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REVIEW

FROM MICROMECHANICS TO STRUCTURAL ENGINEERING —THE DESIGN OF CEMENTITIOUS COMPOSITES FOR CIVIL ENGINEERING APPLICATIONS

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ABSTRACT

This paper reviews the development of pseudo strain-hardening cement based short fiber composites employing the Performance Driven Design Approach. The micromechanics theory behind the design concept is reviewed, and the unique mechanical properties of the resulting composite are summarized. The translation of material properties to structural properties is demonstrated with the structural response of the Ohno shear beam.

INTRODUCTION

The field of structural engineering and the field of micromechanics appear far and wide apart. Recent developments, however, point to a common ground——Materials. Advanced Civil Engineering materials are being developed with the help of micromechanics. And advanced materials are increasingly recognized as an enabling technology for the building and construction industries[1]. A new breed of engineers is needed to exploit the merits of this interdisciplinary field of materials design for structural applications.

This paper surveys the experience of such a research/education program at the University of Michigan. It reviews the framework of the interconnections between structural performance, materials properties, microstructures and materials processing, applied specifically to cementitious composites to be used in shear intensive load bearing structures. The concept of micromechanics deployed for materials development is emphasized, and the resulting advantages in structural performance improvements are highlighted.

PERFORMANCE DRIVEN DESIGN AND THE ACE-MRL

The Performance Driven Design Approach (PDDA)[2] is based fundamentally on the paradigm of materials development as proposed by the United States National Research Council[3]. This paradigm emphasizes the interrelationships between performance-(material) structure-property-processing (**Fig.1**). Note the role of micromechanics as a quantitative link between material structure and mechanical properties.

Structural performance has usually been the domain of the structural engineer, who traditionally has been trained to build the best structures using given materials. For this reason, his/her connection to materials is mostly through materials property testing or property table look-up. The traditional material scientists are mostly concerned with the relationship between processing and formation of microstructures, and the traditional materials engineer can be said to be most interested in the resulting property of the material as influenced by processing. The interrelationship between microstructures and properties engages the applied mechanicians.

The paradigm in **Fig.1** suggests that the materials scientists and engineers, the applied mechanicians and the structural engineers should all work together. Unfortunately this is usually not the case, especially with regard to materials used for the building and construction industries. In fact, building and construction materials, which may be characterized as high volume low cost materials, do not normally attract the attention of the materials scientist and engineers. As a result, the building and construction industries are, in general, well behind many other industries in the development

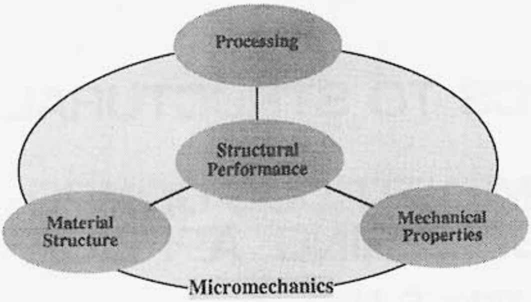

Fig.1 Paradigm of Materials Development.

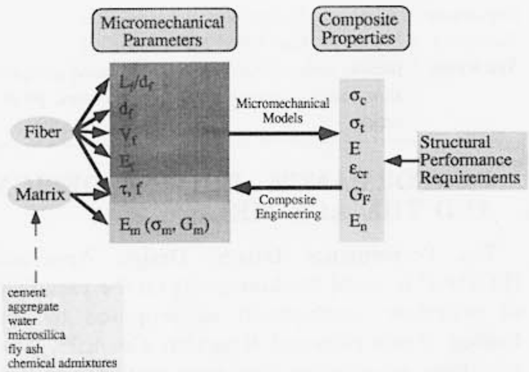

Fig.2 The Performance Driven Design Approach for Engineered Cementitious Composites.

and application of new materials. (Other reasons cited for this technological lag has been industry fragmentation, litigation sensitivity, and code). Because of this gap, and because of the need to address increasingly urgent infrastructure issues faced by modern societies, the University of Michigan has formed the Advanced Civil Engineering Materials Research Laboratory (ACE-MRL) with a mission of advancing materials development for use in the building and construction industries. The ACE-MRL combines the talents of a team of material scientist and engineers, applied mechanicians, and structural engineers and has so far focused on fiber reinforced cementitious composites (FRCC). Structural applications under investigations or planned to be studied include earthquake resistant beam-column connections, continuous pavements, bridge decks, anchor bolts and wall panels. Each of these applications are chosen because of performance problems experienced in the field.

The PDDA applied to FRCC is illustrated in **Fig.2**. Micromechanics provides the important link between material structures and composite properties. This link represents quantification of the influence of material structure on macroscopic behavior by accounting for important features of micromechanisms of deformation. For cementitious composites in which the matrix is brittle, extension of microcracks, and fiber/matrix interaction represent some of the most dominant deformation micromechanisms. Micromechanics creates the possibility of predicting the properties of a composite for a given material structure, and also provides guidance to composite microstructure optimization.

In a FRCC, the material microstructures can be characterized by measurable parameters related to the cementitious matrix (modulus, porosity, flaw density and size distribution, fracture property), the fiber (modulus, strength, bundle sizes, length, diameter, shape), and the interface (bond mechanisms and properties, and snubbing coefficient). These parameters are influenced by the choice of constituent materials, such as cement type, additives, aggregates, fiber types and volume fraction, and by method of processing. Conventional processing involves mixing and casting, and autoclaving. Nowadays a variety of processing tools are available. These include the control of vacuum and temperature during mixing, vibration frequency during casting, addition of chemical admixtures for rheological control, for packing density control, for shrinkage control and others, and microwaving, temperature and/or pressure application during curing. Some of these processing aids are targeted at the control of the cementitious matrix properties, but may also affect or actually targeted at the fiber/matrix interaction level. A clear understanding of the influence of processing parameters on the microstructures and the resulting micromechanisms of deformation is important in materials engineering.

For a given structure or structural component, functional performance (load capacity, durability, seismic resistance, for example) can be specified. Once the performance requirements are translated into material properties (tensile and compressive strength, ultimate strain, modulus, fracture energy, fatigue crack growth resistance, allowable crack width, etc.), the micromechanics models serve as an analytic tool for material structure selection. On one level, material structure selection involves the choice of fiber type and dimensions or the choice of cement and aggregate types. On a more sophisticated level, processing techniques for tailoring the fiber/matrix interaction, or tailoring the defect density and sizes to desired magnitudes must be employed. The PDDA therefore serves as a framework to direct the focus of processing, material microstructures, and properties onto meeting specified structural performance.

It should be emphasized from the outset that the technological implication of the PDDA is not just in boosting structural performance, but that PDDA can lead to economy by optimizing the material microstructure and thus using materials most efficiently. On the other hand, the PDDA even when applied narrowly to cementitious composites, reveals many technological and scientific gaps which must be filled for such an approach to be successful. These knowledge gaps involving materials processing, micromechanics, and the translation of material properties to structural performance, represent critical challenges to the research community in the coming decades. They define the research agenda of the ACE-MRL.

SHEAR INTENSIVE STRUCTURES

Engineers have long recognized that concrete must be reinforced when used as a material for large scale structures. For example, a beam under bending load maintains its ductility by yielding of the reinforcing steel. However, it soon becomes obvious that such reinforced concrete members can also fail in shear, and that shear failure can be catastrophic. A case in point is the punching failure of bridge decks[4]. In addition, shear failure has occurred in anchor bolts embedded in concrete[5], in corbels[6], and in shear keys of segmental bridges[7]. The connection between beam-columns and the base of shear walls are also likely to be subjected to intensive shear during earthquake loading. The typical diagonal crack patterns in the shear failed structures suggest that the structural shear load induces local tensile failure of the material. This means that the shear capacity of concrete structures is limited by the tensile capacity of the concrete material. For large structures, especially those with acute geometry such as in a shear key, the local tensile failure may occur in the form of fracture. For this reason, extensive research in fracture mechanics of concrete structures has been conducted, e.g. in fracture analysis of anchor bolt failure[5]. For smaller structures, shear failure may be controlled by the tensile strength or strain rather than by fracture properties. This is the well known size effect —— transition of failure mode from strength control to fracture control as the concrete structure increases in dimension[8].

To design against shear failure, additional shear reinforcement has been applied. Even if steel reinforcement is possible and/or rebar congestion is allowed, concrete cracks induced by shear load can be quite large in width, reducing long term structural durability.

The above discussion suggests that for improved structural performance in safety and durability, it would be necessary to design structures subjected to intensive shear loads with a material which has enhanced properties in tensile strength, strain and fracture energy. Unfortunately ordinary concrete cannot meet any of these criteria. High strength concrete can reach higher tensile and compressive strength, but their strain capacity and fracture energy remains low. The added propensity in brittle fracture failure therefore requires additional steel rebar reinforcement or steel confinement. For ordinary fiber reinforced concrete (FRC) commonly used, the fracture energy can be enhanced by an order of magnitude, but the tensile strength or strain are typically not much improved. We are therefore forced to look at strain-hardened cementitious composites, since strain-hardening typically brings about additional tensile strength and strain capacities beyond those achievable by FRC. Strain-hardened cementitious composites have been created by a variety of processes such as pultrusion or fiber mat lay-up using continuous fibers[9),10]. Although such materials have shown superior properties, their applications to practical structures are rather limited because of the special processing needs and the expensive labor involved. A different approach using short random fibers has also achieved high tensile strength capacity (although the uniaxial tensile strain capacity and fracture energy has not be clearly measured) in a slurry infiltrated fiber concrete (SIFCON). SIFCON as its name suggests employs a process in which a steel fiber network is infiltrated by cement or mortar slurry. To create the steel fiber network and to achieve good properties, it is typical to use a high fiber volume fraction, from 4 to 25%[11].

For new materials development for civil engineering and building applications, it would be useful to keep in mind the following requirements: 1) Tensile properties much above FRC; 2) Easy processing using as much as possible conventional equipment and low labor cost; 3) Low fiber volume fraction;and 4) No material anisotropically weak planes. These requirements seem to be contradictory. However, micromechanical analyses reveal that composites meeting such requirements can be manufactured. In the following sections, we discuss the micromechanics-based rational for material constituent selections, the tensile properties of such an engineered cementitious composite (ECC), and its application to a simulated shear structure. Comparisons with conventional concrete and shear reinforced (using wire mesh) concrete confirm the advantages expected of ECCs.

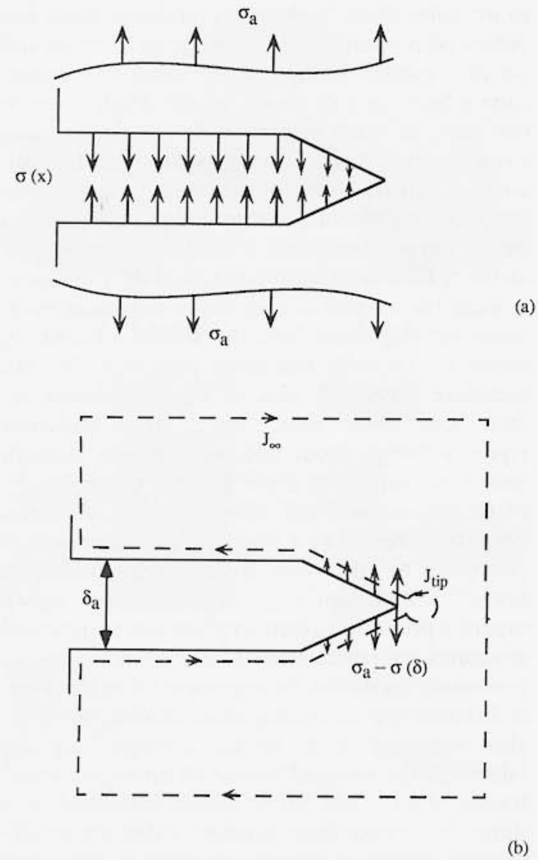

Fig.3 Steady State Cracking (a) Showing Remote Stress, Crack Shape and Traction on Crack; and (b) J-integral Contour on Equivalent Problem (after Marshall and Cox, 1988).

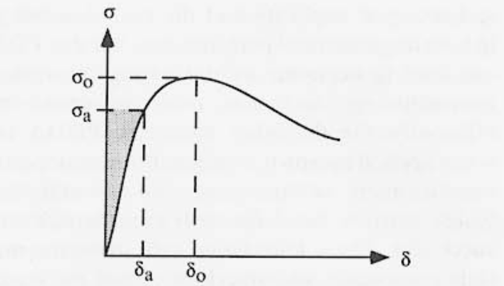

Fig.4 A typical $\sigma-\delta$ Curve of a Discontinuous Fiber Reinforced Cementitious Composites. The shaded area represents the complementary energy. See Eqn. (1) and related text.

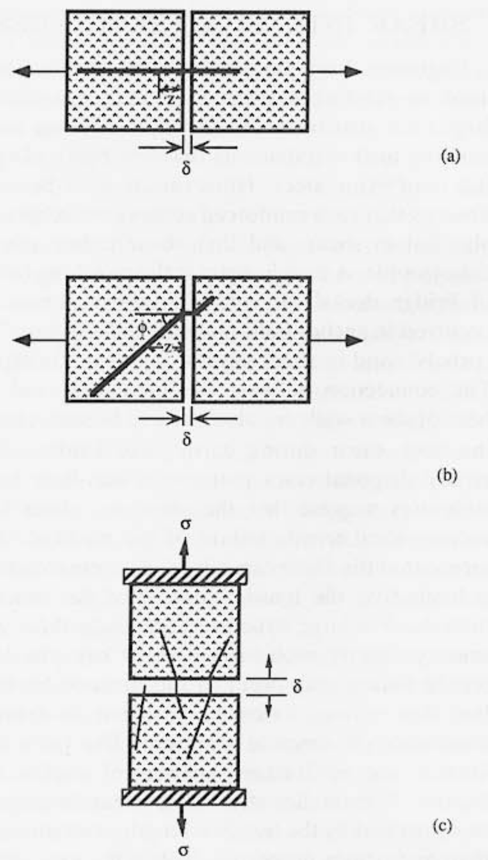

Fig.5 Three Essential Steps in Deriving the $\sigma-\delta$ Relation for Short Random Fiber Reinforced Cementitious Composites (a) Single Fiber Normal Pull-Out. The fiber bridging stress is $\sigma_s(\delta, z)$; (b) Inclined Fiber Pull-Out. The fiber bridging stress is $\sigma_s(\delta, z, \phi)$; (c) Statistical Description of Fiber Distribution.

MICROMECHANICS AND MATERIAL CONSTITUENT SELECTION

Steady State Cracking Analysis

Conditions for pseudo strain-hardening has been reviewed by Li and Wu[12]. In that work, the stress approach was utilized resulting in a more conservative requirement due to the assumption of an elliptical crack shape. In the following, we adopt an energy approach suggested by Marshall and Cox[13] and which does not need to impose any crack shape assumptions. A fundamental requirement of pseudo strain-hardening is that steady state cracking occurs. **Fig.3**(a) shows such a crack propagating under uniform and constant remote tension σ_a. The crack opening is uniform with fiber bridging stress balancing the remote load except for a segment near the crack tip. In this segment the crack opens as the bridging stress rises from zero at the tip to σ_a when this segment joins with the flattened crack segment. The crack opening δ at each point along the crack is directly related to the bridging stress σ as dictated by the details of fiber reinforcement. By making use of the path independent property of the J-integral[14], and after subtracting a uniform stress of σ_a, Marshall and Cox shows that during steady state cracking,

$$J_{tip}=\sigma_a\delta_a-\int_0^{\delta_a}\sigma(\delta)\,d\delta \quad (1)$$

for the contour shown in **Fig.3**(b). The right hand side of (1) is interpretable as the complementary energy of the $\sigma-\delta$ curve as indicated by the shaded area in **Fig.4**. For pseudo strain-hardening, it is required that[15]

$$\sigma_a\leq\sigma_0 \quad (2)$$

where σ_0 is the maximum bridging stress corresponding to the maximum opening δ_0 in Figure 4. Hence pseudo strain hardening requires

$$J_{tip}\leq\sigma_0\delta_0-\int_0^{\delta_0}\sigma(\delta)\,d\delta \quad (3)$$

Micromechanics of Normal Fiber Bridging

The micromechanics of fiber bridging has been described by Li[16] for discontinuous fibers of arbitrary randomness. **Fig.5** illustrates the three essential steps in deriving the $\sigma(\delta)$ relationship. First the mechanics of a single fiber bridging normally to the crack plane (**Fig.5**(a)) must be analyzed. Various assumptions concerning the interface properties and mode of failure can be adopted[17]. Also, depending on the type of fiber, the bridging stress may be terminated by tensile rupture of the fiber[18]. Although there has been a number of theoretical investigations[19)-21] into fracture mode failure of the interface in the form of a tunneling crack, there has been so far no confirmation that such is the case in a fiber reinforced cementitious composite. Shear-lag analysis[19] is typically utilized to relate the single fiber bridging stress σ_s to the crack opening δ:

$$\sigma_s(\delta,z) = fnc\,(\delta, z;\text{fiber properties; interface properties}) \quad (4)$$

where the fiber properties may include the fiber modulus, tensile strength, fiber length, and diameter, and the interface properties may include the cohesive strength or fracture properties and frictional properties. The variable z represents the initial distance (at $\delta=0$) between the centroid of the bridging fiber and the matrix crack plane. Hence the embeddment length can be calculated from z and δ as the crack opens. Accounting for Poisson's effect of the stretched fiber and residual strain effect has been attempted[22),23]. If the fiber is crimped, deformed or with hooked ends, detail accounting of the fiber shape effect on σ_s or an effective interface property should be included in (4).

Micromechanics of Inclined Fiber Bridging

In a composite, fibers often bridge at an angle to the matrix crack. The bridging stress of an inclined fiber (**Fig.5**(b)) has been analyzed for various assumptions of fiber and matrix behavior. For very flexible fibers with high strain capacity typical of polymeric fibers, a snubbing effect may occur due to the local fiber pressure exerted onto the matrix at the fiber exit point[24]. The snubbing effect may reduce the critical fiber length leading to premature fiber failure[25]. For fibers with elastic-plastic behavior typical of steel fibers, local plastic yielding of the fiber at the exit point may occur[26]. For fibers with elastic brittle behavior such as some carbon or glass fibers, fiber failure may occur due to excessive bending[27]. In addition, local spalling of the brittle matrix under the fiber has been observed[24]. This spalling has the effect of relaxing the fiber bridging load. All of these fiber/matrix interactions due to inclined fiber pull-out will alter the bridging stress so that (4) becomes

$$\sigma_s(\delta,\phi,z) = fnc\begin{pmatrix}\delta,\phi,z;\text{fiber properties; interface properties;}\\ \text{local fiber/matrix interaction properties}\end{pmatrix} \quad (5)$$

where ϕ is the inclination angle of the fiber to the matrix crack plane. It should be noted that aging effects can be introduced into (5) by recognizing that the interfacial properties and the fiber/matrix interaction properties change with age. For example Li and Chan[28] observed that interfacial friction bond strength improve with age in a manner similar to that of cement hydration for a steel fiber in a cement matrix. Age effects were also studied by Katz and Bentur[29] in relation to modulus of rupture measurements for carbon fiber reinforced cement composites. They observed that the modulus of rupture first increases and then decreases with age, suggesting that higher amount of fiber breakage occurs either due to increase bond or due to bending of fibers on a stiffer foundation.

Fiber Volume Fraction and Distribution

Finally, the finite length and the random orientation of the fibers dictate the amount of bridging fibers carrying load across the matrix crack (**Fig.5**(c)). These effects are described by probability density functions $p(z)$ and $p(\phi)$. The volume fraction of fibers with centroid located between z and $z+dz$, and with inclination angle between ϕ and $\phi+d\phi$ will be given by $V_f p(\phi)p(z)\,dz d\phi$, where V_f is the total fiber volume fraction in the composite.

Composite $\sigma-\delta$ Relation

The combined mechanistic effect of fiber bridging and the statistical effect of fiber distribution must be brought together to represent the composite $\sigma(\delta)$ relationship[16]:

$$\sigma(\delta) = V_f \int_{\phi=0}^{\pi/2} \int_{z=0}^{(L_f/2)\cos\phi} \sigma_s(\delta, \phi, z) p(\phi) p(z)\, dz d\phi \quad \cdots\cdots (6)$$

The upper integration limit on z ensures the counting of only those fibers which actually bridge the crack. Fibers far from the crack plane or close but lying at an oblique angle so that they do not actually cross the crack are therefore not included in the bridging action of the composite. The integration limits should be modified when fibers fail and stop contributing to the composite bridging stress[25]. Once σ_s, $p(\phi)$, and $p(z)$ are determined, eqn. (6) can be used to determine the composite $\sigma(\delta)$. For steel and brass fibers in a cementitious composite, Li and Chan[27] determined that the failure is controlled by a simple frictional strength τ. Further it appears that a snubbing effect representing a flexible rope passing over a friction pulley works reasonably well[16,24] for steel and polymeric fibers. These considerations lead to a simple form of σ_s:

$$\sigma_s(\delta, \phi, z) = \begin{cases} [4\tau(1+\eta)E_f\delta/d_f]^{1/2} e^{f\phi} & \text{for } 0 \le \delta \le \delta_p \\ [4\tau(\ell+\delta_p-\delta)/d_f] e^{f\phi} & \text{for } \delta_p \le \delta \le \ell \\ 0 & \text{for } \ell \le \delta \end{cases} \quad \cdots\cdots (7)$$

where $\eta = (V_f E_f)/(V_m E_m)$, and $\ell = L_f/2 - z/\cos\phi$ is the embeddment length of a fiber located at z and with an inclination angle ϕ (**Fig.5**(b)). Also $\delta_p = 4\tau\ell^2/[E_f d_f(1+\eta)]$ is the crack opening at which a fiber with embeddment length ℓ will start to slip out on completion of frictional debonding. The coefficient f is a fiber/matrix interaction factor known as the snubbing friction coefficient[24] which must be experimentally determined for a given pair of fiber and matrix.

By further assuming a uniform 3-D random distribution of fibers so that $p(z) = 2/L_f$ and $p(\phi) = \sin\phi$, the $\sigma(\delta)$ relationship has been derived[16]:

$$\sigma(\delta) = \begin{cases} \sigma_0[2(\delta/\delta_0)^{1/2} - (\delta/\delta_0)] & \text{for } \delta \le \delta_0 \\ \sigma_0(1-2\delta/L_f)^2 & \text{for } \delta_0 \le \delta \le L_f/2 \\ 0 & \text{for } L_f/2 \le \delta \end{cases} \quad \cdots\cdots (8)$$

where $\sigma_0 = g\tau V_f L_f/(2d_f)$ is the maximum bridging stress corresponding to a crack opening of $\delta_0 = \tau L_f^2/[E_f d_f(1+\eta)]$, and $g = 2(1+e^{f\pi/2})/(4+f^2)$.

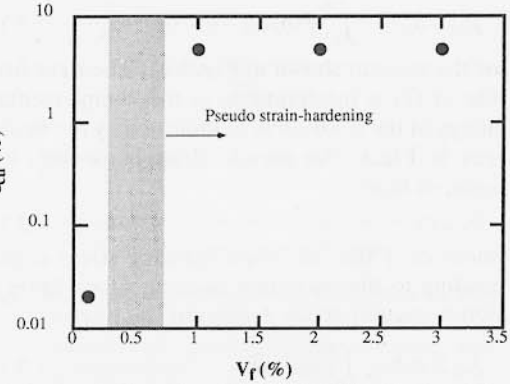

Fig.6 Strain Capacity of Spectra ECC for Various Fiber Volume Fractions. The estimated critical fiber volume fraction is indicated by the shaded strip.

Table 1 Properties of Fiber, Matrix and Interface Used in the Spectra ECC

Fiber			Matrix			Interface	
d_f (μm)	L_f (mm)	E_f (GPa)	K_m (MPa√m)	E_m (GPa)	ν_m	τ (MPa)	g
38	12.7	120	0.2 - 0.3	15	0.25	0.7 - 1	1 - 1.5

Requirements for pseudo strain-hardening

Using eqn. (8) in (3) then results in

$$V_f \ge V_f^{crit} \equiv \frac{12 J_{tip}}{g\tau(L_f/d_f)\delta_0} \quad \cdots\cdots (9)$$

Note that eqn. (9) expresses the condition for pseudo strain-hardening in the form of a critical fiber volume fraction V_f^{crit} which must be exceeded to create a composite with high strain capacity. V_f^{crit} is defined in terms of measurable micromechanical parameters involving matrix properties, fiber properties, interface property and fiber/matrix interaction property. To create pseudo strain-hardening with minimum amount of fiber, it is preferable to aim at low V_f^{crit}. Therefore low matrix toughness (J_{tip}), strong interfacial bond and snubbing friction, high aspect ratio of the fiber, and a large δ_0 are favorable to pseudo strain-hardening. It should be noted that (9) has been derived assuming that the fiber does not rupture. Otherwise, it can be shown that V_f^{crit} grows rapidly with decreasing fiber strength.

ENGINEERED CEMENTITIOUS COMPOSITES

As a demonstration of the implications behind the micromechanical concept contained in (9), **Fig.6** shows the significant composite strain capacity change as a result of pseudo strain-hardening for an Engineered Cementitious Composite (ECC) designed with a polypropylene fiber (Spectra 900, manufactured by Allied Corpora-

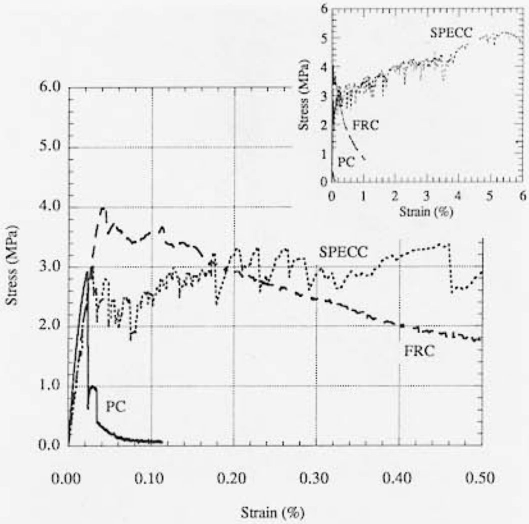

Fig.7 Uniaxial Tensile Stress-Strain Curve of a Spectra ECC($V_f=2\%$), a Plain Concrete (PC); and a Typical steel FRC.

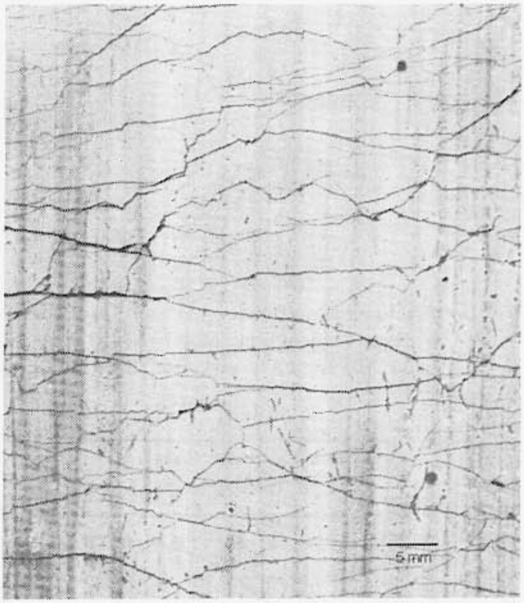

Fig.8 Multiple Cracking in a Spectra ECC($V_f=2\%$) Uniaxial Tensile Specimen.

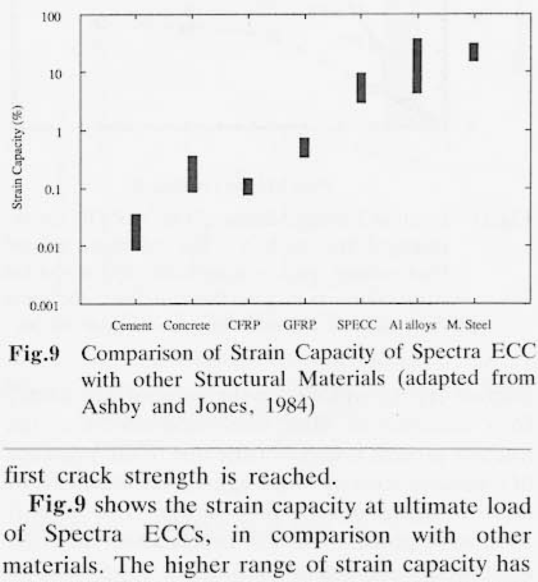

Fig.9 Comparison of Strain Capacity of Spectra ECC with other Structural Materials (adapted from Ashby and Jones, 1984)

tion). Fiber, matrix and interfacial properties are listed in **Table 1**, and the critical fiber volume fraction is determined to be in the range of 0.3-0.7%. Below the critical fiber volume fraction, the composite strain is essentially the same as the cement matrix. Above V_f^{crit}, however, the strain capacity jumps by 2 orders of magnitude to 6%. This Spectra ECC illustrates that by judicious choice of materials composition, it is not necessary to employ extraordinary high fiber volume fraction rendering the material economically infeasible for practical application. Indeed, in terms of composite strain capacity, **Fig.6** reveals that fiber volume fraction much above V_f^{crit} does not bring about further increase in strain capacity. Hence for economic reasons and for ease of processing, it is not recommended that volume fraction much higher than the critical value be used.

The reason for the high strain capacity of ECCs becomes clear when one examines the stress-strain curve (**Fig.7**) and the surface damage of the specimen (**Fig.8**). After first crack, the bridging fibers continue to carry increasing amount of load across this crack, leading to additional cracks elsewhere. This multiple cracking process continues until the maximum bridging stress σ_0 for the $\sigma-\delta$ curve is reached on one of the crack planes. It should be noted that this damage process occurs at increasing load——resulting in a pseudo strain-hardening behavior for the composite. For comparison, the tensile response of a plain conrete (PC) and a typical FRC reinforced with 1% hooked end steel fiber are also shown in **Fig.7**. These latter materials exhibit softening immediately after their first crack strength is reached.

Fig.9 shows the strain capacity at ultimate load of Spectra ECCs, in comparison with other materials. The higher range of strain capacity has been achieved with Spectra fibers which have been pre-treated with a plasma process. It can be seen that the Spectra ECC has achieved a strain capacity comparable to those of aluminum alloys.

The ability to transfer load away from an initial crack in an ECC prompted an investigation of the damage tolerance of such materials. Li and Hashida[30] analyzed the damage process at the tip of a notch casted into a Spectra ECC. They found these ECC material failed in a completely different mode compared to common cementitious materials. In neat cement (**Fig.10**(a)), fracture failure occurs in a very brittle manner, consuming a

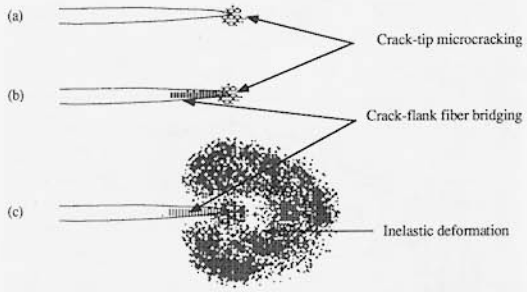

Fig.10 Fracture Failure Mode and Crack Tip Process of Various Cementitious Materials, (a) Neat Cement; (b) Concrete and FRC;and (c) Spectra ECC.

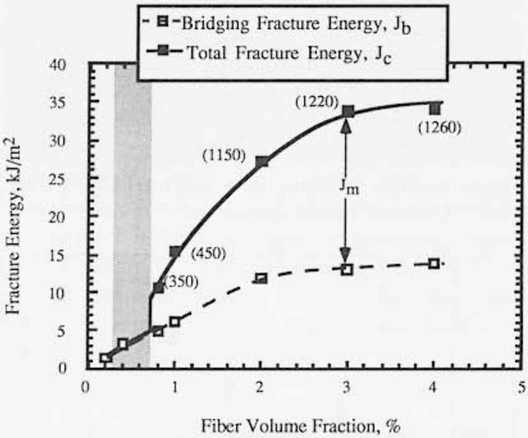

Fig.11 Fracture Energy Measured On- and Off-Crack-Plane of Spectra ECC. The estimated critical fiber volume fraction is indicated by the shaded strip. Numbers in parenthesis indicate the areal dimension of the inelastic process zone in cm^2.

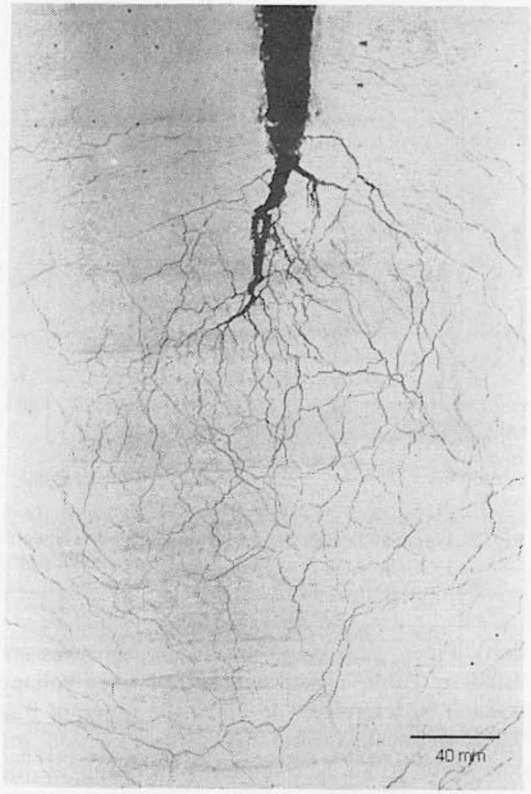

Fig.12 **Extensive Damage Development near the Crack** Tip in a Spectra ECC(V_f=2%) Fracture Specimen.

fracture energy typically on the order of 0.01 kJ/m^2. In a concrete or fiber reinforced concrete, the fracture process is quasi-brittle due to the presence of a process zone in which aggregate, ligament, or fiber bridging occurs (**Fig.10**(b)). This energy dissipation process typically brings about an order of magnitude increase in fracture toughness, to roughly one to several kJ/m^2. In the Spectra ECC, in addition to fiber bridging along the crack plane, the load transfer effect causes additional microcracking off the crack plane (**Fig.10**(c)), thus creating an extensive inelastic energy absorption process and causing the macro-behavior to assume an almost ductile fracture mode.

Fig.11 shows the experimentally measured on- and off-crack-plane fracture energy[31]. The on-crack-plane fracture energy J_b has been determined from the area under the descending branch of a uniaxial tensile test. The off-crack-plane fracture energy J_m has been determined from the total fracture energy J_c based on the J-integral technique, less the on-crack-plane fracture energy. It is seen that the off-crack-plane fracture energy is non-existent when the fiber volume fraction is below the critical value V_f^{crit}. Above V_f^{crit}, however, the off-crack-plane fracture energy increases and eventually exceeds that of the fiber bridging energy consumed on the crack plane. From this investigation, it is clear that the ductile fracture mode is closely associated with the condition of pseudo strain-hardening. The off-crack-plane fracture energy is considered to have derived from the frictional debonding prosess of the fibers crossing the off-crack-plane microcracks. **Fig.12** shows the extensive damage crack tip zone in a 2% Spectra ECC which failed in a ductile fracture mode. The total fracture energy of the Spectra ECC has reached 10-35 kJ/m^2. This is at least three orders of magnitude higher than that of the cement matrix. Apart from the much higher fracture energy level, it is expected that the R-curve behavior of ECCs will be much steeper so that the steady state fracture energy can be accessed with much shorter cracks in comparison with ordinary FRC in which the full fracture energy

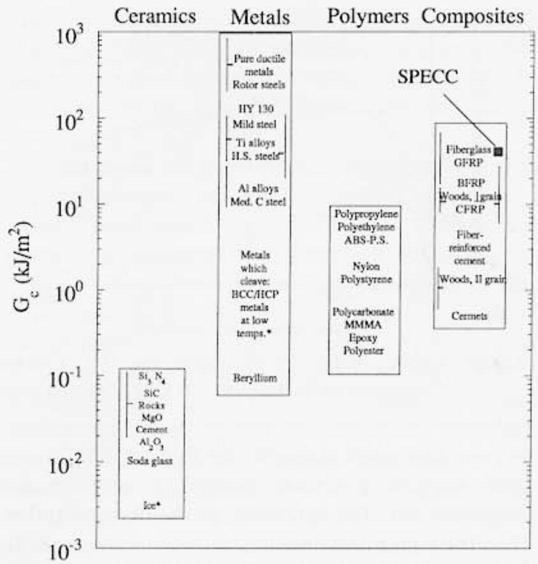

Fig.13 Comparison of Fracture Energy of Spectra ECC with other Structural Materials (adapted from Asbhy and Jones, 1984).

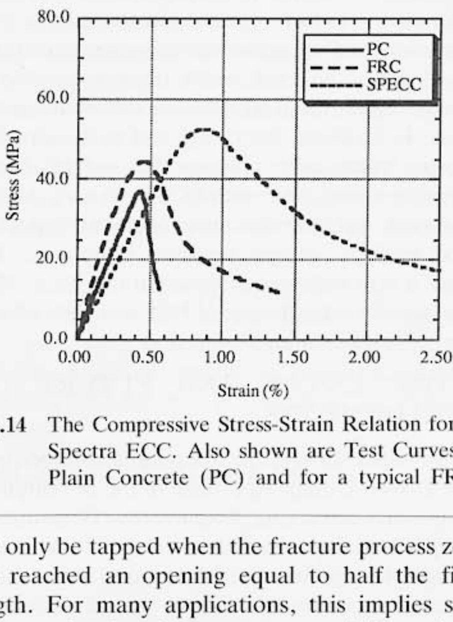

Fig.14 The Compressive Stress-Strain Relation for the Spectra ECC. Also shown are Test Curves for Plain Concrete (PC) and for a typical FRC.

can only be tapped when the fracture process zone has reached an opening equal to half the fiber length. For many applications, this implies such large cracks that the structure would have been rendered unserviceable. The expected R-curve behavior of ECC, however, has not yet been confirmed.

Fig.13 shows a comparison of the fracture energy of various materials including that of Spectra ECC. It is seen that the damage tolerance of this ECC is quite comparable to those of FRP, and competes with some structural metals. For example, the fracture energy of typical aluminum alloys are in the range of 8–30 kJ/m^2 [32].

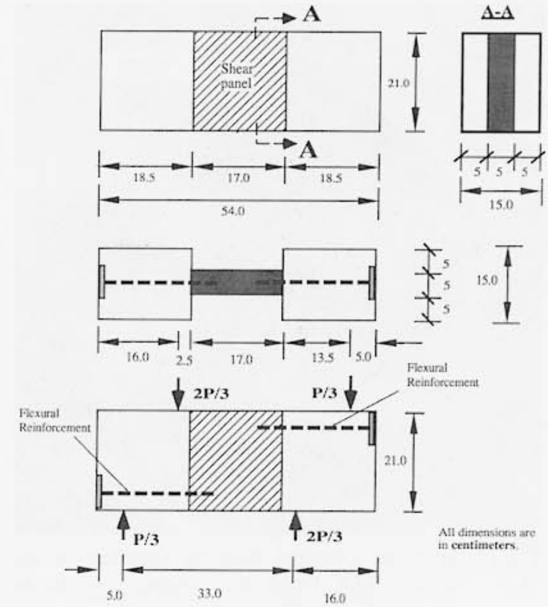

Fig.15 Ohno Shear Beam Geometry, Dimension and Loading Configuration.

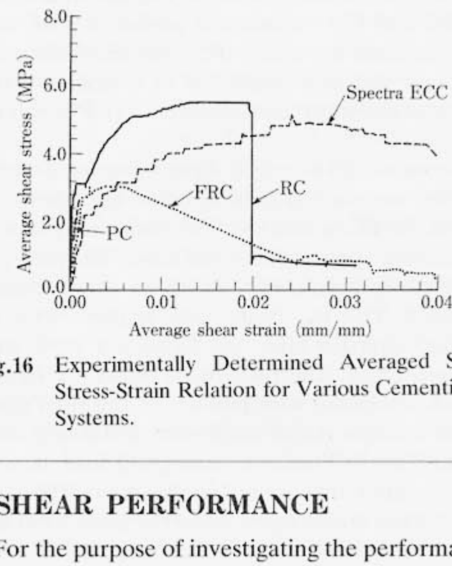

Fig.16 Experimentally Determined Averaged Shear Stress-Strain Relation for Various Cementitious Systems.

SHEAR PERFORMANCE

For the purpose of investigating the performance of shear intensive structures, we have chosen a 2% Spectra ECC which has the tensile behavior shown in **Fig.7**. The compressive strength and strain of this ECC is also quite reasonable in comparison to typical cementitious materials. **Fig.14** shows the compressive stress-strain curves for the ECC, as well as those for the PC and FRC with tensile response shown in **Fig.7**.

The shear test[33] was aimed at clarifying the shear load carrying capability of the cementitious material so that contribution of axial reinforcement was minimized as much as is possible. The Ohno Shear Beam[34] was chosen with geometry, dimension and

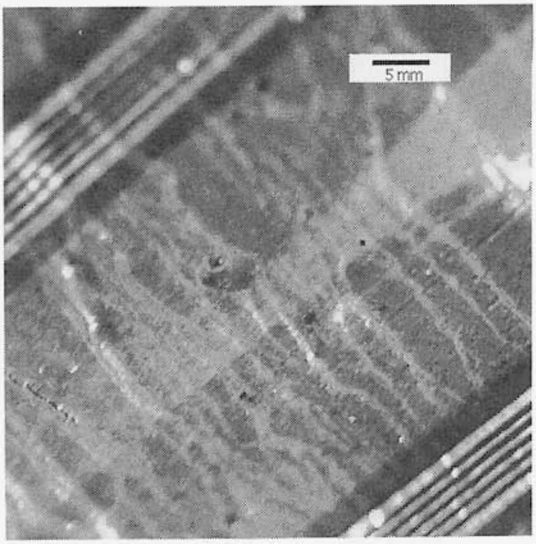

Fig.17 Hair-line Diagonal Multiple Cracking in the Spectra ECC Ohno Shear Beam. Two Strain Gages are also shown.

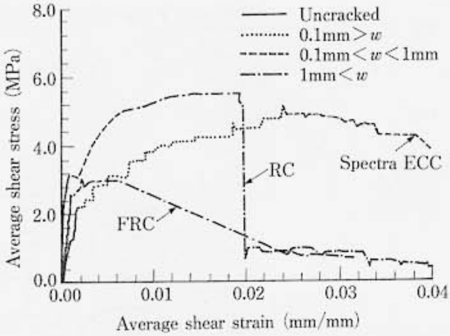

Fig.18 Crack Width Development for the Various Cementitious Systems in the Ohno Shear Beam

loading configuration shown in **Fig.15**. Apart from the PC and FRC mentioned earlier, a steel wire mesh reinforced concrete (RC) was also included in the shear test as a simulation of a structure with conventional shear reinforcements (1.5% volume fraction).

The measured averaged shear stress versus strain for the various material systems are shown in **Fig.16**. It is seen that the first crack strength in all systems are approximately the same. The post-first crack strength behavior, however, are decidedly different. The PC beam fails brittley, with no residual strength after the formation of a large diagonal crack. The FRC beam shows a softening branch associated with pull-out of the steel fibers across a single major crack with increasing crack width. The RC beam reveals good load bearing capacity after first crack. As the major (typically one or two) cracks open, concrete spalls form and expose the wire mesh which appear to show localized deformation associated with the peak load. For the ECC beam, localized cracking did not occur beyond first crack. Instead, the composite spreads the damage. As the beam continues to be loaded, hair line sub-parallel diagonal cracks appear on the mid-section of the beam (**Fig.17**). This beam reaches the highest ductility before load softening occurs, despite the fact that it has no steel reinforcement at all. Thus it is clear that the strain-hardening advantages designed into the Spectra ECC material was translated into the improved shear response of the structural beam.

Apart from the safety performance when loaded beyond first crack strength, the Spectra ECC beam also suggest potential durability performance improvement. The spreading of the damage rather than the continued opening of one or two cracks to large crack widths suggest that prevention of aggressive agent penetration into the interior of the structure will be minimized by the ECC. Penetration of aggressive agents have been identified as the major cause of reinforcement, prestressing or post-tensioning tendon corrosion in concrete structures. **Fig.18** shows the crack width development for the various cementitious systems at different loading stages. In addition, the rising load as the structure deforms inelastically indicates that energy absorption of structures built with ECC materials can be a significant performance improvement especially when used in seismic resistant structures. This aspect is now being investigated at the ACE-MRL in connection with the use of ECC as a plastic hinge near a beam-column connection.

CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper surveys the adoption of the performance Driven Design Approach in the development of a strain-hardening Engineered Cementitious Composite designed for shear intensive structures. A major link between structural performance and material structure tailoring is provided by micromechanics tools. By proper selection of fiber, matrix and interface, it is demonstrated that a composite with improved strength, strain and fracture energy properties can be manufactured, and that the amount of fiber reinforcement does not necessarily have to be excessively high. This last aspect make it possible to achieve cost-effectiveness, and the structural performance in safety, durability and energy absorption capacity further justifies the practical application of this new class of materials.

The Spectra ECC described in this paper is but one of several ECC materials being developed at the ACE-MRL. ECCs with steel, carbon and other polymeric fiber types are being investigated. In addition, ECCs with aggregates are also being developed.

Apart from shear properties, energy absorption properties under low cycle reversed loading are being investigated, as alluded to before for earthquake resistant structures. In addition, the limited Ohno Shear beam tests described in this paper also indicates beneficial effects of lateral compression in enhancing the biaxial property of ECC over that of the uniaxial tensile properties[33]. Fatigue properties are also being researched, and micromechanical models will be used to relate structural high cycle fatigue performance to micromechanical properties. And of course the fundamental tensile properties, some of which elaborated in this paper, will continue to receive attention with respect to influence of fiber, matrix and interface properties. These properties are strongly influenced by processing conditions so that details of their effects must be carefully analyzed.

As is clear from the discussions in the main text, a high performance cementitious composite must be defined in terms of the structural application it is intended for. It is envisioned in future that specific ECCs can be designed for structural members employed for different functions. This approach should lead to optimal use of expensive components in the ECCs. In other words, additional cost of the material must be more than off-set by the performance boost in the overall structural system. The PDDA provides a conceptual framework for the first step towards this ideal. Successful technological implementation, however, cannot be achieved without the participation of industrial partners.

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