Can Concrete Be Bendable?

The notoriously brittle building material may yet stretch instead of breaking

Victor C. Li

Since the Industrial Revolution and the invention of Portland cement by British bricklayer Joseph Aspdin in 1824, concrete has evolved into the most important construction material to support quality of life in modern society. In 1889, the Lake Alvord Bridge, the first reinforced concrete bridge in the United States, was built in San Francisco. The first concrete street in the United States was built in 1891 in Bellefontaine, Ohio. The first major concrete dams—the Hoover Dam and the Grand Coulee Dam—were constructed in 1936. Fast-forwarding to the present: The Burj Khalifa Tower in Dubai ranks as the tallest building in the world. The 165-kilometer-long Danyang-Kunshan Grand Bridge in China is currently the longest bridge in existence. Both are concrete structures. In 2012, the amount of concrete produced for constructed facilities is estimated at about 12 billion tonnes, or about 2 tonnes per person worldwide per year. Today, concrete is used not only for buildings, roadways and dams but also for essentially all civil infrastructure that enables fundamental human activities—raising a family at home, working in offices and factories, mobilizing transportation, accessing water and routing energy.

Fabrication of concrete is a multistage process that uses considerable energy. The binder in the majority of concrete, Portland cement, is made by grinding together limestone (for its calcium content) and clay (for its silicon content) into powder, then heating the mixture in a kiln to more than 1,450 degrees Celsius. At such high temperatures, the molecules from each material diffuse into each other, in a process called *sintering.* The resulting solid pieces, called *clinker,* are then ground again with other trace materials. A distinguishing characteristic of Portland cement is that it contains two forms of calcium-silicon compounds, *alite* and *belite.* Alite gives the material strength early in the curing process, whereas belite provides structural integrity over time. (This type of cement gets its name because it is similar in color to Portland stone, a limestone used to build such well-known structures in England as Buckingham Palace and St. Paul's Cathedral.)

To make concrete, cement is mixed with an aggregate—such as gravel and sand—to give it structure, then water is added. Chemical reactions with the water, collectively called *hydration,* cause the material to harden, even if its surroundings are wet. Heat is usually generated from the reactions that occur during the curing process.

Concrete became a structural material when Joseph Monier of France introduced the idea of reinforcing the brittle substance with steel wires in 1867. But advances in concrete have happened continually since its invention. One of the most notable developments in concrete technology has been its improvement in *compressive strength* (when it is pushed or squeezed). Other improvements—such as the introduction of self-consolidating concrete that does not need to be manually vibrated after it is laid to compact it and release air pockets—allow faster and higher quality construction with less manpower. In recent years, it has become common practice to incorporate industrial by-products—such as fly ash from coal-based power plants or slags (agglomerations of mineral impurities) from steel production—into greener concrete mixes. Although concrete as an engineered material has a long history, it has constantly been changed and improved in response to industrial and societal needs.

As concrete became critically important to everyday life, its limitations were also increasingly noticeable. Concrete is a strong material in compression but weak in tension (when it is pulled, bent or stretched). It is essentially a brittle material. The amount of stress, weight or load a material can bear determines its strength. Under tensile loading, concrete responds with a sudden loss of load capacity when a crack propagates from a preexisting flaw, typically at the weak interface between aggregates and the cement binder. Although concrete is not usually designed to take tensile loads, tensile stresses exist nonetheless when a concrete member experiences bending, shear (or sliding) or restrained deformation (such as shrinkage as it dries). There are useful techniques to make concrete usable in large structural members. In addition to steel reinforcement, "tendons" of stretched cables can be added to cast slabs to balance tension forces with compressive forces. (If the tendons are stretched before casting, the process is called *prestressing;* if they are stretched afterward it is called *post-tensioning.*) Despite these measures, catastrophic failures of concrete infrastructure under extreme loading, such as earthquakes, have highlighted the material's limitations.

Recent eye-catching events punctuate the critical nature of concrete's brittleness. Such was the case when more than 69,000 lives were lost during the 2008 Sichuan earthquake in China. Many improperly reinforced concrete structures underwent brittle fracture failure and collapsed. An-

Victor C. Li holds the E.B. Wylie Collegiate Chair Professorship at the University of Michigan, where he is a professor of civil and environmental engineering, and of materials science and engineering. He received his Ph.D. in solid and structural mechanics from Brown University in 1981. He has received the Stephen S. Atwood Award and the Distinguished Faculty Achievement Award from the University of Michigan. He holds nine U.S. patents. His research aims to nurture global sustainable development via harmonious coexistence between built and natural environments through advanced materials technology. Address: Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125. Email: vcli@engin.umich.edu

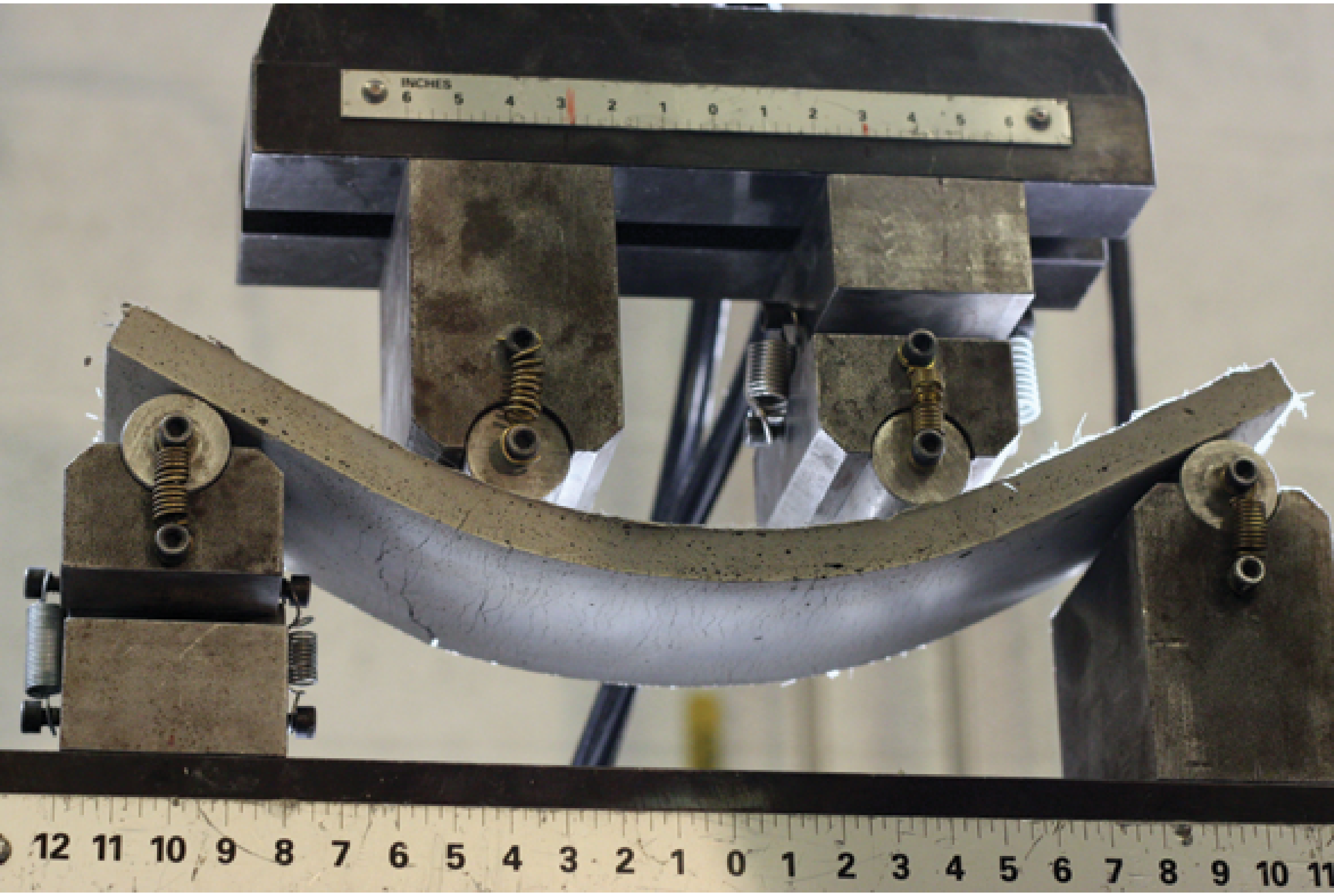


Figure 1. Concrete is not known for its ability to bend, but as this experimental example shows, special formulations of the material can be both flexible and strong. The key is not to prevent cracks completely, but to allow the formation of distributed microcracks that can continue to bear an increasing load. The material has been successfully used in buildings, bridges and repairs of roadways and other infrastructures such as irrigation channels. It may also have future uses in structures that self-repair and self-monitor for damage. (All images are courtesy of the author, unless otherwise indicated.)

other recent case was the uncontrolled spewing of radioactive water into the Pacific Ocean from a 20-centimeter-long concrete fracture in the crippled Fukushima No. 2 nuclear power plant following the 2011 Tohoku earthquake and tsunami in Japan. Civil infrastructure could be made much more resilient if concrete brittleness could be suppressed.

Apart from the safety concerns of concrete infrastructure exposed to major hazards, there are also economic, social and environmental implications associated with infrastructure deterioration under normal service conditions. In 2009, the American Society of Civil Engineers gave an average score of D for U.S. civil infrastructure. It is estimated that a five-year investment of $2.2 trillion is needed to restore infrastructural health. In the category of roads alone, the estimated time lost by motorists stuck in traffic jams often associated with road reconstruction amounts to 4.2 billion hours per year. In addition, the production of cement needed for concrete construction is responsible for about 5 percent of the manmade carbon dioxide released to the atmosphere—an out-of-proportion contribution to global warming potential. The current practice of repeatedly repairing concrete structures due to cracks and surface spalls (where pieces break off) is decidedly unsustainable. The National Academy of Engineers has identified decaying infrastructure in the United States as a grand challenge of the 21st century. For concrete construction, brittleness is synonymous with deterioration and poses significant costs. Despite the many advances in concrete technology, brittleness remains the biggest obstacle to it becoming a truly miracle material for civil infrastructure.

Given that concrete brittleness compromises safety, durability and sustainability, it seems natural to ask: Can brittle concrete be made ductile, so that when stressed it can stretch and bend some without fracturing? This fundamental question becomes even more urgent with increasing development and associated infrastructure worldwide. But before we attempt to answer that question, it may be helpful to ask a related one: Why is concrete brittle?

Origins of Concrete Brittleness

Cracks grow from preexisting defects or flaws in concrete and stop propagating only if the material can find other means to dissipate the energy due to an applied load. Concrete does not possess such mechanisms, so cracks result in an unstable fracture and rapid loss of load-bearing capacity.

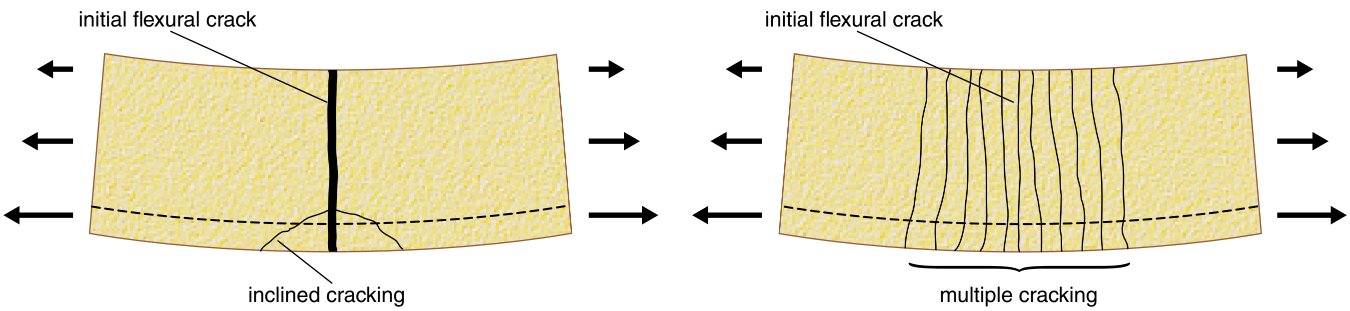


Figure 2. When a conventional steel-reinforced concrete member is bent *(left, showing the side in tension)*, an initial crack forms in the center, which can induce a failure in the bond between the steel and concrete and local sliding of the reinforcement *(dashed line)* relative to the concrete, often resulting in inclined cracking that *spalls* (or breaks off) the concrete covering the steel. Subsequently the steel reinforcement may buckle when the member flexes in the opposite direction during cyclic loading *(black arrows)*, as in an earthquake. The concrete core then loses confinement due to the buckled reinforcing steel and fails by crushing. When concrete is replaced by Engineered Cementitious Composite (ECC), the initial flexural crack spreads into a band of multiple microcracks *(right)*. This smeared-out microcracking allows the reinforcement to deform in sync with the ECC, so that no relative sliding of the steel inside the ECC occurs. Thus the ECC cover remains intact, and the integrity of the structural member is maintained.

Defects in concrete come in different forms. The interface between the stone aggregate and the cement binder is relatively weak because this region has higher porosity and a larger amount of weak calcium hydroxide crystals than in the bulk binder. Air bubbles and restrained shrinkage cracks also serve as initial defects. In the bulk binder, the gel-like compound formed by the hydration reaction with cement and water, calcium silicate hydrate, resists the penetration of a propagating crack, but the energy required to separate the gel is relatively low. A crack initiated from a defect and penetrating the binder finds little resistance to turning into a fast fracture, resulting in a brittle concrete.

For comparison, structural steel has a built-in energy dissipation mechanism, based on the dislocation of bonds between its constituent atoms, which results in crack propagation resistance several orders of magnitude higher than that in concrete. Even in the presence of a preexisting defect, the dislocation mechanism in steel can blunt the crack, suppress crack propagation and lead to tensile ductility. The lack of such energy dissipation mechanism in concrete results in a brittleness akin to that of glass.

Over the past several decades, a significant amount of effort has been expended to make concrete "stronger" by eliminating preexisting flaws. Limiting the size of the aggregates can minimize the defects at the interface between them and the cement binder. Alternatively, this weak, porous interfacial transition

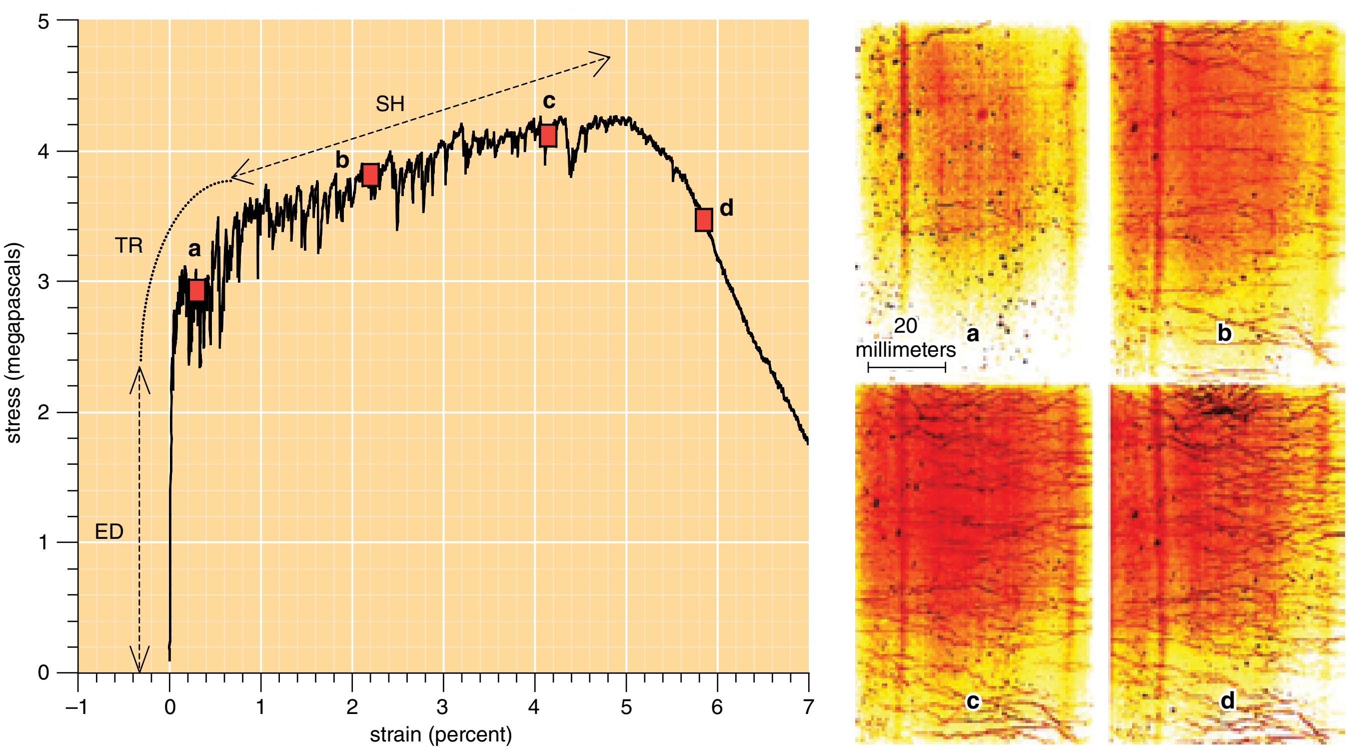


Figure 3. In a stress-strain curve, the material is stressed until failure to determine its strength. This curve for ECC has three regimes before failure: elastic deformation (ED), transition regime (TR) and strain hardening (SH); the regime labeled d with a sharp decline is after failure (or loss of load capacity). Color-enhanced images of ECC *(right, a–d)* show the evolution of cracking patterns at corresponding points on the curve. The initial crack is not necessarily the one that caused final fracture failure, showing the distributed nature of cracking within ECC. The transition and strain-hardening regimes do not exist in the stress-strain curve for ordinary concrete, even if it is fiber reinforced.

zone can be made denser and stronger by including in the concrete mix particles of "microsilica" 100 times smaller than Portland cement grains. The flaws inside the cement binder can also be minimized by tightly packing the powder, lowering mix water content to reduce capillary-size pores that form as the material cures, or applying shear pressure and chemical additives during manufacturing to "squeeze" out any trapped air voids. The use of particles that reduce local stress concentrations also lowers the likelihood of initiating a crack at such a location. Although such techniques are successful at providing higher strength in tension and particularly in compression by delaying the initiation of a fast-running crack, the material remains, and usually becomes even more, brittle. The increase in the amount of elastic energy stored and then released when a crack finally does propagate is not compensated with any significant increase in energy dissipation. In essence, the focus on eliminating flaws instead of introducing energy dissipation mechanisms leads to a high-strength but more brittle concrete.

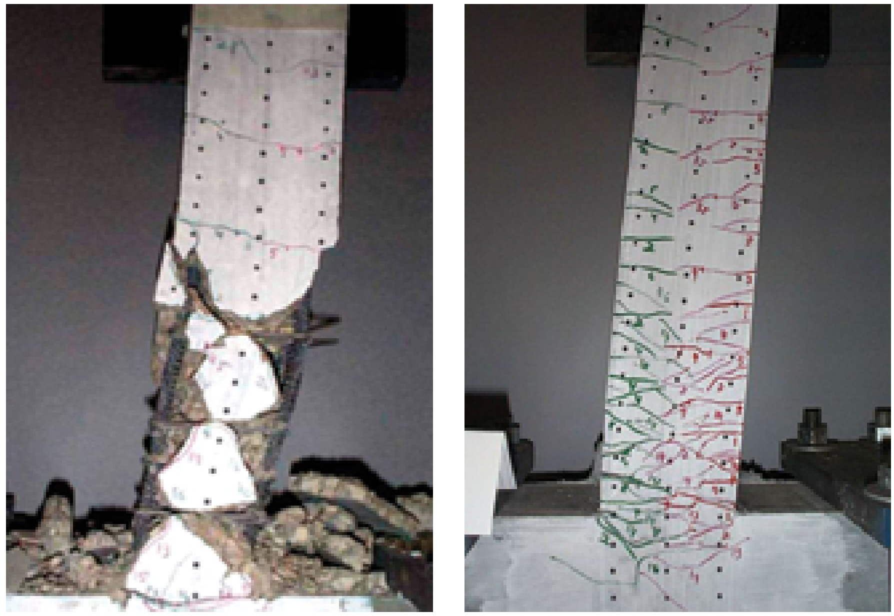


Figure 4. A conventional reinforced concrete column *(left)* subjected to a cyclic sideways drift similar to what might occur during an earthquake shows severe bond splitting between reinforcement and the concrete matrix, and spalling. An ECC column *(right)* under the same loading conditions shows microcracking *(red and green marker lines)* but remains intact, even without shear reinforcement.

Fiber-reinforced concrete, which contains a network of short strands usually made of steel, glass or polymer, can significantly enhance *fracture toughness*, the amount of energy (per unit area) dissipated at the crack tip as the crack extends. Fibers can effectively introduce new mechanisms to dissipate energy, such as chemical debonding at the fiber–matrix interface, or frictional sliding as strands pull partway out of the material. However, such mechanisms are limited to a small region on the fracture plane near the tip of a propagating crack. The result is a modified failure mode from brittle catastrophic fracture failure in conventional concrete to what's called a *quasi-brittle* tension-softening fracture failure in fiber-reinforced concrete. In this failure mode, the load-bearing ability drops gradually rather than catastrophically as the fracture opens.

Fiber reinforcement reduces, but does not eliminate, the brittleness of concrete. "Ductile concrete" is thus usually considered an oxymoron. The construction of bridges and buildings out of ductile concrete has seemed to be an impossibility—until recently.

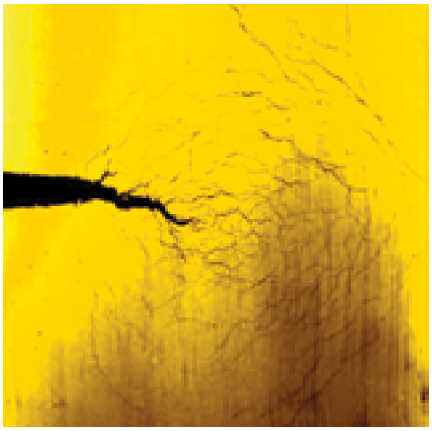
Properties of Ductile Concrete

Concrete is not rubber and never will be—it certainly wouldn't make a good building material if it were floppy. Instead, a ductile concrete is just as stiff as normal concrete under normal service, but yields and deforms without loss of load-bearing capacity under severe conditions. Tiny "microcracks" in the material are inevitable, and indeed, such small, distributed flaws allow the structure to resist catastrophic collapse.

For a material to exhibit tensile ductility and not just toughness, it should be resilient to severe loading and maintain its load-carrying capacity. All materials have an *elastic limit* beyond which they cannot be stressed without incurring irreversible damage. When loads exceed this limit, ductile materials undergo *volumetric inelastic deformation,* meaning that they are permanently altered throughout their bulk but they still don't fall apart. A material possessing such capability will also be highly damage tolerant. When high stress concentration is present, such as that induced by the acute geometry of a notch cut into its side, a ductile material has the ability to redistribute the stress to the adjacent volume of material, thus preventing catastrophic failure from the development and unstable propagation of a crack *(see Figure 5).* In essence, the material becomes notch insensitive. The fracture mode of failure is delayed in a tough material by extending the elastic limit, but is suppressed in a truly ductile material by inelastic deformation.

Over the past two decades, my research group at the University of Michigan has developed a ductile concrete known as Engineered Cementitious Composite (ECC), popularly known as "bendable concrete." First I will describe some unique characteristics of this material at the macroscopic scale, then I will detail some mesoscopic and microscopic phenomena that underlie the macroscale tensile ductility.

The ductility of materials is tested by measuring the strain value (how much materials can stretch) under increasing tensile deformation until the material finally loses its load-bearing capability. Thus, ductility is quantified by this maximum strain value, or the *strain capacity.* In the laboratory, a rectangular test specimen is held on its ends by hydraulic grips and pulled, while the load and stretching of the specimen are monitored. The load is then converted to stress by dividing by the cross-sectional area of the specimen, and the stretching is converted to strain by dividing by the original length of the specimen. The resulting stress-strain curve quantifies the mechanical behavior of the material under load. (The stress-strain curve is used instead of a load-stretching curve because the latter depends on the specimen's geometric dimensions.) For brittle materials, this curve is basically a straight line, terminated by a fracture in the specimen that causes sudden unloading. The strain capacity of normal concrete, a brittle material, is about 0.01 percent. A typical stress-strain curve for ECC is shown in Figure 3. The curve is



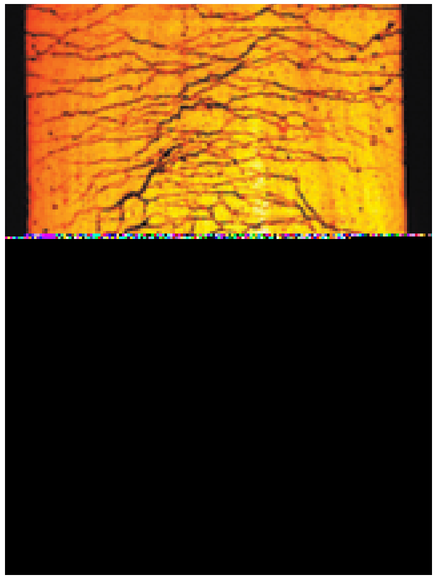


Figure 5. Colorized images of ECC under tension with one *(left)* or two notches *(right)* show that the microcracks formed spread away from the notches, which redistributes the high-stress concentrations at the notch tips.

made of three characteristic regimes: the linear "elastic-deforming" regime (during which time the material can recover its shape if the stress is removed), a "transition" regime with a gradual reduction of effective stiffness (the tangent of the stress-strain curve as it bends over), and the almost-linear "inelastic strain-hardening" regime with significantly lower *effective stiffness* (the slope of the stress-strain curve beyond the elastic limit). The elastic-deforming regime terminates at a strain value of about 0.01 percent, similar to the strain of a normal concrete at catastrophic failure. The strain-hardening regime terminates at about 2 to 5 percent strain, depending on the specific version of ECC. This tensile strain capacity in ECC is two orders of magnitude higher compared with that in normal concrete, making ECC the most ductile concrete in full-scale application.

The strain-hardening regime of the curve for ECC is associated with the activation of a large number of almost parallel microcracks that grow in a direction normal to the tensile loading axis, and emanate from a pre-existing flaw population in the material. Unlike fully developed cracks in concrete or ordinary fiber-reinforced concrete, these microcracks continue to carry an increasing amount of load until the composite strain capacity is reached. The controlled opening of these microcracks is the source of tensile ductility in ECC. They allow the material to dissipate a growing amount of energy due to an increasing load before any one flaw can develop into a major fracture. Much like a crumple zone in a car during an accident, this inelastic straining in ECC also serves to dissipate the energy introduced by an applied load.

The transition regime on the curve spans a strain range from 0.01 to about 1 percent, as stress continues to rise. Beyond the elastic limit, the larger preexisting flaws are activated first, followed by initiation of microcracks from smaller and smaller flaws. This behavior implies a statistical distribution of flaw sizes. If flaws were of a uniform size, the stress-strain curve would be a bilinear line with a kink at the end of the elastic limit; the transition regime would be a single point at the kink, beyond which inelastic deformation would occur at a constant stress level. The flaw size distribution plays an important role in the progressive development of microcracks as the specimen is loaded.

Figure 3 also shows the developing microcrack pattern at different stages of loading. The repeated load-drops in the transition and strain-hardening regimes are associated with the formation of microcracks, which grow in number as the applied tension on the specimen increases. As new microcracks develop, the distance between them narrows, until they reach saturation at a spacing of about 1 millimeter. The microcrack width increases almost linearly with strain up to about 1 percent, after which it stabilizes despite further straining, typically at a value of less than 100 micrometers, depending on the particular mix composition of the ECC. We have designed an ECC with crack widths that have been limited to about 20 micrometers. Microcracks do not convert into a true fracture until the material's strain limit is reached, reflecting the loss of load-carrying capacity at one of the already formed microcracks. The crack pattern developed is unique to ECC.

Damage Tolerance

The ability of ductile ECC to redistribute strain under high-stress concentrations is illustrated by a notched specimen tested under tension. Figure 5 shows the diffused damage in a volume of material surrounding the notch tip. Instead of localizing into a sharp fracture, as would be the case for a brittle or quasi-brittle material, ECC redistributes the stress and strain through its inelastic deformation ability. The onion-shaped damage zone expands outward from the notch tip toward the boundary of the specimen. The microcracks are curved to orient normal to the local principal tensile stress directions around the notch tip. In some tests, microcrack damage is observed to reach the specimen boundaries even when the specimen is as large as 361 millimeters long by 300 millimeters wide and 61 millimeters thick. In contrast, ordinary fiber-reinforced concrete shows fracture localization only on the plane of the material ahead of the notch, with fibers in the concrete bridging across the crack tip on this plane. The volumetric distribution of inelastic response of ECC around a notch is indicative of a truly ductile material.

The notch insensitivity of ECC is best revealed in a double edge-notched specimen tested in tension. Microcracking initiates around the notches. Instead of localizing into a fracture plane, the damage zone expands and extends away from the width-reduced section of the specimen. A notch-insensitive material is expected to show a linear decrease in maximum load with notch depth, whereas a notch-sensitive material is expected to show a faster drop in load capacity. Interestingly, the double edge-notched ECC specimens show strengths slightly above the expected linear decrease. These observations suggest that the tensile strength of ECC is determined by the weakest microcrack plane that would have been spontaneously activated first in a standard test specimen. This plane may be one with the least amount of bridging fibers when fiber dispersion is less than uniform in the specimen. The pre-notching removes this natural selection process, resulting in a higher strength value by artificially forcing the failure into the reduced section of the specimen. The spreading of damage away from the reduced section,

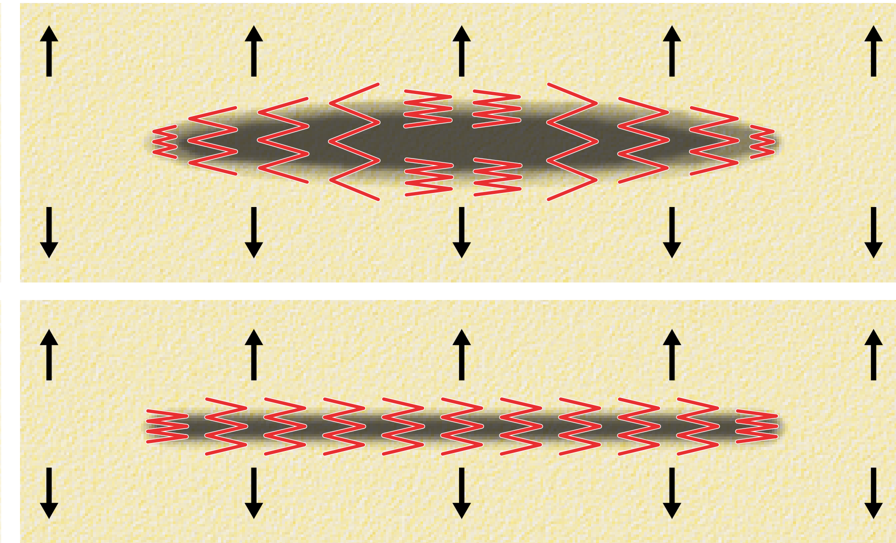


Figure 8. Fibers bridging cracks are modeled as springs. In the flat-crack propagation mode *(bottom)* designed into ECC, the microcrack extends under tensile loading *(black arrows)* with stress and crack width at constant values. In the common Griffith mode *(top)*, as the crack extends, its opening continuously widens and its ability to bear a load decreases correspondingly as fibers in the widest center section break or pull out from the matrix.

dicative of the bridging fibers interacting with the surrounding matrix. They provide inelastic energy absorption that enhances the ability of the microcracks to propagate without breaking the fibers or pulling them out, as the width of the microcracks reaches a constant value soon after crack initiation. This mode is known as a flat-crack propagation, and it is distinct from the more common mode called *Griffith crack propagation,* where the maximum crack opening scales with the square root of the crack length. During steady-state flat-crack propagation, the microcrack extends with the crack width fixed, except for a small region at the crack tip, so the fibers remain intact and attached to the surrounding matrix. Once a flat microcrack has formed, the load transfer capability of the bridging fibers allows additional stress to be applied to the specimen, which in turn triggers additional flaws to initiate new microcracks. In other words, the shape of the nonlinear stress-crack opening relation provided by microcrack bridging fibers at the mesoscale plays a dominant role in the multiple-microcracking pattern and tensile strain hardening in ECC on the macroscale.

The capacity of the bridging fibers governs the tensile load capacity of the existing microcracks in the multiple cracking process. There is statistical variation in the fiber bridging capacity from one crack plane to another, which is associated with the imperfect dispersion of fibers inside the composite. The ultimate tensile strength of ECC is reached when the capacity of fiber bridging on any of these microcrack planes is exhausted.

When the capacity of the bridging fibers is limited, smaller initial defects will not be activated to form additional microcracks. Thus, the peak value of the stress-crack opening relation depends on the volume content of fibers, the diameter of the fibers and the strength of the fiber. Together with the initial flaw size distribution, these parameters determine the density of microcracks and have a direct bearing on the composite tensile ductility.

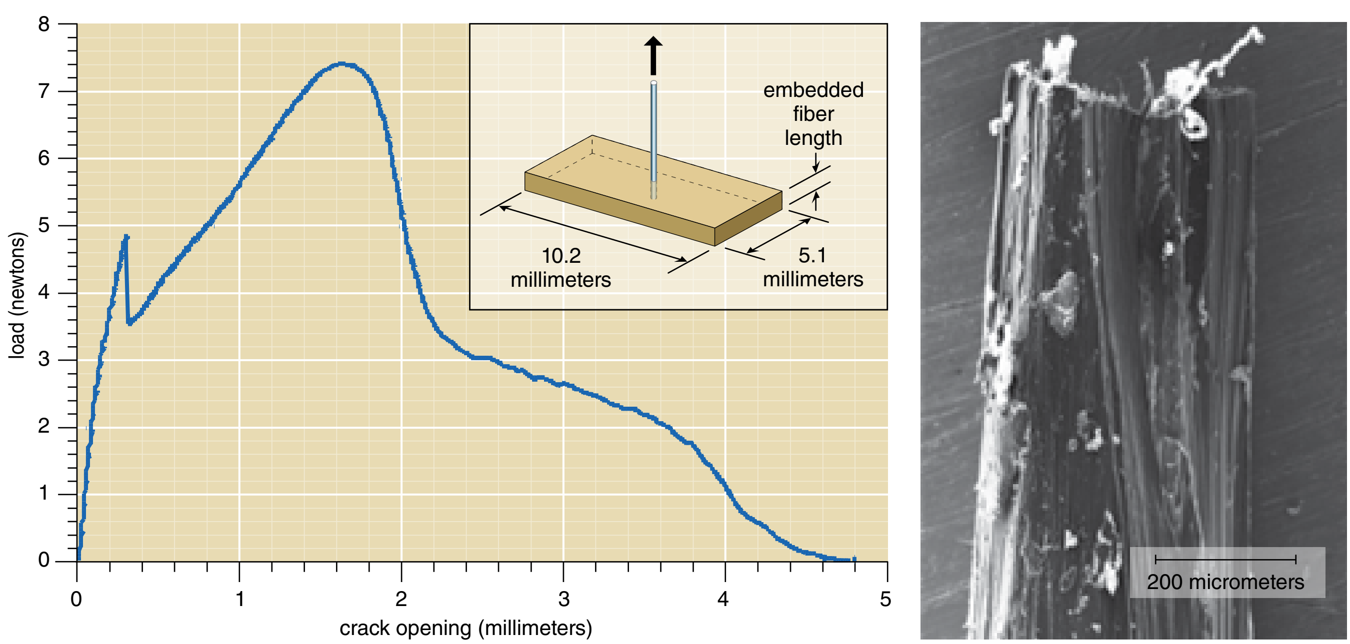


Figure 9. A test to see the load that a single model PVA fiber can withstand before it pulls out of a sample ECC-matrix block *(inset)* shows multiple stages. At the first peak of the graph *(left)*, the adhesive bonding between fiber and matrix is broken, dropping the load abruptly. However, surface abrasion as the fiber slips out *(shown in micrograph at right)* leads to an increase in resistance until a larger second peak is reached, and continues at a decreased rate until the fiber completely pulls out at the end of the graph. If the fiber were more tightly adhered to the matrix, the first peak would be higher, but then the fiber would break immediately, so there would be no added load-bearing ability from surface abrasion and associated fiber slippage.

Fiber Behavior

The interaction between fibers and microcracks is complex, especially when fibers cross the crack at an inclined angle, as would be the case for most fibers when they are randomly oriented inside the mortar matrix. However, the most important and fundamental interaction that supports the desirable nonlinear stress-crack opening response derives from debonding and sliding of each individual fiber during the opening of the crack. If the fibers did not slip somewhat, they would break instead of bridging the crack. If the fibers slip excessively, however, composite action is lost, so the microcrack loses its flat crack shape and turns into a macroscopic fracture.

The nature of fiber debonding and sliding inside the composite is best studied using a single fiber pullout setup, where an individual fiber emerging from a small slab is pulled until the whole fiber comes out. The pullout force must overcome the adhesive bond between the fiber and the matrix material to begin the slippage process. In ECC, slippage is not a simple frictional process but involves a *slip-hardening response*, meaning that the sliding resistance of the interface between the fiber and the surrounding mortar increases as sliding progresses. This slip-hardening response *(as shown in Figure 9)* of the fiber–matrix interface at the single fiber level governs the details of the stress-crack opening relation at the composite's mesoscale level, so it must be carefully controlled.

The highly nonlinear slip-hardening response is a result of deliberately engineered damage to the fiber as it slips against the matrix material. Figure 9 shows abrasion on the PVA fiber after it has completely slid out of the matrix. During sliding, the fiber surface is progressively "peeled" by the rough matrix tunnel, with the deep end of the fiber experiencing the most damage as it undergoes the most sliding before exiting the matrix. The peeling causes a "bulking" effect on the remaining bonded fiber, jamming it against the matrix tunnel and requiring greater forces to pull the fiber out. This fiber surface abrasion-bulking-jamming mechanism is responsible for the slip-hardening phenomenon observed in single fiber pullout experiments.

To control the fiber–matrix adhesive debonding and slippage process, the surface chemistry of the fiber must be systematically tailored. In ECC, a strong slip-resistant process is preferred over strong chemical (adhesive) bonding. Breaking strong chemical bonds does not dissipate as much energy as slip processes involving inelastic mechanisms, such as surface abrasion, bulking and jamming. PVA fiber is valued for its hydrophilic surface chemistry, as most other polymer fibers repel water, and hydrophobic strands pull out with little resistance from cement. However, the hydrophilic surface of PVA fiber also makes it bond too strongly to the cement matrix: The chemical structure of PVA favors complex cluster formation with metal hydroxides. As a result, pure PVA fibers tend to rupture when pulled from a cement matrix. So the PVA fiber designed for use in ECC contains a thin coating of a custom hydrophobic material. This surface coating, 10 to 100 nanometers thick, is enough to dramatically alter the interaction between the PVA fiber and the cement matrix. The coating material and thickness on the PVA fiber are chosen to allow a limited amount of adhesive bond that breaks before a pulled fiber ruptures and supports the slip-hardening process.

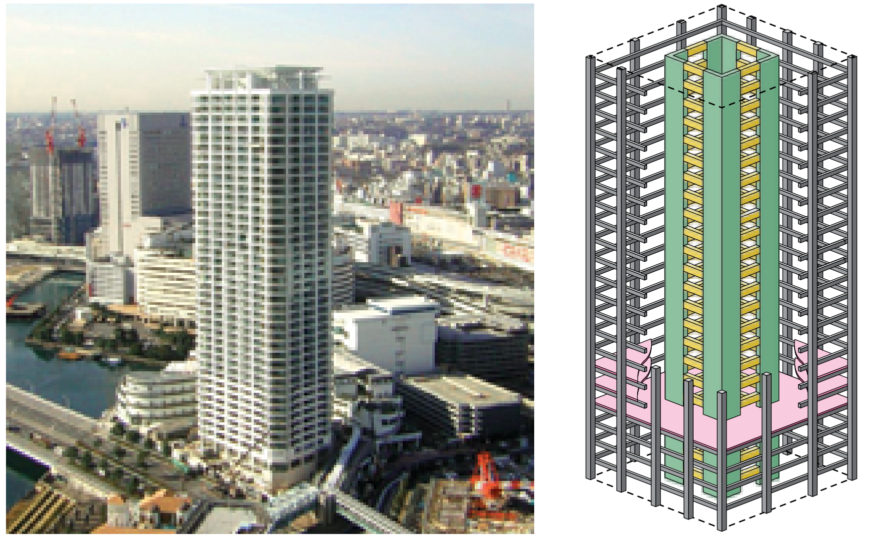


Figure 10. The 41-story Nabeaure Yokohama Residential Tower *(left)* was completed in 2007. It contains four ductile, energy-absorbing ECC coupling beams *(right, yellow)* on each floor, which will reduce damage to core walls *(green)* during an earthquake and stabilize the building.

Figure 11. An ECC link-slab was cast on a bridge deck in southeast Michigan in 2005 *(left)*. The "jointless joint" is nearly seamless *(right)* and has not required any maintenance since installation, unlike conventional bridge deck expansion joints that need frequent repairs.

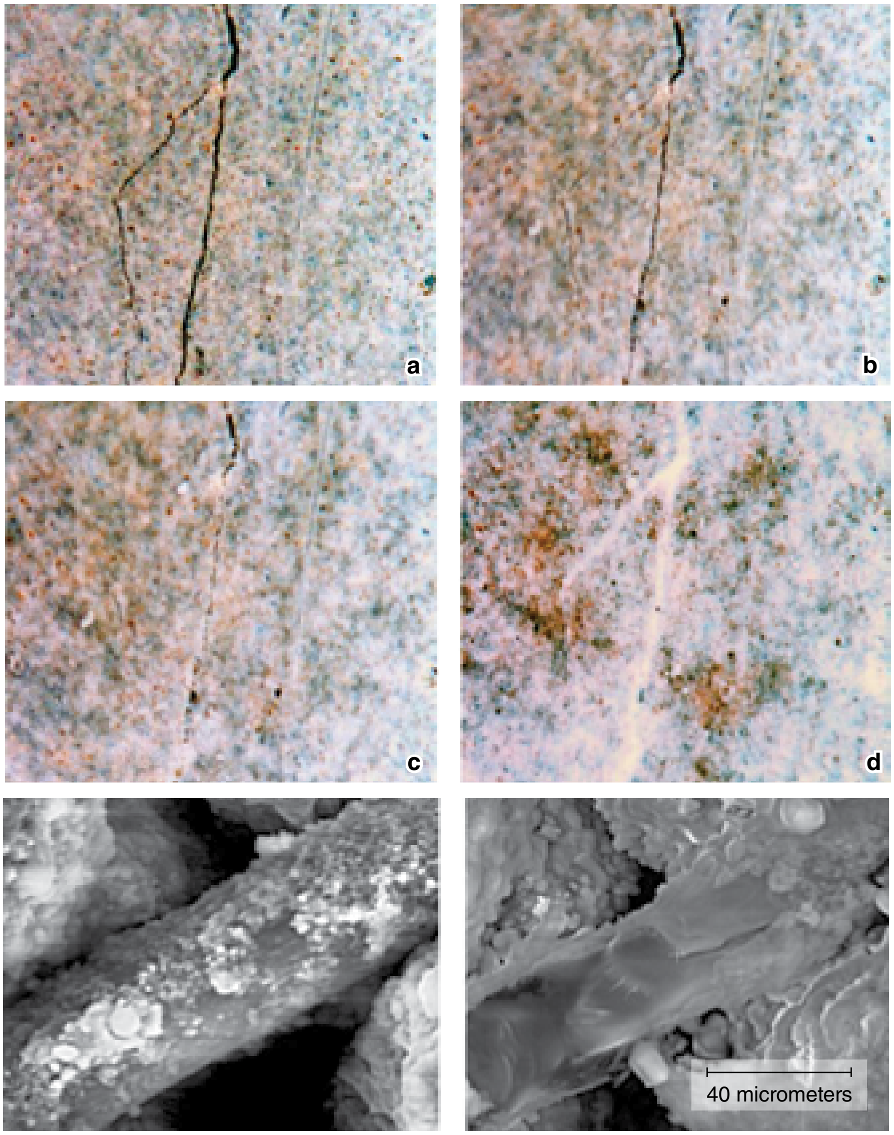


Figure 12. Time-lapse photographs *(a–d)* show an ECC test piece undergoing self-healing. Micrographs show the crack faces and fiber surface immediately after cracking *(bottom left)* and with new healing products formed after 36 hours of immersion in water *(bottom right).*

Infrastructure Resilience

The damage-tolerant behavior of ECC, specifically its tensile ductility and its self-controlled narrow crack width, have been translated into infrastructure advances in several recent full-scale applications.

The tensile ductility of ECC has been used in precast beams in the core of several tall buildings in Japan to enhance the buildings' resiliency against large earthquakes. The 41-story Nabeaure Yokohama Residential Tower in Japan, complete in 2007, was built with this design. (This building is in Tokyo, which did not experience much damage from the Tohoku earthquake.) ECC beams were positioned to couple the corner core walls of the structure, so four were used on each floor. During an earthquake, these coupling beams experience large shear deformation, undergoing microcracking and dissipating the energy imparted into the building by the seismic event. Because shear deformation is essentially a combination of diagonal tension and compression, the coupling beams develop two sets of diagonal microcracks under seismic cyclic loading, and limit the load placed on other parts of the building. Damage-tolerant ECC coupling beams retain load capacity and preserve the building integrity and occupant safety.

ECC with a tight microcrack width contributes to infrastructure durability by minimizing or delaying freezing and thawing damage, chloride penetration (from road salt) and the resulting rusting of steel reinforcement bars, and fatigue cracking. A link-slab made of ECC has replaced a conventional concrete expansion joint on a bridge in southeast Michigan. Standard expansion joints need frequent repair, sometimes annually for some heavily traveled bridges. The ECC link-slab connects to the adjacent concrete bridge slabs using rebar and partially connects to steel girders. It performs the normal function of an expansion joint by stretching via its inelastic tensile deformation when the bridge girders expand in length in response to a rise in temperature, and returning to its original size by closing the microcracks when the bridge girders contract in length in response to cooler weather. Unlike conventional expansion joints, however, the ECC link-slab does not jam or leak chloride-laden water through the joint. The ECC link-slab, acting as a "jointless joint," has remained in the same condition as when it was installed in 2005—no repair has been necessary.

Smart Infrastructure

The tensile characteristics of ECC lend themselves to a number of novel functions that could support smart civil infrastructure. These include, for example, the functionalities of self-healing and self-sensing. Self-healing ECC is envisioned to contribute to future concrete constructions that perform self-repair without any human intervention when damage occurs to the structure. The self-sensing functionality enables structural health monitoring by self-reporting damage (and healing) to remote control stations. Both functions, currently undergoing research at the University of Michigan, depend on the damage-tolerant nature of ECC. The new concrete technologies with smart abilities are expected to further contribute to safer and more durable civil infrastructure with lower carbon and energy footprints.

A time-lapse photo sequence of an ECC specimen shows that it can undergo self-healing *(see Figure 12).* The specimen was previously damaged in a loading machine and underwent self-healing of its microcracks when exposed to cycles of wetting and drying in the laboratory. The healing process is revealed under a scanning electron microscope as new chemical products grew on the surface of the bridging fibers inside the crack, as well as on the crack faces. The chemical products are found to be a mixture of calcium silicate hydrate and calcium bicarbonate, formed when water and air (carrying carbon dioxide) entered the microcracks and

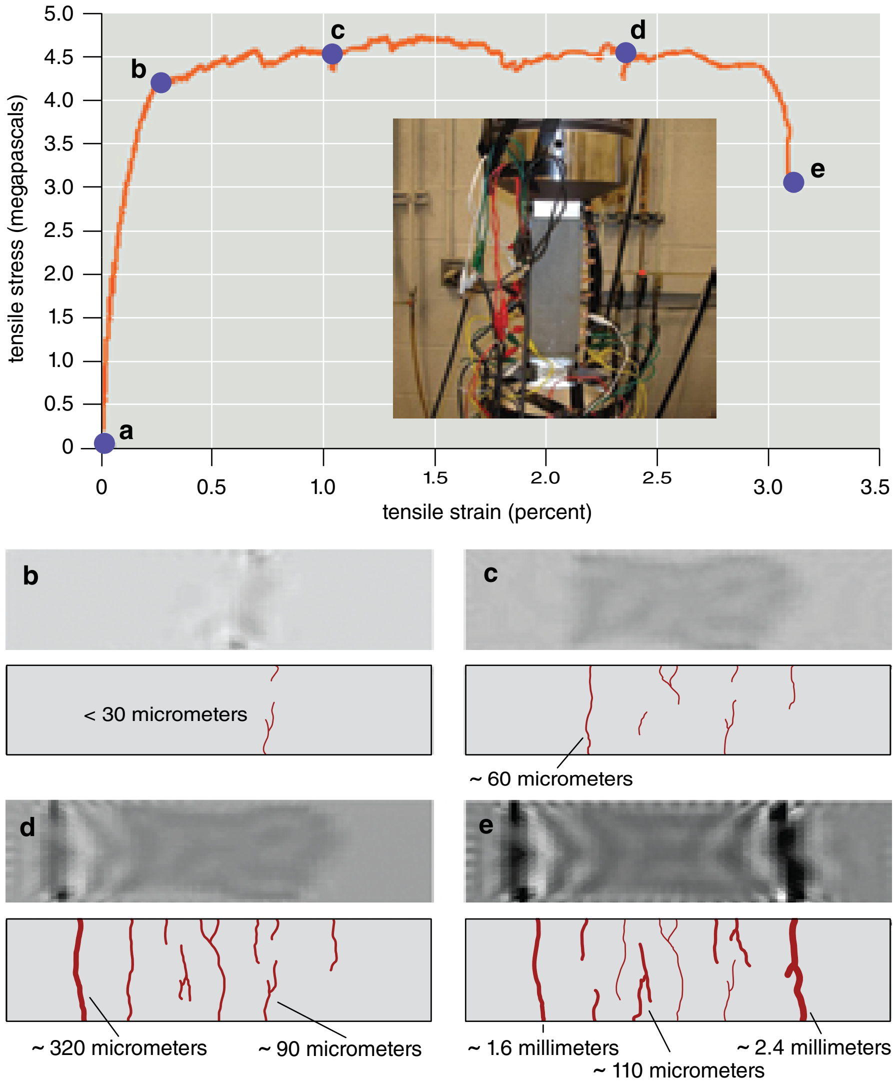


Figure 13. At various points on a stress-strain curve *(top)*, electrical measurements were taken of ECC using the apparatus shown in the inset image. The corresponding electrical impedance tomography (EIT) maps of microcracked ECC *(b–e, top)* show that the conductivity is lower *(darker shades)* where cracks exist *(tracings at bottom of b–e)* and decreases as crack width increases.

reacted with the leached calcium ions in the ECC. In time, the chemical products completely sealed the microcrack.

The healing products grow around, and therefore are automatically reinforced by, the bridging fibers, resulting in a strong microcomposite inside the original crack that is responsible for the ability of damaged ECC to regain its mechanical properties. The magnitude of mechanical property recovery has been studied using resonant frequency measurement of samples before and after self-healing. A sharp drop in resonant frequency is observed after initial damage, but almost complete recovery is seen with just a few wet-dry cycles. Another critical test of mechanical property recovery is done by reloading the healed specimen under tension. It has been found that the original stiffness, strength and ductility are recovered after self-healing under most common loading and exposure scenarios.

Self-sensing functionality also can be embedded in ECC, particularly in the strain-hardening stage. When an electric potential is established between two points on an ECC specimen, a current is induced by the movement of ions in the tortuously connected capillary pores in the cement. The flow of ions is partially interrupted when microcracks are formed, effectively increasing the local resistivity of the material. When voltages (resulting from an electrical current stimulus) are measured on boundary points surrounding a damaged area, the data can be inverted to create a conductivity map of the medium within this boundary. This electrical impedance tomographic (EIT) imaging technique is being investigated by the Laboratory for Intelligent Structural Technology, led by Jerome Lynch at the University of Michigan. Preliminary results of an EIT map of a microcracked ECC show that, as expected, the higher resistivity lines (or reduced conductivity) correlate well with the locations of the microcracks observed optically. With further development, this technique may provide an inexpensive means of structural health monitoring without attachment of additional sensors. The ECC structural material becomes ubiquitously self-sensing throughout the surface and interior of the structure.

In the future, it may be feasible to endow an ECC material with both self-sensing and self-healing functionality similar to that of skin. When a structure built with such a material is damaged, it will be able to initiate self-repair, all the while monitoring the magnitude of its initial damage and the level of recovery. Future concrete will not only be ductile, it will be smart. Such a concrete will help realize dramatically more intelligent civil infrastructure and buildings while substantially enhancing the resiliency and sustainability of dense urban communities.

Bibliography

Hou, T., and J. P. Lynch. 2009. Electrical impedance tomographic methods for sensing strain fields and crack damage in cementitious structures. *Journal of Intelligent Material Systems and Structures* 20:1363–1379.

Lepech, M. D., and V. C. Li. 2008. Large-scale processing of Engineered Cementitious Composites. *ACI Materials Journal* 105:358–366.

Lepech, M. D., and V. C. Li. 2009. Application of ECC for bridge deck link slabs. *Materials and Structures* 42:1185–1195.

Li, V. C. 2003. On engineered cementitious composites (ECC): A review of the material and its applications. *Journal of Advanced Concrete Technology* 1:215–230.

Li, V. C. 2007. Integrated structures and materials design. *Materials and Structures* 40:387–396.

Li, V. C. 2012. Tailoring ECC for special attributes: A review. *International Journal of Concrete Structures and Materials* 6:135–144.

Li, V. C., and E. Herbert. 2012. Robust self-healing concrete for sustainable infrastructure. *Journal of Advanced Concrete Technology* 10:207–218.

Sahmaran, M., and V. C. Li. 2010. Engineered Cementitious Composites: Can composites be accepted as a crack-free concrete? *Transportation Research Record* 2164:1–8.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/issues/id.99/past.aspx