Invited Paper

On Engineered Cementitious Composites (ECC)
A Review of the Material and Its Applications

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Abstract

This article surveys the research and development of Engineered Cementitious Composites (ECC) over the last decade since its invention in the early 1990's. The importance of micromechanics in the materials design strategy is emphasized. Observations of unique characteristics of ECC based on a broad range of theoretical and experimental research are examined. The advantageous use of ECC in certain categories of structural, and repair and retrofit applications is reviewed. While reflecting on past advances, future challenges for continued development and deployment of ECC are noted. This article is based on a keynote address given at the International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) – Applications and Evaluations, sponsored by the Japan Concrete Institute, and held in October 2002 at Takayama, Japan.

1. Introduction

ECC is a class of ultra ductile fiber reinforced cementitious composites developed for applications in the large material volume usage, cost sensitive construction industry. Since the introduction of this non-proprietary material a decade ago, ECC has undergone major evolution in both materials development and the range of emerging applications. The discovery of ECC has benefited from pioneering research by the IPC group (Aveston et al. 1971), one of the first groups which applied fracture mechanics concepts to analyzing fiber reinforced cementitious composite systems. The current advances in ECC technology could not have happened without the active participations of many organizations internationally.

The following sections describe important elements of research and development in ECC, from materials design to commercial applications. The importance of micromechanics playing the role of materials design, optimization, and constitutive ingredient tailoring is emphasized. Reflections on material ductility, performance characteristics of reinforced ECC, or R/ECC, and cost considerations are examined. Future directions of ECC materials development and structural applications are indicated. At this point, it is clear that a milestone has been reached where there is a broad international community, involving academic, industrial and governmental concerns engaged in ECC science and technol-

ogy development. ECC is no longer confined to the academic research laboratory. It is finding its way into precast plants, construction sites, and repair and retrofitting jobs.

It is the hope of the author that by sharing knowledge as they are generated, ECC technologies will continue to accelerate in the next decade, benefiting society via the enhanced safety, durability, construction productivity and sustainable development of our physical infrastructures.

2. From theoretical materials design to commercial applications

Since ECC was introduced about ten years ago, significant developments in research and commercialization of ECC technologies have occurred both in the academic and in the industrial communities. **Figure 1** shows a flow-chart of some important elements of ECC R&D, from basic materials design theory to practical commercial applications.

Micromechanics relates macroscopic properties to the microstructures of a composite, and forms the backbone of *materials design theory*. Specifically, it allows systematic *microstructure tailoring* of ECC as well as *materials optimization*. This topic will be discussed further in the next section. For now, we recognize that microstructure tailoring can lead to extreme composite ductility of several percent in tension, a *material property* not seen before in discontinuous fiber reinforced cementitious composites. **Figure 2** shows an ECC with tensile strain capacity of 5% (Li et al. 2001), approximately 500 times larger than that of normal concrete or fiber reinforced concrete (FRC). An increasingly large database of mechanical (including tension, compression, shear, fatigue, and creep) and physical properties (in-

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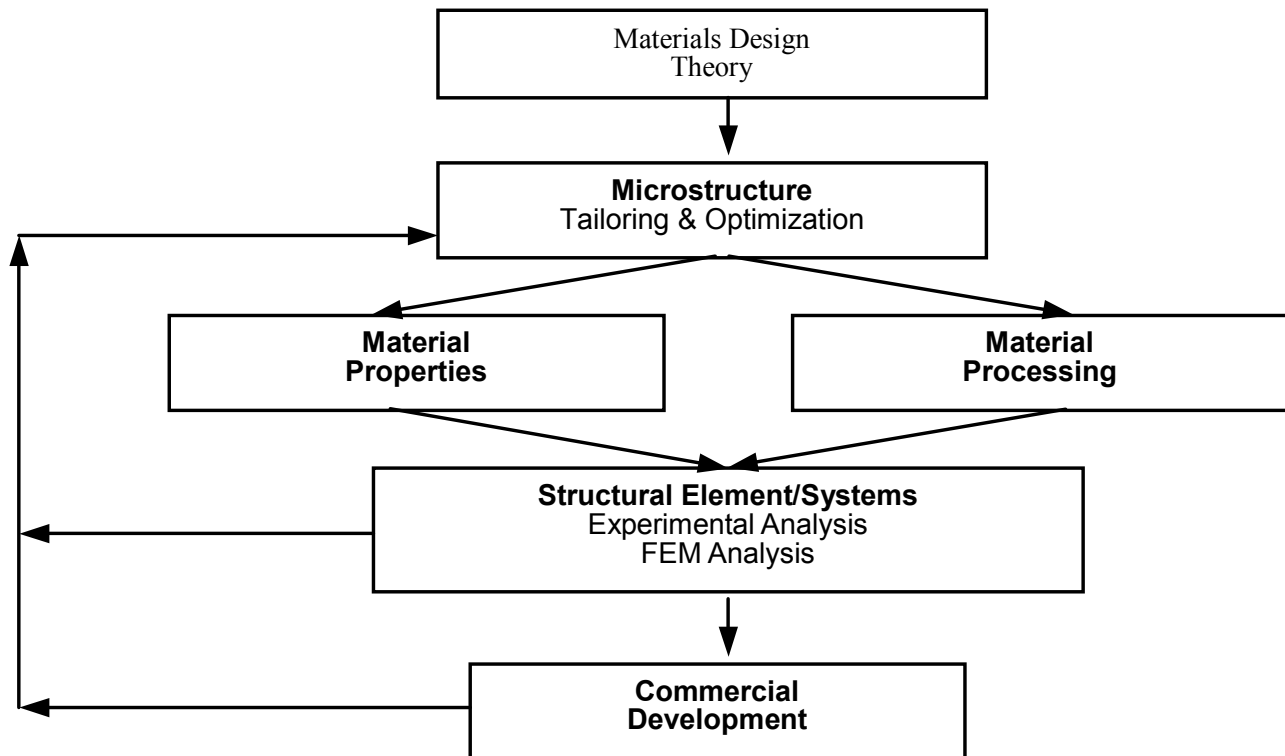*E-mail:* vcli@umich.edu

Fig. 1 Flow-chart of important elements of the research and development of *Engineered* Cementitious Composites. Investigations into structural applications and commercial developments provide feedback to materials improvement via microstructure tailoring.

cluding shrinkage, and freeze-thaw durability) of ECC is now being established. Materials optimization also leads to compositions (e.g. moderately low fiber volume fraction less than 2-3%, coupled with suitable matrix design) that make it possible for very flexible *materials processing*. ECC can now be cast (including self-compacting casting (Kong et al. 2003)), extruded (Stang and Li 1999), or sprayed (Kanda et al. 2001; Kim et al. 2003a). It is the deliberate constituent tailoring and optimization methodology embodied in ECC that gives its name *Engineered* Cementitious Composite.

The advantages of high composite ductility in the hardened state and flexible processing in the fresh state make ECC attractive for a broad range of *applications*. A variety of *experiments* have been performed to assess the performance of ECC at the structural level (see e.g. Fukuyama et al. 1999; Parra-Montesinos and Wight 2000; Yoon and Billington 2002; Fischer and Li 2003a,b; Li et al. 2002) for both seismic and non-seismic structural applications. These experiments provide new insights into how the material properties elevate the response performance of the structure. At the same time, constitutive models (Kabele 2001; Han et al. 2002a) of ECC have been constructed and implemented into *FEM* codes for prediction of structural behavior. They should be useful for exploring the selective use of ECC in critical elements of a structural system, without excessive demands on expensive experimentation. These activities are important in establishing rational

means of designing structures made with ECC material.

Commercial development of ECC technologies imposes additional considerations, in addition to those described in the previous paragraphs. The adoption of a new technology must be justified with advantages in cost-benefit ratio. While the initial raw material cost of ECC is higher than normal concrete, the long term benefits are sufficient to potentially drive this technology into the commercialization stage in the near future in a number of countries, including Japan, Korea, Australia, Switzerland and the US. Nonetheless, materials optimization for cost reduction of ECC remains important.

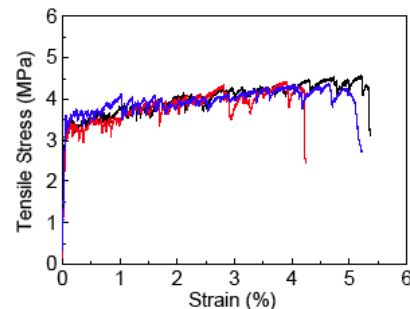It is expected that as investigations into structural re-

Fig. 2 Uniaxial tensile stress-strain curves of an ECC reinforced with 2% PVA-REC15 fibers, showing high tensile ductility of about 5%.

sponse and commercial development of ECC technologies proceed, a feedback loop (**Fig. 1**) to microstructure tailoring for refinement in ECC materials will occur. In addition, special functionalities, such as lightweightedness, or high early strength, will drive the development of specialized versions of ECC for different applications with unique demands. Each of the R&D elements and especially the feedback process will benefit from collaborations among researchers, material suppliers, precasters, and design and construction contractors.

3. Micromechanics

Extensive research has shown that the most fundamental property of a fiber reinforced cementitious material is the fiber bridging property across a matrix crack, generally referred to as the $\sigma-\delta$ curve (Li 1992b; Li et al. 1993; Lin and Li 1997). This is the averaged tensile stress σ transmitted across a crack with uniform crack opening δ as envisioned in a uniaxial tensile specimen. The $\sigma-\delta$ curve provides a link between composite material constituents – fiber, matrix and interface, and the composite tensile ductility (**Fig. 3**).

To understand the fundamental mechanisms governing strain-hardening ECC behavior versus tension-softening FRC behavior, it is necessary to recognize the load bearing and energy absorption roles of fiber bridging. The $\sigma-\delta$ curve (**Fig. 4**) can be thought of as a spring law describing the behavior of non-linear springs connecting the opposite surfaces of a crack, representing the averaged forces of the bridging fibers acting against the opening of the crack when the composite is tension loaded. One of the criteria for multiple cracking is that the matrix cracking strength (including the first crack strength associated with the first crack) must not exceed the maximum bridging stress σ_{cu}. (The cracking strength is dominated by the matrix flaw size.) We may label this as the strength criterion for multiple cracking. A second criterion for multiple cracking is concerned with the mode of crack propagation which in turn is governed by the energetics of crack extension. We may label this as the energy criterion for
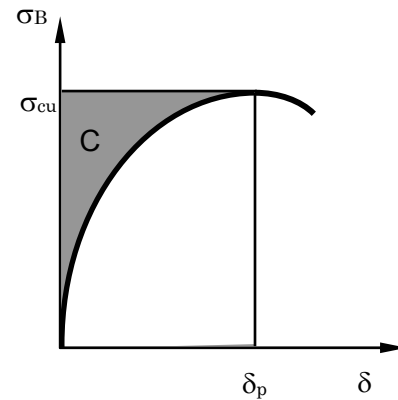

Fig. 3 The linkages between material constituents, crack bridging property and composite tensile ductility.

Fig. 4 The $\sigma-\delta$ curve and the concept of complementary energy (shaded area labeled C). High bridging strength σ_{cu} and large complementary energy C are conducive to composite strain-hardening.

multiple cracking. Clearly, violation of the strength criterion leads to a crack across which the loading cannot be supported by the fiber bridging stress. The energy criterion is less obvious and deserves a more detailed explanation.

When the fiber/matrix interface is too weak, pull-out of fibers occurs, resulting in a $\sigma-\delta$ curve with low peak strength σ_{cu}. When the interface is too strong, the springs cannot stretch, resulting in rupture and a small value of critical opening δ_p. In either case, the complementary energy shown as the shaded area C to the left of the $\sigma-\delta$ curve in **Fig. 4** will be small. Steady state crack analysis (Li and Leung 1992) reveals that when the complementary energy is small (in comparison to crack tip toughness, the energy needed to break down the crack tip material to extend the bridged crack), the crack will behave like a typical Griffith crack (**Fig. 5a**). As the crack propagates, unloading of the springs will initiate at the middle of the crack, where the opening is maximum, when δ_m exceeds δ_p in **Fig. 4**. An expanding traction free or tension-softening region will follow the crack tip as the crack continues to propagate. After the passage of this crack, the composite will fail with reduced load carrying capacity, resulting in the tension-softening behavior of a normal FRC. In contrast, if the complementary energy is large, the crack will remain flat as it propagates so that the steady state crack opening $\delta_{ss} < \delta_p$ (**Fig. 5b**), and maintains tensile load carrying capacity after its passage. As a result, load can be transferred from this crack plane back into the matrix and cause the formation of another crack, which may initiate from a different matrix defect site. Repetition of this process creates the well-known phenomenon of multiple cracking. The shape of the $\sigma-\delta$ curve therefore plays a critical role in determining whether a composite strain-hardens as in ECC, or tension-softens, as in normal FRC, under uniaxial tensile load.

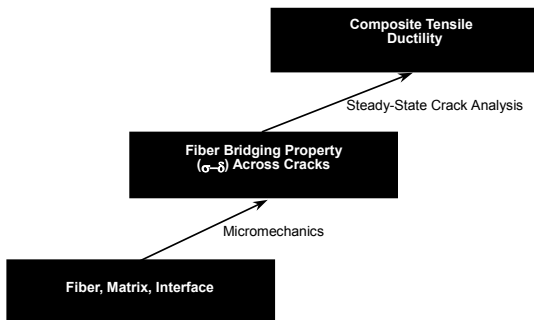The strength and energy criteria for multiple cracking

(a)   **Griffith** Type Crack

Broken or
softening
"springs"

$\delta_m > \delta_p$

(b)   Steady State **Flat** Crack
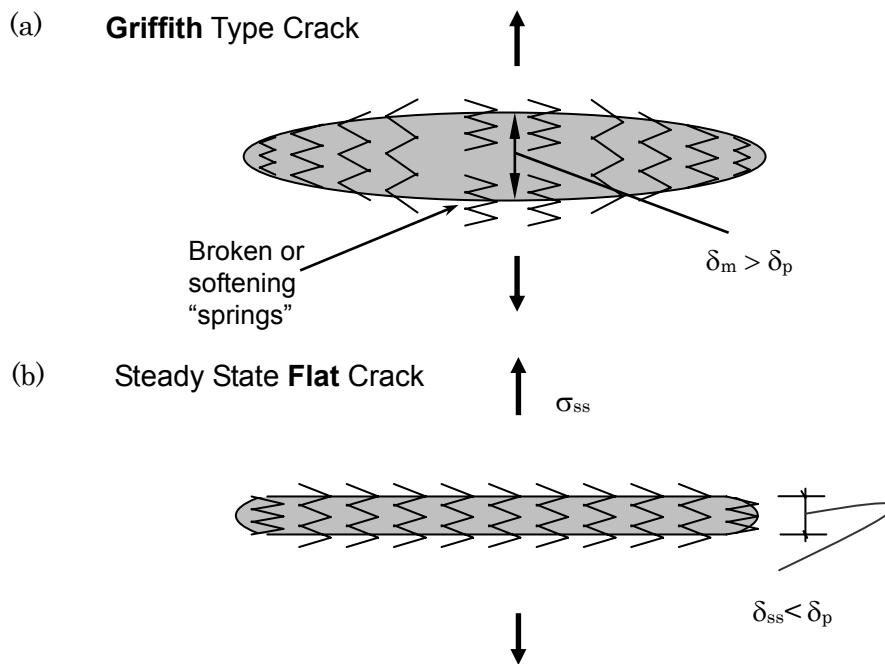
σ_{ss}

$\delta_{ss} < \delta_p$

Fig. 5 Steady state crack analysis (Li and Leung 1992) reveals two crack propagation scenarios: (a) Low complementary energy in comparison to crack tip toughness results in Griffith type cracking. The fibers, illustrated schematically as springs, slide out or break in the mid-crack section where the opening δ_m exceeds δ_p. (b) High complementary energy results in a flat crack propagation configuration. The fibers/springs remain intact as the crack propagates under a constant steady state stress σ_{ss}, with the opening δ_m less than δ_p. After the passage of a flat crack, additional cracks can form under increasing ambient load, resulting in the phenomenon of multiple cracking.

provide guidelines for tailoring the fiber, matrix and interface for ECC materials.

The shape of the $\sigma-\delta$ curve is governed by the fiber volume fraction, diameter, length, strength and modulus, in addition to the fiber/matrix interaction parameters that include the interfacial chemical and frictional bond properties (Lin et al. 1999). Controlling the shape of the $\sigma-\delta$ curve, therefore, boils down to controlling the fiber and fiber/matrix interaction parameters (Li et al. 2002b). This forms the tailoring strategy for the REC15 fiber now manufactured by Kuraray Co. Ltd. (Japan) for ECC reinforcements.

The $\sigma-\delta$ curve has a direct bearing on the constitutive law in general, and the tensile stress-strain curve of the composite in particular, since it determines whether strain-hardening will occur or not. This composite material constitutive law in turn governs the response of a structure built with ECC material. Hence, the $\sigma-\delta$ curve may be seen as a critical link between materials design (lower triangle, **Fig. 6**) and structural design (upper triangle, **Fig. 6**).

From the above discussion, it can be seen that micromechanics serves as a useful tool to direct materials design for achieving desired structural performance. This is the concept behind the Performance Driven Design Approach (PDDA) (Li 1992a) proposed for materials engineering.

As the structural design community moves away from traditional prescriptive design guidelines to a performance based design concept (PBDC) (SEAOC 1995), there will be significant opportunities for innovative use of materials. PDDA and PBDC can be combined to form the integrated structures-materials design (ISMD) scheme (Li and Fischer 2002) shown in **Fig. 6**. We expect that ISMD will serve as an important platform for collaborations between structural engineers and materials engineers, leading to innovative structural and materials designs. The common practices of adding fibers by trial-and-error and then testing for structural element response will not be an efficient approach to materials design, or for achieving deliberate levels of structural performance.

Micromechanics also serves as a tool for materials optimization. The construction industry is a highly cost-sensitive industry. Any new material introduced must be cost-effective. Since fibers are much more expensive than cement, sand or water, it is imperative to minimize the amount of fibers used while maintaining the strain-hardening property. This concept is implemented in ECC in the form of minimizing the critical fiber volume fraction, the amount of fibers that just switch the material from a normal tension-softening FRC behavior to a strain-hardening ECC behavior. The critical fiber volume fraction can be determined based
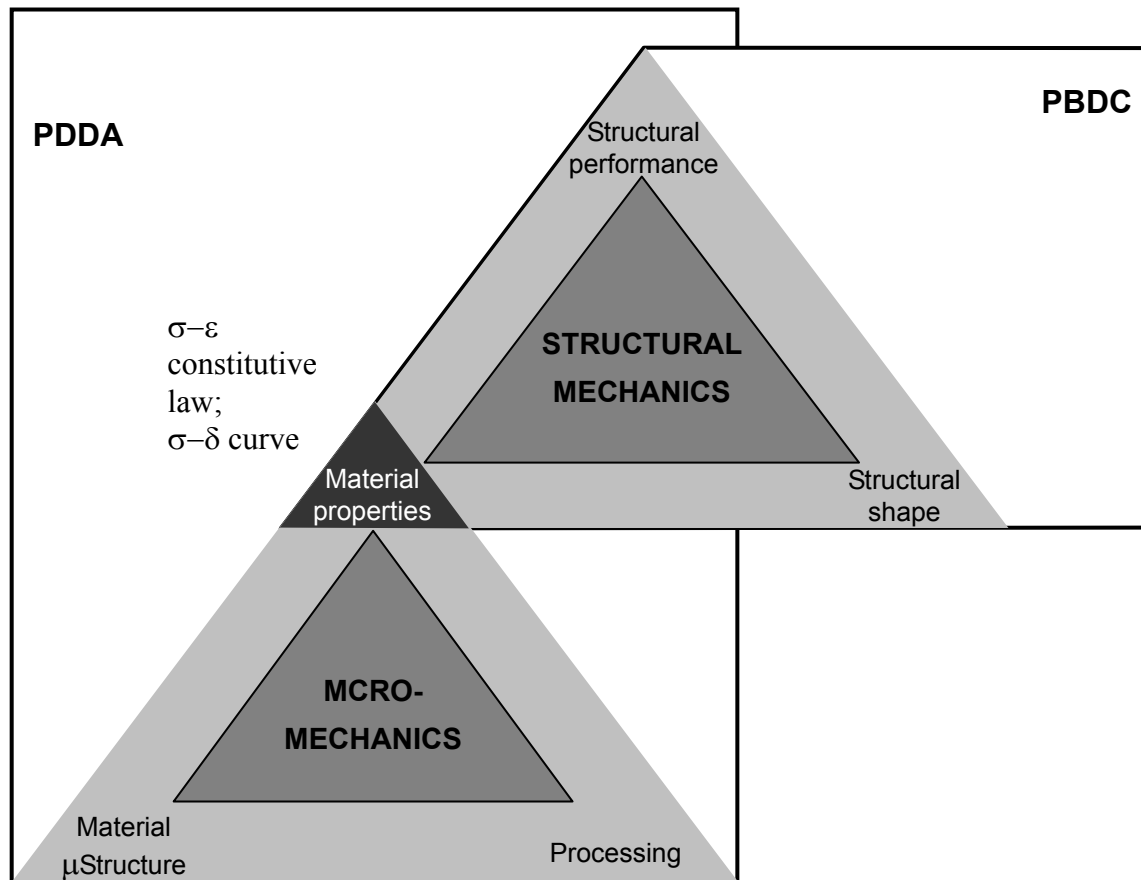
Fig. 6 Concept of Integrated Structures and Materials Design (ISMD). In the upper triangle, structural mechanics relates material properties and structural shape to structural performance. The Performance Based Design Concept (PBDC) suggests the selection of suitable material properties and structural shape to meet structural performance. In the lower triangle, micromechanics relates material microstructure (which affects and is affected by material processing) to material properties. In ECC, the most important material property is the $\sigma-\delta$ curve (used for materials engineering) and the resulting composite tensile stress-strain curve (used for structural design). The use of targeted structural performance to constrain material properties, microstructure and processing is the Performance Driven Design Approach (PDDA) proposed for materials engineering. Thus material properties (middle small triangle) serve as a natural interface between structural engineering (upper triangle) and materials engineering (lower triangle). ISMD integrates PBDC and PDDA into a single materials and structural design platform.

on knowledge of fiber, matrix and interface properties (Li and Leung, 1992; Lin et al. 1999). Using fiber content below this critical value will lead to normal FRC tension-softening behavior. On the other hand, using fiber content greatly in excess of this critical value leads to not only high cost of material, but also creates difficulties in material processing. A fiber volume fraction at just above the critical value provides a composite optimal in performance, cost, and processability.

It is clear that a low critical fiber volume fraction is desirable. Since this parameter is associated with fiber and interface properties, micromechanics provides guidelines to tailoring the fiber and the interface to minimize the critical fiber volume fraction. **Figures 7 and 8** illustrate the dramatic effect of tailoring the interfacial bond on the tensile strain capacity. The tailor-

ing is implemented via control of the surface coating of the PVA fiber. For this hydrophilic fiber, the untreated fiber has a too high chemical and frictional bond with cementitious material. A surface coating content between 0.8 and 1.2% by weight of fibers tends to lower the interface chemical and frictional bond properties to a level that causes the critical fiber volume fraction to drop to a minimum of about 2% (Li et al. 2002b). **Figure 9** shows the influence of surface coating on protecting the fiber from damage during the pull-out process.

In the development of ECC, micromechanics serves multiple purposes:

(1) Micromechanics enables ISMD,
(2) It creates an analytic tool for composite optimization, making it feasible to achieve high perform-
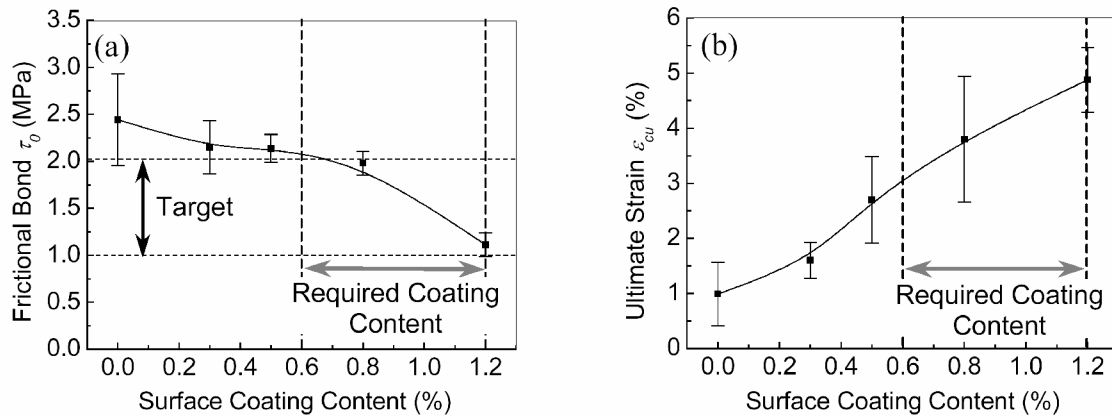
Fig. 7 Micromechanics determines an optimal range of frictional bond τ_0 of 1-2 MPa for the PVA KII fiber, to achieve strain-hardening with 2% fiber content (Li et al. 2002b). (a) Single fiber pull-out testing shows that this target range (vertical arrow) can be achieved with surface coating content between 0.6 and 1.2%, shown as the horizontal arrow, (b) Composite uniaxial tensile test confirms increase of tensile strain capacity from 1 to 5% when the surface coating content reaches 1.2%. The tailored fiber with proper surface coating is labeled REC15 by Kuraray Co. Ltd. The stress-strain curves for the composite with non-coated fibers and the composite with 1.2% coated fibers are shown in Figs. 8a and 8b.

ance and flexible processing at minimum fiber content, and

(3) It creates a systematic approach to materi-als tailoring, resulting for example, in the rapid development of the REC15 fiber.

For these reasons, ECC is not only a cementitious composite with high ductility performance; it is also an engineered material that embodies a micromechanics-based design concept.

4. Strength vs. ductility

The unique feature of ECC is its ultra high ductility.

This implies that structural failure by fracture is significantly less likely in comparison to normal concrete or FRC.

In traditional R/C structural design, the most common and most important material parameter of concrete is its compressive strength. For this reason, structural strength (and more generally, structural performance) is often perceived to be governed by material strength. This means that higher material strength (usually referred to compressive strength in the concrete literature) is expected to lead to higher structural strength. This concept is correct only if the material strength property truly governs the failure mode. However, if tensile fracture failure occurs, a high strength material does not neces-
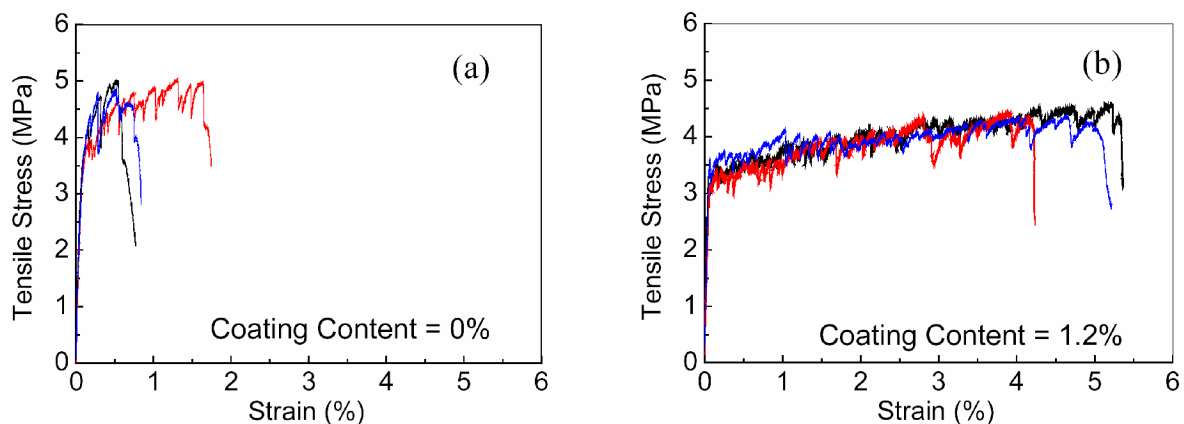

Fig. 8 (a) Excessive bond strength and severe fiber rupture limits the tensile strain capacity when PVA fiber is used untreated, (b) Significant tensile strain-hardening is revealed when the PVA fiber is properly coated with guidance from micromechanical models for interface property control.
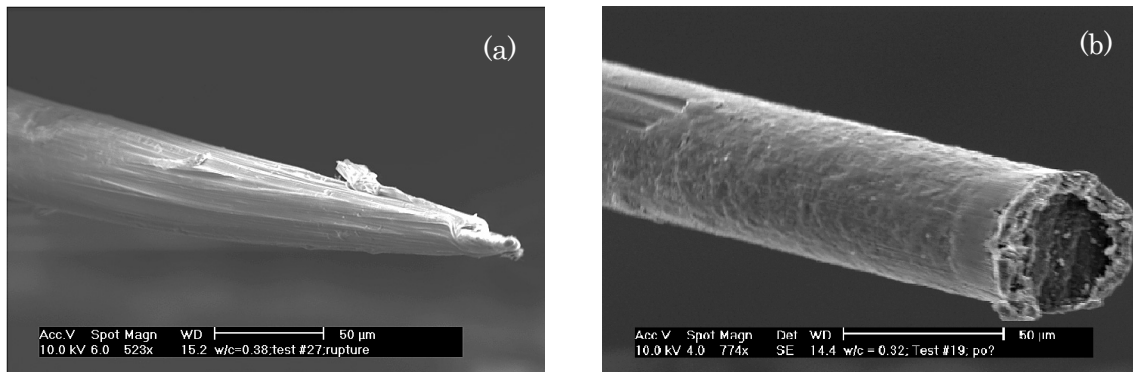
Fig. 9 Micrograph of fibers from composite fracture surface: (a) Untreated fiber experience damage by delamination during pull-out, (b) Fiber protected from damage when surface coated.

sarily mean higher structural strength. Rather, a high toughness material, and in the extreme, a ductile material like an ECC, can lead to a higher structural strength.

A number of recent experimental observations (Lim and Li 1997; Kanda et al. 1998; Kesner and Billington 2002) provide support for the above concept. For example, precast in-fill wall panels for seismic retrofitting of buildings have been studied experimentally and numerically. Fully reversed cyclic shear load tests (Kesner and Billington 2002) confirmed that a panel with a concrete of compressive strength of 50 MPa attained a structural strength of 38 kN, while a similar panel made with ECC material of lower compressive strength (41 MPa) achieved a higher structural strength of 56 kN. The over 35% structural strength gain in the R/ECC panel can be attributed to the material ductility of the ECC that maintained integrity of the panel to a larger drift level. Similarly, detailed numerical analysis (Kabele 2001) of a wall panel made with ECC demonstrated a structural strength three times larger than that of the panel made with FRC, despite the fact that both materials had the same tensile and compressive strengths.

5. Performance of R/ECC elements

Experimental and FEM investigations have revealed a number of unique behaviors of ECC in structural applications. These behaviors are expected to have direct impact on infrastructure safety, durability and construction productivity. When ECC replaces concrete in reinforced structures, we refer to these as R/ECC structures or R/ECC elements. Below we describe some general characteristics observed in R/ECC structural elements and broad targets of ECC applications.
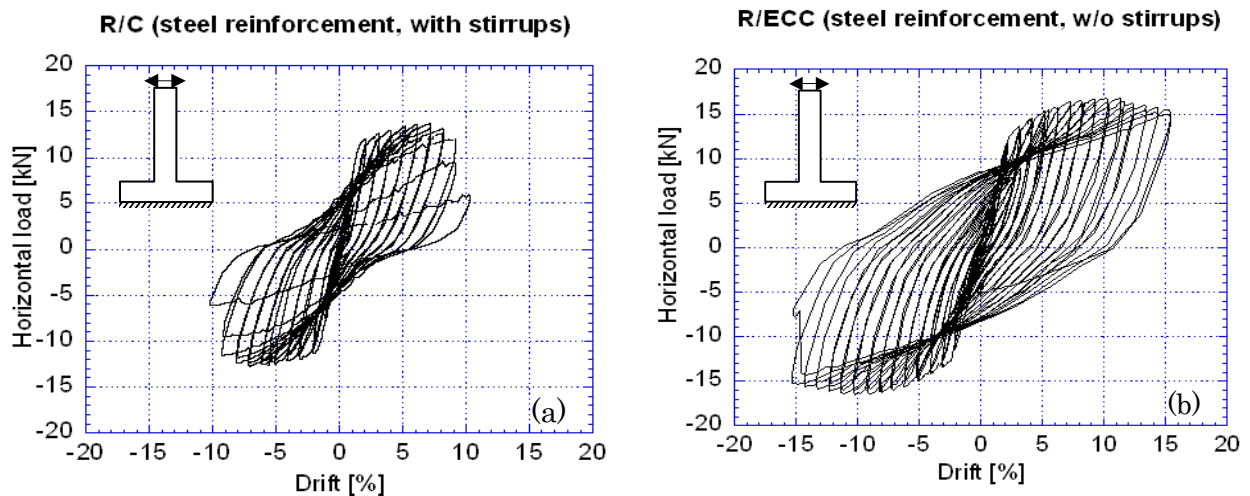

Fig. 10 Hysteresis loops of column members under fully reversed cyclic loading for (a) R/C, and (b) R/ECC without stirrups. Higher energy absorption, more stable hysteresis loop, and much lower damage (shown in Fig. 11) were observed in the R/ECC member, despite the total elimination of shear stirrups.

Fig. 11 Damage behavior of (a) R/C and (b) R/ECC without stirrups, shown at 10% drift. Even at this high drift level, no spalling of the ECC was observed. In contrast, the R/C column lost the concrete cover after bond splitting and spalling occurred.

5.1 General Characteristics of R/ECC structural behavior

Reduction or elimination of shear reinforcement: ECC has excellent shear capacity, as demonstrated by Ohno shear beam tests (Li et al. 1994). Under shear, ECC develops multiple cracking with cracks aligned normal to the principal tensile direction. Because the tensile behavior of ECC is ductile, the shear response is correspondingly ductile. As a result, R/ECC elements may need less or no conventional steel shear reinforcements. For example, test results of flexural members (Fischer and Li 2002b) subjected to cyclic loading confirm that the load carrying capacity and the energy absorption of R/ECC without shear stirrups exceed those of a standard R/C with stirrups (**Figs. 10** and **11**). Similarly, ECC beams without shear reinforcement demonstrate superior performance to HSC beams with closely spaced steel stirrups, suggesting that elimination of shear reinforcement is feasible when concrete matrix is replaced by ECC (Li and Wang 2002). Experiments on the cyclic response of unbonded post-tensioned precast columns with ECC hinge zones (Yoon and Billington 2002) and R/ECC columns (Fischer et al. 2002) also confirmed that the column integrity could be maintained better when concrete is replaced by ECC without any seismic shear detailing.

Sustaining large imposed deformation: With tensile strain-hardening and ultra high tensile strain capacity, ECC can sustain very large deformation without damage localization. This behavior can be utilized in a number of situations where the imposed deformation on a structure is expected to be high. As an example, ECC may be used in link-slabs that replace conventional joints in concrete decks. The ECC can then accommodate the

deck movements induced by shrinkage, temperature variation or creep. Zhang et al. (2002) demonstrated this idea by applying a strip of ECC sandwiched between concrete segments. Uniaxial tensile test of this arrangement (**Fig. 12**) confirms that large deformation (1.3% strain) can be imposed without causing any cracks in the concrete segments. All the deformation was absorbed by the ECC strip. Full scale test (Kim et al. 2003b) demonstrated that the ECC link-slab technology is feasible.

Compatible deformation between ECC and reinforcement: In R/ECC with steel reinforcement, both the steel and the ECC can be considered as elastic-plastic material capable of sustaining deformation up to several percent strain. As a result, the two materials remain compatible in deformation even as steel yields. Compatible deformation implies that there is no shear lag between the steel and the ECC, resulting in a very low level of shear stress at their interface. This phenomenon is unique in R/ECC. As a result of low interfacial stress between steel and ECC, the bond between ECC and reinforcement is not as critical as in normal R/C, since stress can be transmitted directly through the ECC (via bridging fibers) even after microcracking. In contrast, in R/C members, the stress must be transferred via the interface to the concrete away from the crack site. After concrete cracks in an R/C element, the concrete unloads elastically near the crack site, while the steel takes over the additional load shed by the concrete. This leads to incompatible deformation and high interface shear stress responsible for the commonly observed failure modes such as bond splitting and/or spalling of the concrete cover. The compatible deformation between ECC and reinforcement has been experimentally confirmed (Fischer and Li 2002a). **Figure 13** shows the contrasting behavior of R/ECC and R/C near the interface revealed
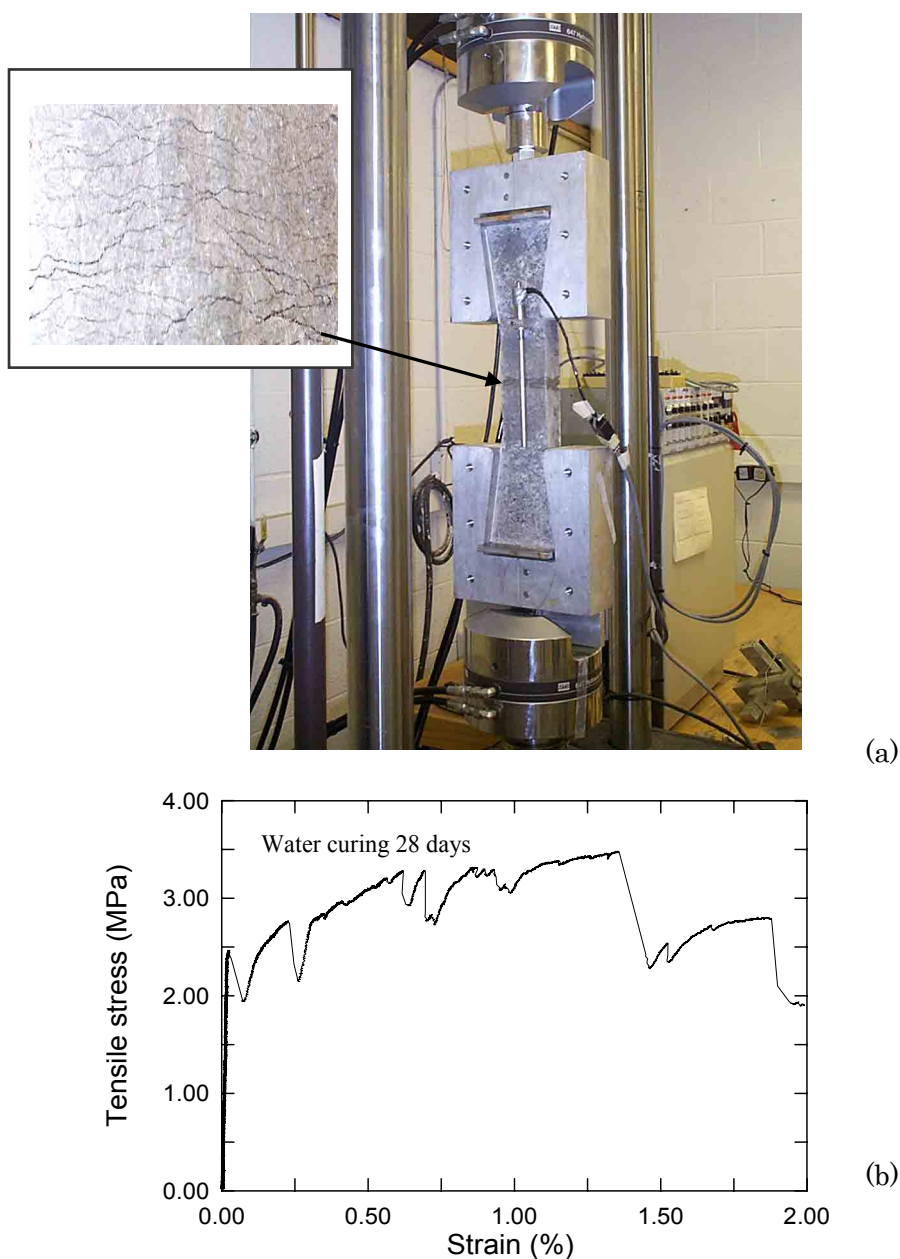
(a)

(b)

Fig. 12 Uniaxial tension test of regular concrete slabs with a strip of ECC material sandwiched in between. The large deformability of the ECC strip accommodates the imposed straining of the sandwich structure, and is reflected as micro-cracking in the insert of (a). The corresponding load–deformation curve is shown in (b). While overall strain capacity reached 1.3%, the concrete segments did not crack.

in a cross-sectional cut of tension-stiffening specimens.

Synergistic interaction with FRP reinforcement: The use of fiber reinforced plastic (FRP) reinforcement in R/C structural elements is often met with difficulty (Fukuyama et al. 1995) due to the premature failure of FRP after the brittle concrete cracks, especially under compression loads when the structure is subjected to reverse cyclic loading. Such failure of FRP is prevented in R/ECC (Fischer and Li 2003a) since the ECC does not form major fracture planes and continues to provide

a protective concrete cover even when strained to the inelastic stage. This phenomenon removes a major concern of using FRP as reinforcement, while allowing the exploitation of the unique properties of FRP in R/ECC structures, including the large elastic deformation range and corrosion resistance of FRP. In addition, extensive test results of R/ECC beams reinforced with FRP (Li and Wang 2002) revealed significant improvement in flexural performance in terms of ductility, load-carrying capacity, shear resistance and damage control (crack
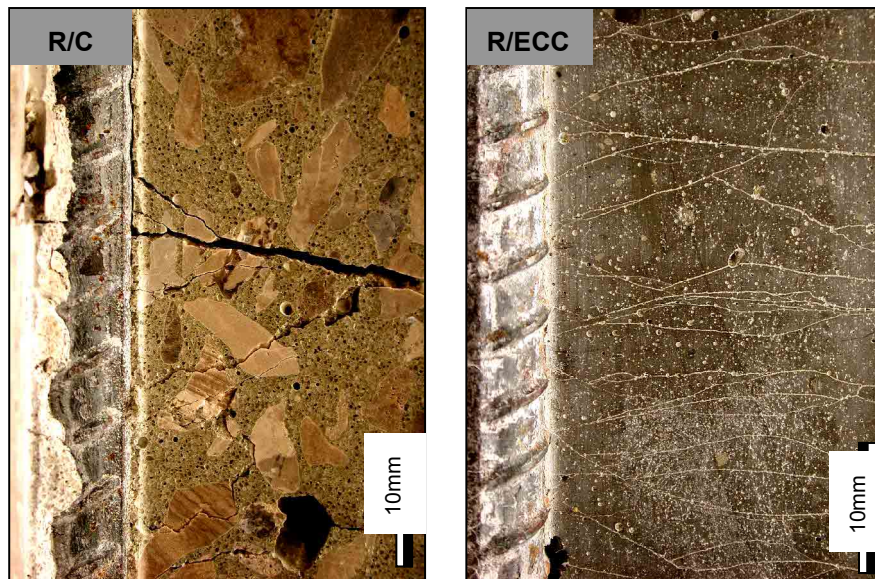
Fig. 13 Compatible deformation between ECC and steel reinforcement (right) showing microcracking in ECC with load transmitted via bridging fibers. In contrast, the brittle fracture of concrete in normal R/C (left) causes unloading of concrete, resulting in high interfacial shear and bond breakage.

width, spalling) compared with the counterpart high strength concrete (HSC) beam with the same reinforcement configurations.

High damage tolerance and reduction: Damage tolerance is a measure of the residue strength of a material or structure when damage is introduced. The damage tolerance of ECC has been investigated (Li 1997). Tensile loading of a specimen with deliberately introduced notches of different lengths demonstrated that ECC is remarkably notch insensitive. The high damage tolerance of ECC is reflected in the failure mode, e.g. under an indentation test (Kanda et al.1998), where the high stress concentration at the edge of the indent did not lead to fracture failure. Indeed, the high damage tolerance of ECC makes this material highly suitable for use in structural elements where high stress concentration is difficult to avoid. As an example, the interaction of the steel beam with an R/C column in a beam-column connection test (Parra-Montesinos and Wight 2000) leads to high stress concentration where the steel flange bears on the concrete material when the assembly was subjected to repeated cyclic loading. No fracture failure was observed when ECC was used, despite deliberate removal of all shear stirrups. In contrast, severe spalling results in the case of conventional concrete (**Fig. 14**).

Under fully reversed cyclic loading, a set of orthogonal cracks is formed. In R/ECC specimens of different geometries tested (Fukuyama et al. 1999; Parra Montesinos and Wight 2000; Yoon and Billington 2002; Fischer and Li 2003a,b; Kanda et al. 1998; Kesner et al. 2002), these orthogonal cracks do not lead to surface spalling as often observed in R/C specimens after large load reversals, resulting in significant reduction in damage.

Tight crack width control: When an ECC structural element is loaded (flexure or shear) to beyond the elastic range, the inelastic deformation is associated with microcracking with continued load carrying capacity across these cracks. The microcrack width is dependent on the type of fiber and interface properties. However, it is generally less than 100 micron when PVA fiber is used. **Figure 15** shows the crack width development as a function of tensile strain in a uniaxial tension specimen. The crack width first increases, but reaches a more or less steady state value beyond about 1% strain. For this specimen using 2% of REC15 fiber with 0.8% surface coating content, the crack width stabilizes at about 80 micron. The tight crack width in ECC has advantageous implications on structural durability (more below), and on the minimization of repair needs subsequent to severe loading of an ECC member.

5.2 Classes of Target Applications
The observed characteristics of R/ECC structural elements described above suggest at least three broad classes of target applications. These include structures requiring collapse resistance under severe mechanical loading, and structures requiring durability even when subjected to harsh environmental loading. Finally, ECC is expected to support enhanced construction productivity.

Safe infrastructure subjected to severe mechanical loading: The most investigated group of structures in this category is seismic resistant structural members tested under fully reversed cyclic loading. Investigations have been carried out in beam elements (Fukuyama et al. 1999; Kanda et al. 1998), in column members (Fischer et al. 2002), in hybrid steel beam-concrete column con-

nections (Parra-Montesinos and Wight 2000), in ECC smart frames which self-center subsequent to seismic loading (Fischer and Li 2003b), in precast infill retrofit of open frame walls (Kanda et al. 1998; Kesner and Billington 2002; Horii et al. 1998), in precast segmental concrete bridge pier systems (Yoon and Billington 2002), and in damping elements (Fukuyama et al. 2002), amongst others. These studies demonstrate superior seismic resistant response as well as minimum post-earthquake repair requirements when R/ECC is used in place of R/C.

While it may be intuitively appealing to associate observed high energy absorption of R/ECC members under cyclic loading directly with the material ductility of ECC, the real situation is more intricate than this. Fischer and Li (2002a) showed that the high energy absorption in R/ECC members derived from the extended use of the steel reinforcement both in the sense of a longer segment of the reinforcement undergoing plastic yielding in tension and compression and in the sense of more stable hysteretic loops. These phenomena are directly related to the compatible deformation between steel and ECC as described in the previous subsection.

Durable infrastructure subjected to severe environmental loading: The most investigated applications in this category belong to repair of infrastructures using ECC. These include planned repairs of a dam (Japan), the underdeck of a bridge (Japan), a sewage line (Korea),

tunnel linings (Switzerland) and concrete bridge decks (US).

There are a number of characteristics of ECC that make it attractive as a repair material. ECC can eliminate premature delamination or surface spalling in an ECC/concrete repaired system (Lim and Li 1997). Interface defects can be absorbed into the ECC layer, and arrested without forming spalls, thus extending the service life. Suthiwarapirak et al. (2002) showed that ECC has fatigue resistance significantly higher than that of commonly used repair materials such as polymer mortar. ECC also has good freeze-thaw resistance and restrained shrinkage crack control (Li et al. 2002a).

There is increasing evidence that a crack width of 100 micron represents a threshold above which water flow through cracks becomes appreciable (Tsukamoto 1990; Wang et al. 1997; Lawler et al. 2002). Since the crack width of ECC can be kept below this limit (**Fig. 15**), it is likely that ECC would serve as an excellent "concrete-cover" in R/ECC structures. The low transport rate of aggressive agents through ECC may delay steel corrosion leading to extended service life in, e.g. structures in coastal regions. Further research is needed to directly confirm this expectation.

Infrastructure construction productivity: ECC may lead to enhanced construction productivity in several ways. The most direct means is by elimination of labor-intensive installation of shear reinforcing bars in
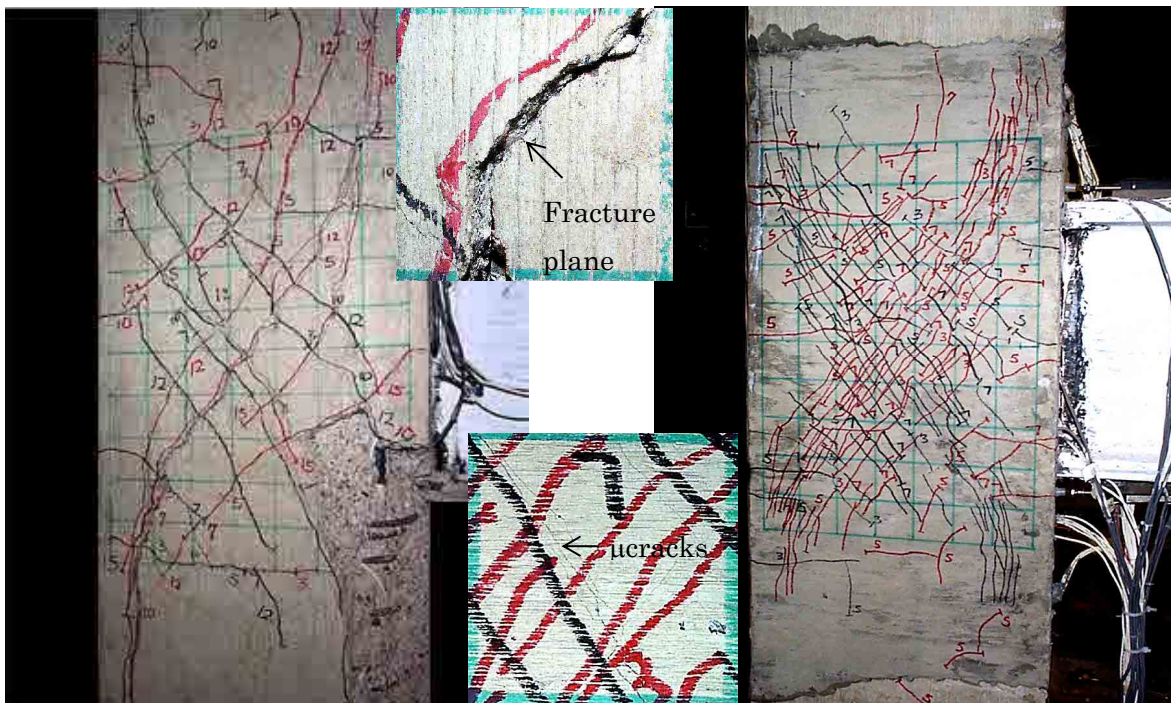

Fig. 14 The damage behavior of the shear panel of a hybrid connection after cyclic loading (Parra-Montesinos and Wight 2000). The R/C column (left) shows severe spalling of the concrete where the beam bears on it. Fracture planes with large crack width are shown in insert. In contrast, the R/ECC column (right) shows no spalling. The microcracks with small crack widths are shown in insert.
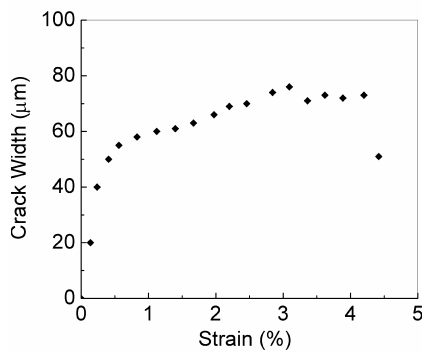
Fig. 15 Crack width development in a ECC with 2% REC15 fibers. The crack width increases after first crack strain is reached, then increases very slowly to about 80 micron after approximately 1% strain. Continued deformation of the specimen is accommodated by additional microcracks without significant increase in crack width.

seismic structures. As discussed earlier, the high shear capacity of ECC decreases or even eliminates the need for shear reinforcement.

The flexible processing routes of ECC also lend themselves to efficient methods of application of ECC in construction sites or in precast plants. For example, for many repair applications, or in tunnel lining construction, the use of spray processing can speed up the construction process. Similarly, extrusion of ECC can provide a continuous method of manufacturing high quality ECC products with low waste (Stang and Li 1999; Takashima et al. 2003). Self-compacting ECC lends itself to challenging construction conditions, including where horizontal formwork or "concrete" filled tubes are utilized, with potentially significant reduction in labor requirements.

6. Cost of ECC

The additional cost of ECC over normal concrete derives mostly from the use of fibers and higher cement content. This is the reason why optimization of the composite to minimize the fiber content is so important, as pointed out in Section 2 above. In comparison to steel fibers used in many FRCs, polymer fibers such as PVA may be more expensive on a unit weight basis. However, it should be noted that polymer fibers have density six to seven times lower than that of steel, and it is the volume content of fibers and not the weight content which governs the performance of the cementitious composite. Partial substitution of cement with industrial by-products such as flyash should further reduce the cost of ECC, although the resulting change in interface and matrix properties and their effects on composite strain capacity should be carefully examined. Finally, the cost of ECC in comparison to other high performance construction material such as polymer mortar currently in use for repair of infrastructure can be much lower.

Ultimately, the economics of ECC should be based on cost/benefit analyses. The potential benefits of using ECC have been discussed in the previous sections. The life cycle cost of a structure includes not only the initial material cost, but also the construction cost (labor and speed) and maintenance cost. By reducing or eliminating shear reinforcement, there will be cost advantages in constructing infrastructure with ECC material, associated with the reduction of steel as well as reduction of on-site labor, while speeding up the construction process. The durability of ECC and ECC structures should extend the service life of infrastructures while reducing maintenance cost.

A full analysis should take into account social and environmental cost and benefits of using ECC. Such
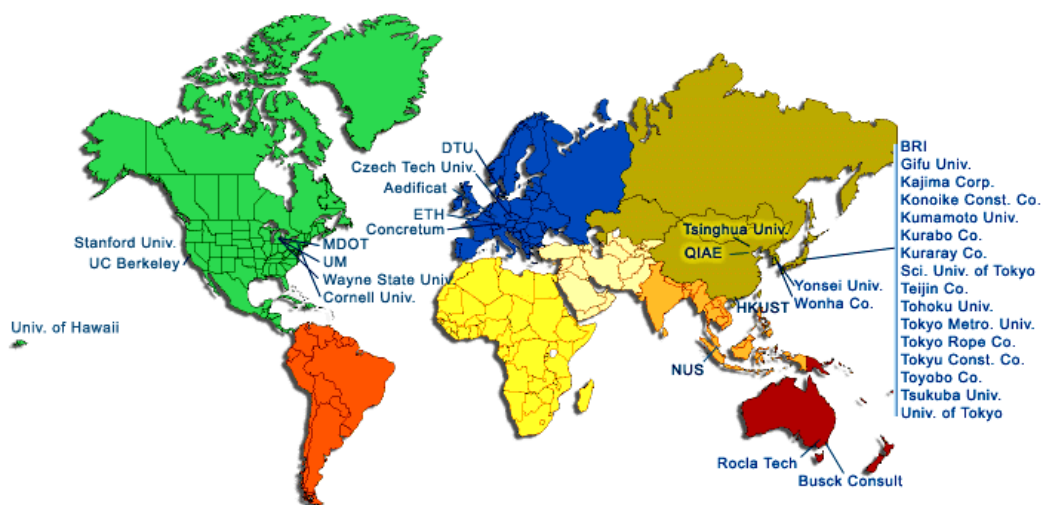

Fig. 16 The ECC Technology Network. Members include academic, industrial and governmental organizations. They conduct research, development and commercialization of ECC technologies.

life-cycle assessment has important ramifications in the broad adoption of ECC and in the sustainable development of this material (Li et al, 2004).

7. The ECC technology network

ECC is a relatively new material emerging from laboratory to precast plants and construction sites. The material continues to evolve, and new material characteristics continue to be uncovered. More and more applications are being found for ECC. There is a need to exchange evolving information between academic, industrial and governmental concerns. For this reason, the ECC Technology Network was established in 2001.

The ECC Technology Network is an informal organization composed of members that are interested in developing and promoting ECC technology. A web site hosted by the University of Michigan at www.engineeredcomposites.com provides an international platform for sharing news and knowledge of ECC materials and application technologies. There is no cost to joining this organization, just a commitment to further advance ECC. Current members are indicated in **Fig. 16**.

8. Future outlook and conclusions

While rapid progress has been made in ECC technological development over the last decade, it may be expected that the coming decade will be even more exciting. As research advances, we will continue to discover more favorable characteristics of ECC that lend themselves to new infrastructure applications. It may be envisioned that a new generation of ECC material embodying the advantages of both steel (ductility) and concrete will be developed. These new materials will be
- designable for achieving targeted structural performance levels
- sustainable with respect to social, economic and environmental dimensions
- self-healing when damaged
- functional to meet requirements beyond structural capacity

Associated with this material, a new generation of infrastructure systems that have one or more of these characteristics will emerge:
- safe with minimum repair needs even after subjected to severe loading conditions
- smart with self-adapting ability
- mega-scale but without size-effect drawback
- zero-maintenance even when exposed to severe environment
- constructable at high speed and with low waste

Meanwhile, attention is needed in the following R&D areas:

(1) Standardized mix design: Improved versions of ECC will continue to evolve for some time. While this is a natural consequence of research, the user community may benefit from a "reference" standard mix. Consideration of cost and ingredient material availability should be taken into account to establish this standard mix. These considerations are as important as those for ECC performance and material processability. The standard mix can provide a baseline for property assurance.

(2) Pre-mix ECC: It is not reasonable to expect the user community to conduct micromechanics calculations to create suitable mix composition. Apart from standardized mix design, another step towards user-friendliness is to create pre-mix ECC with specific but simple instructions of applications.

(3) Basic material supply: The construction industry is a high volume but also highly cost-sensitive industry. Widely available material supply at competitive pricing is important to the ECC user community. Micromechanics remains to be a central tool for tailoring fiber and matrix materials suitable for ECC applications.

(4) Material performance specifications: For structural designers, there should be a minimum material performance specifications for ECC so that structures designed with ECC would behave as expected. The fundamental material performance specification may be based on tensile strain capacity, tensile strength and the presence of multiple cracking.

(5) Standardized test methods: An increasingly complete material database is being established for the properties of ECC under various mechanical loading, including tension (Li 1998; Li et al. 2001), compression (Li 1998), shear (Li et al. 1994), cyclic loading (Fukuyama et al. 1999; Kesner et al. 2002), fatigue (Suthiwarapirak et al. 2002), creep (Billington and Rouse 2003) and fracture (Li and Hashida 2003). The responses of ECC to environmental loading such as drying shrinkage (Weimann and Li, 2003), freeze-thaw cycles (Lepech et al. 2003), hot and humid weather cycles (Li et al. 2003), are being documented. There is a need to develop standardized test methods, particularly for the fundamental uniaxial tensile stress-strain curve, for ease of comparisons of ECC materials. Careful examination of the potential influence of specimen size and geometry on the measured material properties should be included.

(6) Numerical tools: Robust numerical tools are needed for simulation of structural systems containing ECC materials. Constitutive models capable of capturing the essence of ECC behavior under complex stress-states embedded into industrial strength FEM codes should help structural designers take full advantage of ECC material in infrastructure system design.

(7) Consolidation of knowledge in specific application fields: Broad categories of ECC applications, such as seismic applications, or repair and retrofitting, are emerging, as described in Section 5. Valuable knowledge is being accumulated. They should be periodically consolidated and shared, in order to further advance each application field.

(8) Sustainable development: As an emerging infrastructure construction material, ECC is in an excellent position to embrace sustainable development of infrastructures. Both the cement (Battelle Memorial Institute 2002) and concrete (Mehta 2002) industries are moving in this direction. Sustainable development addresses sustainability indices of social, economic and environmental. The gain in performance (safety, durability, and construction productivity) must be balanced with the ecological impacts of raw material ingredients usage. Adoption of suitable recycled material, including flyash and waste fibers, should be considered. Detailed life-cycle assessment of ECC should be conducted.

(9) Structural innovations: ECC can be viewed as a ductile metal-like material on the macroscopic scale, with an essentially bi-linear tensile stress-strain curve. The significant difference from the property of normal concrete makes designing structures with ECC more challenging as traditional design guidelines for R/C may not be adequate (and probably too conservative). Innovative structural design concepts are needed to fully exploit the unique behavior of ECC. As an example, Fischer and Li (2003b) developed an auto-adaptive frame which took advantage of the distinct behaviors of R/ECC with steel and R/ECC with FRP reinforcements, allowing the frame to automatically switch to a lower stiffness at large drift level to limit the force acting on the frame, while providing a self-centering characteristic after earthquake loading.

(10) Integrated Structures and Materials Design: As described in connection with **Fig. 6**, the micromechanics theory behind the design of ECC enables the vertical integration of structural and materials design.   Examples of this two-way feedback are being created (e.g. Kim et al. 2003b). Research is needed to further demonstrate and elucidate the feasibility and advantages of this new approach.

ECC has enjoyed broad based support from developers and users, material suppliers and construction/design companies, and academic research groups and commercial enterprises. There are a variety of social needs that create an exciting environment for continued ECC developments. These include greater infrastructure security (against both man-made and natural hazards) and sustainability and the continuing movement towards performance based design. Together, the ECC technology community can contribute to improving the quality of life in our modern society through innovations in materials and structures technologies.

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