure includes prefabricated modular floor and roof panels comprised of a thin-walled ECC slab and a steel truss substructure (Fischer et al, 2009). The advantageous characteristics of these composite panels include a lightweight, high loading capacity and modular manufacturing process.

ECC was applied to transportation infrastructure as a link-slab (FIGURE 7) in a bridge deck (Lepech and Li, 2009) on Grove Street Bridge in Southeast Michigan in 2005. The tensile deformability of ECC was exploited to accommodate bridge deck movements induced by thermal expansions and contractions. The objective was to eliminate the maintenance requirements associated with typical bridge-deck-expansion joints. The Michigan Department of Transportation's ECC Special Provision states a minimum of tensile strain capacity of two percent to accommodate the deformation demand due to combined temperature, shrinkage and life loading.

Figure 5. ECC surface coating for oil/gas pipe protection. Image courtesy of Lepech et al, 2010.

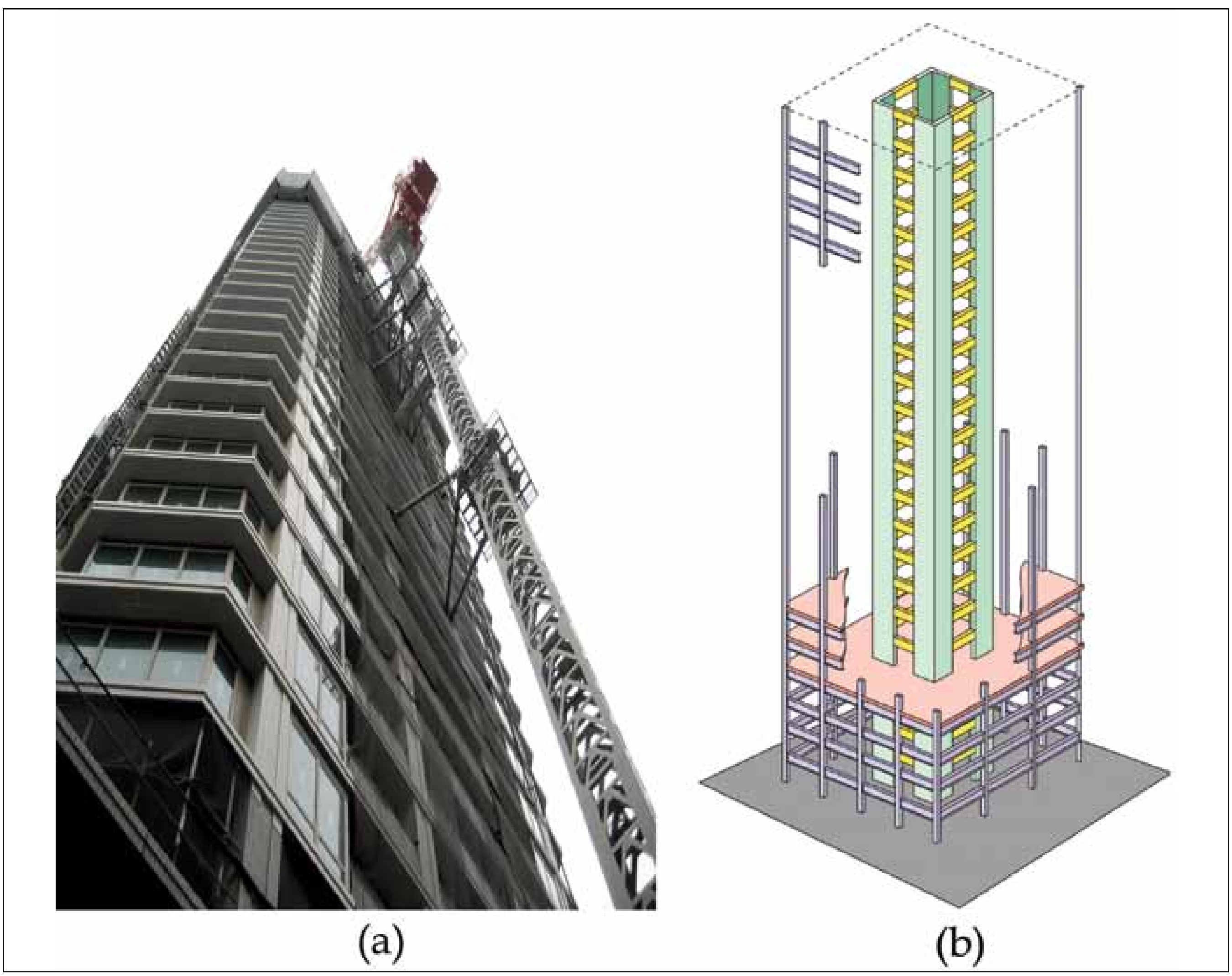

Figure 6. (a) The 41-story Nabeaure Yokohama Tower under construction and (b) Schematics showing coupling beams (in yellow) on each floor. Image courtesy of T. Kanda, 2005.

percent reduction of water pollutants were estimated (Keoleian et al, 2005). This ECC link-slab design was adopted in 2006 in the A22 highway segment that extends from Bolzano to the Austrian border bridge in north Italy. In addition, the 972m long cable-stayed Mihara Bridge in Hokkaido, Japan employed a 38mm thick continuous ECC overlay on a steel plate (Mitamura et al, 2005). This bridge opened to traffic in 2005. In this application, the high tensile ductility of ECC was converted into higher flexural resistance with a thinner cross section of the bridge deck.

CONCLUSIONS

ECC has been established as one of the most ductile concretes in full-scale applications today. Its tensile ductility has been translated into enhanced safety and durability, and the environmental sustainability of a broad array of civil infrastructures in the water, energy, building and transportation sectors. These initial applications demonstrate several important considerations in any newly developed material, including economic feasibility, field scale processing of the material, and material ingredient localization. Equally important, they add to the knowledge base of how and where such a material should be applied in future infrastructure systems.

While an increasingly large database of mechanical and physical properties has been accumulated by researchers around the world that supports the damage-tolerant behavior of ECC under a variety of mechanical and environmental loading types, its potential application for infrastructure resiliency against multi-hazards should be further studied systematically. The impact resistance of ECC was recently investigated by Yang and Li (2006, 2010) using drop weight tests. These studies reveal that special care must be exercised in formulating ECC for high-rate loading, which induces rate sensitivity. When the fiber, matrix and fiber/matrix interface are properly tailored, however, the extreme ductility shown in FIGURE 1 can be retained under impact loading. These investigations should be expanded to include high-velocity projectile and blast loading effects.

The fact that ECC exhibits damage tolerance also makes it attractive as a future multifunctional material. For example, the self-healing ability of ECC was recently reported. Both recovery of transport (permeability) and mechanical properties (stiffness) were observed (Yang et al, 2009) after the deliberately damaged sample was exposed to water and air. In addition, self-sensing functionality of ECC is being studied (Hou, 2008). It is envisioned that future generations of resilient civil infrastructure will also be intelligent with the ability to self-report health conditions in terms of damage and recovery extents. Such intelligence supports the recovery of infrastructure functions subsequent to extreme loading events, as well as assists in maintenance scheduling optimized for safety and sustainability under normal service loading. ■

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Victor C. Li is an E. Benjamin Wylie Collegiate Professor of Civil and Environmental Engineering as well as a Professor of Materials Science and Engineering at the University of Michigan. His research interests include the design, processing and characterization of advanced fiber-reinforced cementitious composites, and the elevating of the ultra-ductility of such materials to the mechanical and durability performance of structural elements and systems.

Figure 7. (a) ECC link-slab on (b) Grove Street Bridge in Ypsilanti, MI. Image courtesy of Lepech and Li, 2009.

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