Self compacting Engineered cementatious composites micromechanics to the structural application

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I. INTRODUCTION

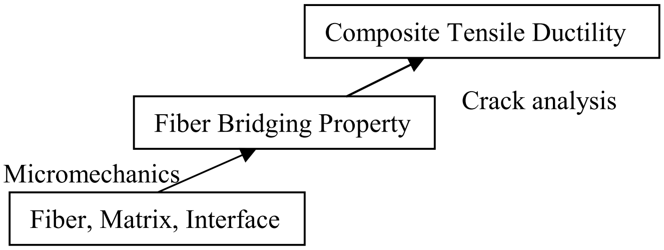
M*ICROSTRUCTURE TAILORING AND OPTIMIZATION*

Since the introduction of ECC, significant developments in research and commercialization of ECC technologies have occurred both in the academic and in the industrial communities. FIG. 3.1 shows a flow – chart of some important elements of ECC R & D, from basic materials design theory to practical commercial applications [27].

Micromechanics relate macroscopic properties to the microstructures of composite and form the backbone of materials design theory. Specifically, it allows systematic microstructure tailoring of ECC as well as materials optimization. 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. Material optimization also leads to compositions (e.g. moderately low fiber volume fraction coupled with suitable matrix design) that make it possible for very flexible materials processing. It is 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.

Steady state crack and Energy criterion

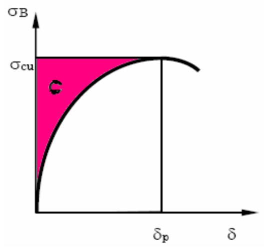
Most fundamental property of a fiber reinforced cementitious material is the fiber bridging property across a matrix crack. Generally it is referred to as the σ - δ curve [5]. It is the averaged tensile stress σ transmitted across a crack with uniform crack opening δ as envisioned in a uniaxial tensile specimen. The σ - δ curve provides a link between composite material constituents – fiber, matrix and interface and the composite tensile ductility which is shown graphically in fig.



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 σ - δ curve shown in FIG. 3 can be thought of as a spring law. This spring law describes 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 must not exceed the maximum bridging stress σcu. One 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 energy of crack extension. One may label this as the energy criterion for 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, pullout of fibers occurs, resulting in σ - δ curve with low peak strength σcu. When the interface is too strong, the springs cannot stretch, resulting in rupture and a small value of critical opening δp. In either case, the complementary energy shown as the shaded area C to the left of the σ - δ curve in FIG. 3.3 will be small. Steady state crack analysis carried out by Li and Leung in 1992 [27] revealed 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 as shown in FIG. 4 (a). As the crack propagates, unloading of the



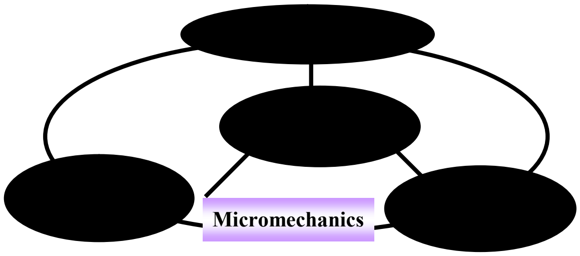
springs will initiate at the middle of the crack, where the opening is maximum, when δm exceeds δp in FIG. 3.3. An expanding traction free or tension-softening region will follow the crack tip as the crack continues to propagate. After the passage of this crack, the composite will fail with reduced load carrying capacity, resulting in the tension - softening behaviour of a normal FRC. In contrast, if the complementary energy is large, the crack will re-main flat as it propagates so that the steady state crack opening δss < δp as shown in FIG..4 (b) 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 strength and energy criteria for multiple cracking provide guideline for tailoring the fiber, matrix and interface for ECC materials. So controlling of σ - δ curve controls the fiber and fiber/matrix interaction parameters . The σ - δ curve has a direct bearing on the constitutive law in general and the tensile stress-strain curve of the composite in particular.

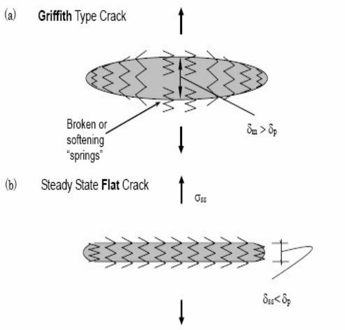
Performance Driven Design Approach

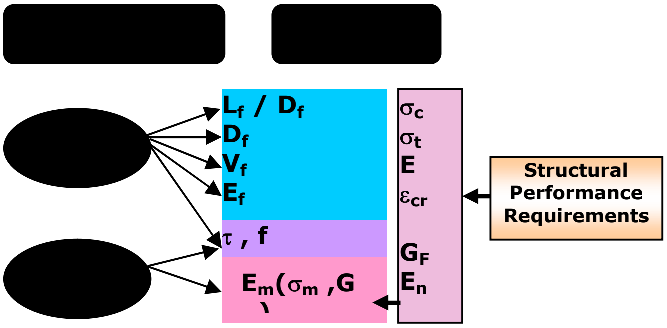
The Performance Driven Design Approach (PDDA) is based fundamentally on the paradigm of materials development as proposed by the United States National Research Council . This paradigm emphasizes the interrelationships between performance – (material) structure – property – processing as shown in FIG. 5.

The performance of a given structural component may be defined as deflection control, light weight, seismic resistance, dimensional stability, reliability and durability. The properties may include moduli, various strengths, ductility, toughness, notch sensitivity, density, and permeability, coefficient of expansion, impact, temperature, fatigue and wear resistant properties. The material structure for ECC generally includes the fiber, matrix and interface, although it is clear that each of these have their own microstructures as well .



The idea of the performance driven design approach is basically one where the performance and functionalities of a given structure or structural component are specified and a material must be chosen so that the properties can meet the expected structural demand. Consider the approach a step further that is, given the required properties, the fiber, matrix and interface are tailored to optimize the needed properties. In other words, the performance driven design approach ensures a direct link between the material composition and the structural performance as shown in FIG. 6.



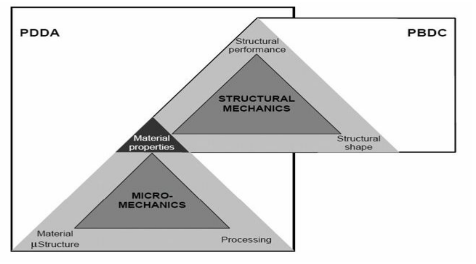


The quantitative link between material properties and the associated material microstructures is often known as micromechanics. Micromechanics takes into account the material structure and local deformation mechanisms in predicting the composite macroscopic behaviour.

While the performance driven design approach is attractive, it has been difficult to implement because most structural engineers do not design materials, whereas materials engineers do not design structures. While there are quantitative linkages between certain structural performance and material properties, some important ones such as structural durability and related material properties are often not well established. Apart from a few exceptional cases, most quantitative linkages between material properties and material structures are also weak. As a result, direct linkages between structural performance and material structure are almost non-existent. This phenomenon produces two inhibiting effects: The improper and limited use of ECC in structures and the slow development of advanced ECC. To overcome these inhibiting effects, it is necessary to launch a fresh approach in ECC research.

Integrated structures and materials design

The primary objective of is to explore the concept of the integrated structures and materials design (ISMD) as a collaborative research platform. ISMD acknowledges material (macroscopic or composite) properties as the common link between structural engineering and materials engineering, and that these material properties are ‘‘designable’’ by suitable microstructure tailoring. In the following, the concept of ISMD is described .



In the world of structural engineering, materials are shaped into structural elements that are then assembled into structural systems in order to meet targeted structural functions and performance goals. The performance goals are often stated in terms of ultimate limit states or serviceability limit states. Typically, design codes provide the structural design framework with respect to material selection, dimensioning, and in the case of reinforced concrete, reinforcement detailing. Embodied within design codes are deep knowledge developed from structural mechanics analyses and verified by extensive experimental investigations and experience. Structural analyses utilize mechanical properties of materials in the form of constitutive laws. Thus structural mechanics forms the basic analytic tool for structural engineers. This body of knowledge while not visible to the eye is the fundamental reason why structures (in most instances) carry anticipated loads in a predictable way. The world of structural engineering, shaping materials into structural elements and joining them to form structural systems, with structural performance as the target, is depicted as the upper triangle in FIG. 7.

In the world of materials engineering, raw ingredients are shaped into a composite through processing. Traditionally, raw ingredient selection is based on empiricism. In recent years, as knowledge of the impact the various phases in a composite have upon macroscopic properties in-creases, composite materials with specific desirable properties have been systematically designed. A particularly useful set of analytic tools for fiber reinforced cementitious composite design is micromechanics, which quantifies the mechanical interaction between fiber, matrix and fiber/matrix interface and relates this interaction to composite material properties. Micromechanics in this form can be considered analogous to structural mechanics where the fiber, matrix and interface serve as loading-carrying ‘members’, and the composite is regarded as the structural system.

Naturally, the length scales are much smaller, and some mechanical or physical phenomena are unique to composite materials. Micromechanics can be a powerful tool to deliberately tailor the composite ingredients, such as fiber dimensions and surface coatings, along with sand particle amount and size. In addition, knowledge of material processing and its effect on both fresh and hardened properties aids in composite design. Again, while not visible to the eye, this body of knowledge on micromechanics and processing allows systematic development of composites with properties not reachable heretofore. The world of materials engineering, with composite property as the target, is depicted as the lower triangle in FIG. 7.

It is clear from the above discussion and from FIG. 7 that the common link between structural engineering and materials engineering is composite properties. As pointed out previously, performance based design of structures provides flexibility and incentive to deliberately select composite materials with properties that efficiently meet the structural performance target. In turn, modern materials engineering provides the tools for intentionally tailoring material ingredients for desired composite properties. Thus, the integration of structural and materials design is a natural joining of these technical fields. In other engineering fields such as aerospace engineering, such integration has already been in practice for some time. In the discipline of civil engineering, this tighter integration can bring about innovative structural systems unattainable if chasms between the structural engineering and materials engineering fields remain.

The upper triangle in FIG. 7 needs to embrace the lower triangle as an additional degree of freedom of structural design (beyond dimensioning, reinforcement detailing, and choice of concrete compressive strength), while the lower triangle needs to reach upward and embrace structural performance as the ultimate material design objective. These expanded mind-frames support meaningful interactions and collaboration between the two allied communities necessary for the common good of next-generation infrastructure systems, which are safe, durable, and sustainable. It can be observed that the application of ISMD requires the following: The structural engineer, in consultation with the owner of the structure, sets the agenda, in the form of specifying the structural performance target, and translating that target into a set of required composite material properties. The materials engineer conducts materials design based on this set of required composite material properties.

MICROMECHANICS BASED DESIGN METHODOLOGY

Micromechanical models constructed on the basis of fracture mechanics and deformation mechanisms provide an opportunity of tailoring microparameters so as to control the failure mode, the tensile strength, and ultimate tensile strain of the composite. Three types of tensile failure modes have been observed in cementitious materials i.e. brittle, quasi-brittle, and ductile failure. Brittle failure can be observed in hardened cement paste material. It is characterized by a linear stress-strain curve followed by a sudden drop in stress at first cracking with an ultimate tensile strain of the order of 0.01 %. Quasi-brittle failure can be observed in concrete and most fiber reinforced cements and concretes. It is characterized by a linear stress-strain curve followed by a softening tail after first cracking, due to the bridging action of aggregates, cement ligaments, and/or fibers. The ultimate tensile strain of quasi-brittle materials is of the same order of magnitude as that for brittle materials. Strain-hardening materials are characterized by their ability to sustain increasing levels of loading after first cracking while undergoing large deformation. The ultimate strain value (at peak tensile load) of a strain-hardening material can be orders of magnitude higher than that of brittle or quasi-brittle material.

One of the most important conditions for the transition of quasi-brittle to strain-hardening failure mode is the presence of 'steady state' cracking. In fiber composites, the extension of a matrix crack is accompanied by fiber bridging across the crack flanks. As the matrix crack extends, the bridging zone increases in length. During crack opening, the bridging stress increases as fiber/matrix interfaces debond and the debonded segments of fibers stretch. When the bridging stress increases to the magnitude of the applied load, the crack flanks flatten to maintain the constant applied stress level. This load level is termed as the steady state cracking stress. The crack has now gone into the steady state cracking mode, extending without the need of further increase in applied load. Thus during steady state cracking, the tensile load is independent of crack length. This is in contrast to the well known Griffith residual strength concept, which relates a decreasing tensile load to increasing crack size.

In HPFRCC, the Griffith type crack in brittle material is replaced by flat steady state crack. This mode of cracking is necessary for pseudo strain-hardening in HPFECC. In the following, the criterion for steady state cracking to occur is derived based on an energy balance argument.

As we know from earlier discussion on σ-δ curve, σ0 is the maximum bridging stress while δ0 is the crack opening at which the maximum crack bridging stress is reached. FIG. 8 shows a through crack lying along the X-axis under uniaxial tensile stress in the Y-direction. For the crack to extend by an amount Δa on each side FIG. 8 (b), the additional work done on the system (dW) must be equal to the sum of the strain energy change of the system (dU) and the energy for forming the new crack surface (dEs). If steady state cracking occurs, the applied stress remains constant at σss as a small crack increases in size to form a through crack with part of the crack profile remaining flat at a constant crack opening δss. By definition, σss is the first cracking strength. Then, by comparing FIG. 8 (a)and 8 (b) for the configurations before and after crack extension, it is obvious that the strain energy change dU of the system is equal to two times the energy difference between a strip of material Δa in length perpendicular to the flat part of the crack profile (A-A in FIG. 8 (b)) and a strip of the same size in the un-cracked material far away from the crack tip (B-B in FIG. 8 (b)). The additional work done on the system is due to a displacement δss of the applied stress over the newly formed crack surface of length 2Δa. The change in surface energy is equal to Jtip (the crack tip critical energy release rate of the composite) times the newly formed crack area. For a unit thickness of specimen;

$$dW = (2\Delta a)\sigma_{ss}\delta_{ss}$$

$$dU = (2\Delta a)\left[\int_0^{\sigma_{ss}} \sigma\ (\delta)\ d\delta\right]$$

$$dE_s = (2\Delta a)\ J_{tip}$$

$$\sigma_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \sigma(\delta) d\delta = J_{tip}$$

The left hand side of Eqn. 3.4 represents the complementary energy of the σ-δ curve shown by C area in FIG. 3.3. If the σ-δ relation for a given composite is known, the first cracking stress σss can be readily obtained. For steady state cracking to be possible, the complementary energy has to reach the energy for crack propagation, Jtip. Since the complementary energy reaches its maximum value when σss equals, the condition that makes steady state cracking possible is given by;

$$\sigma(\delta) = \sigma_0\left[2(\delta / \delta_0)^{1/2} - (\delta / \delta_0)\right] \quad \text{for,} \delta \le \delta_0$$

$$\sigma(\delta) = \sigma_0(1 - 2\delta / L_f)^2 \quad \text{for,} \delta_0 \le \delta \le L_f / 2$$

$$\sigma(\delta) = 0 \quad \text{for,} L_f / 2 \le \delta$$

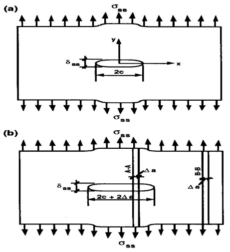


Fig. 3.8 Crack Extension under Steady State Condition

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

…… (5)

Eqns. 4 and 5 were first derived by Marshall and Cox [2]. Since the analyses in Marshall & Cox and Li are based on the J integral, the crack tip fracture resistance term is denoted by Jtip. Eqns. 4 and 5 are generalized equations and their applications to various fiber composite systems with known σ-δ relations can be found in Marshall and Cox, Li and Leung. The steady state stress σss and the flattened crack opening δss are related via the bridging law σ (δ). The bridging law describes the relationship between the averaged stress carried by the fibers bridging across a matrix crack and the opening of this crack. For steady state cracking to occur at all, the steady state cracking stress must be less than the maximum bridging stress σo in the bridging law. That is,

$$\sigma_{ss} \leq \sigma_0$$

…… .6)

Eqns.4 and 6 together provide a general condition for transition from quasi brittle to strain-hardening failure mode. Apart from steady state cracking condition, it is also necessary for the critical flaw size dependent first crack strength to be less than the maximum bridging stress. Otherwise, the bridging fibers will not be able to bear the tensile load shed by the matrix at first crack.

For Eqn. 6 to be useful in fiber, matrix and interface tailoring, it will be necessary to determine the bridging law specific for a given composite system. In fiber reinforced cementitious composite in which the fibers are randomly oriented and in which pull-out (rather than fiber rupture) are expected, Li suggested that the bridging law can be derived as;

…… (7)

where δ0 = is the crack opening corresponding to the maximum bridging stress σ0.

$$\delta_0 = \tau L_f^2 /(E_f d_f (1+\eta))$$

…… (8)

$$\sigma_0 = \frac{1}{2} g\tau V_f \frac{L_f}{d_f}$$

…… (9)

Corresponding Equations for cases where fibers can rupture and for cases where fibers are of variable length can be found in Eqns. 8 and 9. V f, L f, df, and Ef are the fiber volume fraction, length, diameter and Young's Modulus, respectively. τ is the fiber/matrix frictional bond strength, and the snubbing factor,

$$g = \frac{2}{(4+f^2)}(1+e^{f\pi/2})$$

Where, f is a snubbing friction coefficient which must be determined experimentally for a given fiber/matrix system. The snubbing friction coefficient raises the bridging stress of fibers bridging at an angle inclined to the matrix crack plane, appropriate for flexible fibers exiting the matrix analogous to a rope passing over a friction pulley.

Finally, η = (V f Ef) / (Vm Em), where Vm and Em are the matrix volume fraction and Young's Modulus, respectively. The condition for steady state cracking expressed in Eqn. 6 can now be interpreted as a critical fiber volume fraction above which the composite will show pseudo strain hardening. Using Eqns. 4 and 7 in Eqn. 6, this critical fiber volume fraction can be defined in terms of the fiber, matrix and interface parameters:

$$V_f^{crit} = \frac{12\ J_{tip}}{g\tau\ (L_f / d_f)\ \delta_0}$$

…… (11)

Equation 11 is important for composite design. It provides guidelines for tailoring the microparameters such that V f crit is minimized. Strain-hardening composites can then be designed with the minimum fiber content. ECC contains three main phases in its microstructure: (1) Fiber (2) Matrix and (3) Interface. Each phase can be characterized by several micro-parameters (Table 1).

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