2 PERFORMANCE DRIVEN DESIGN OF FIBER REINFORCED CEMENTITIOUS COMPOSITES

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Abstract
This paper describes the performance driven approach in the design of fiber reinforced cementitious composites. This approach is illustrated with structural durability as an example. The identified material property, crack width, is then related quantitatively to material structures -- fiber, matrix and interface properties, by means of micromechanics. It is suggested that tailoring of material structure can lead to controlled crack widths, and hence directly influences the durability of built structures. Success in the performance driven design of fiber reinforced cementitious composites will depend on future research in quantifying links between specific structural performance, material properties, and material structures.
Keywords: Performance, Fiber Concrete, Composites, Design, Micromechanics, Durability, Crack Width.

1 Introduction

The performance of a structure is directly associated with the mechanical and physical properties of the material used to build it. The properties of a material are in turn controlled by its own constituents. Hence details of the material make-up dictate the performance of a built structure. Composites in particular, provide broad latitudes in influencing structural performance because of the possibility of material structure tailoring. (In this paper, when the word *structure* is preceded by *material*, as in *material structure*, we mean the fiber, matrix, and interface of the cementitious composites. Otherwise, the word structure is used in the sense of a built or constructed facility). While this philosophy is well known, its application to fiber reinforced cementitious composites (FRCC) has met with only limited success so far. This paper surveys the advantages of the performance driven design approach, the obstacles in the adoption of such an approach, and some potential solutions offered by recent developments in micromechanics. A practical example -- structural durability, is used to illustrate the concepts described. The discussion is limited to the materials aspects of structural performance, and specifically relate to fiber reinforced cementitious composites. It is

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hoped that stronger recognition of the performance-property-microstructure relationships will provide more rational and systematic development of FRCC and enhanced usage of this versatile material.

2 The Performance Driven Design Approach

Because a given constructed facility is usually made up of many structural components, with potentially different materials chosen for different components, it is more convenient to discuss here the performance of structural components rather than structural systems. Some structural components that have utilized FRCC include slab on grades, bridge decks, wall panels, facade elements and water-tight structures. In addition, high performance FRCCs may be selectively applied to local parts of a structure. For example, Naaman (1991) suggested their use in beam-column connections in earthquake resistant frames, selected plastic hinge or fuse locations in seismic structures, the lower sections of shear walls or the lower columns in high rise buildings, the disturbed regions near the anchorages at the end of prestressed concrete girders, the high bending and punching shear zones around columns in two-way slab systems, and tie-back anchors. Clearly the diversity of these components and strategic structural locations lead to a diversity of performance requirements. It may also be pointed out that as our understanding of performance-property-microstructure relationships of FRCC increases, and as our confidence in their near and long term performance are enhanced by experience, further applications of FRCC will be found. Increasingly more load-carrying structural members will employ FRCC.

Figure 1 illustrates the performance driven design approach for FRCC. Apart from the performance-property-material structure nodes, a fourth node -- processing, may be included. Processing (as, e.g., pursued by Krenchel and co-workers) is of course crucial in any materials development, but it has been left out here to simplify the discussion and focus on the main theme. 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 (tensile, compressive, flexural, shear, etc.), ductility, toughness, notch sensitivity, density, permeability, coefficient of expansion, and impact, temperature, fatigue and wear resistant properties. The material structure for FRCC generally include 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. Such an approach is of course routinely used. However it has been rare to 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. 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 behavior.

Because of the increasing availability of a wide range of fibers with generally declining cost, an equally wide range of cement based matrixes with a variety of chemical admixtures, and to a certain extent, controllable interfaces, the properties of an FRCC can significantly vary with different combinations of fibers, matrices, and interfaces. As an example, the flexural strength and fracture toughness of an FRCC can vary over at least one order of magnitude, and strain capacity can vary by two orders of magnitude. It is therefore quite plausible that fiber, matrix and interface properties be tailored in an FRCC with composite properties required for specified structural performance.

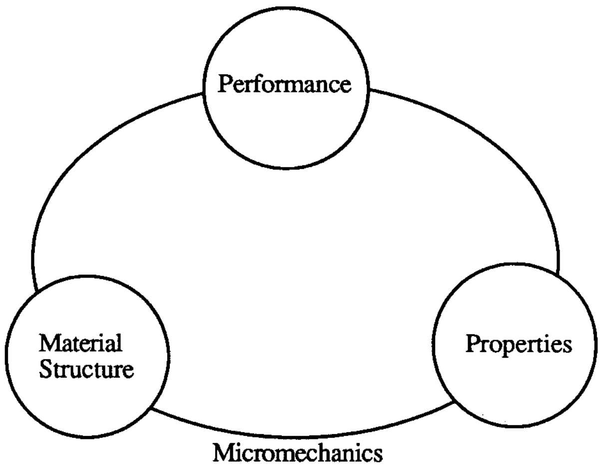

Figure 1: The Performance Driven Design Approach. Micromechanics Provides the Quantitative Link between Material Structure and Properties

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 FRCC in structures, and the slow development of advanced FRCCs. To overcome these inhibiting effects, it is necessary to launch a fresh approach in FRCC research. Structural performance which can benefit from the special properties of FRCC should be identified, and these properties should be related to the microstructure of the FRCC. Such an approach affords specific guidelines for the engineering of specific FRCC to meet specific performance requirements in a specific structure.

3 Structural Durability

The industrialized world is currently facing an increasingly aggravating infrastructural decay problem. Just in concrete structures alone, it has been estimated that the rehabilitation cost in the U.S. will reach into trillions of dollars over the next twenty years (National Research Council, 1987). It is no wonder, then, whether in considering rehabilitation of an aged structure or in new construction, the issue of structural durability has been a major concern. Interestingly, the study of durability of FRCC has been on the rise in recent years. In general, studies on steel FRCC (Balaguru and Ramakrishnan, 1986; Hoff, 1987; Kosa et al, 1991), polypropylene FRCC (Hannant and Zonsveld, 1980; Swamy and Hussin, 1986), and carbon FRCC (Akihama et al, 1984) indicate that the material durability is either enhanced or unchanged in the presence of fibers. These studies establish the baseline that FRCC can be used as a durable construction material. However, they do not directly address whether structural life will be extended or not by use of FRCC. In the following, an attempt is made to address durability as a structural performance. The related properties are then established. Finally the material structure most suitable for optimizing these properties are discussed in the context of recently developed micromechanical models. This presentation is offered as an illustration of the performance-driven design approach described in the previous section. While the various links are described, it will be clear that the success of this approach awaits further research.

In concrete structures, most durability issues arise because of concrete cover scaling and rebar corrosion. It has been long known that these problems are associated with the permeability of concrete to water and aggressive agents such as chloride ions. Concrete permeability, in turn, is dominated by the presence of cracks in concrete. Improving durability of concrete structures, therefore, requires in part the control of cracks in concrete (see, e.g., Mindess and Young, 1981).

Cracks in concrete can be generated in a number of ways. They exist as processing defects in the cement paste or in the aggregate/cement interface. Cracks can result from shrinkage stresses due to drying or carbonation, in addition to thermal and mechanical loads (see, e.g., Neville and Brooks, 1987). Concrete cover delamination in bridge decks has been associated with cracks generated from the pressure exerted by the expanding corrosion debris of the re-bar on the surrounding concrete. Figure 2, for example, illustrates a bridge deck cutout which exposes large scale delamination at the upper layer of reinforcements. Similarly if the concrete is used as a surface layer, sub-structure movements can lead to high imposed strains. Because of the low strain capacity of cementitious materials, large cracks may result. Whenever cracks are generated, the migration of aggressive agents into the concrete then depends on the crack width.

Figure 2: Cutout of Bridge Deck Showing Extensive Delamination Deterioration (Photo Courtesy of Dr. K. Maser)

From the above discussion, it seems that a general approach to crack control in FRCC would be to create a composite with pseudo strain-hardening behavior (Aveston et al, 1971; Ali et al, 1975; Baggott, 1983; Krenchel and Jensen, 1980; Laws, 1987; Oakley and Proctor, 1975; Stang and Shah, 1989; Li and Wu, 1991). This results in: 1) high first cracking strength and strain by stabilizing microcracks, and 2) load redistribution capability so that macrocracks can be delayed (Li and Hashida, 1992) and multiple cracking crack widths can be controlled. The following discussion will focus on crack width as the material property governing structural durability, taking advantage of recent studies relating crack width to water penetration in FRCC. This view may be unnecessarily narrow, and as our understanding of links between durability and other composite properties improves, there is no doubt that they should be incorporated into a more comprehensive approach to structural durability design. The following discussion is also not meant to imply that crack width control is the only means of dealing with structural durability, as this complex problem can be attacked from various angles, such as by chemical means. However, since migration of aggressive agents requires a pathway, and since typical concrete has low resistance to cracking, crack width control can be a very effective method of improving structural durability. Our intention, therefore, is to relate material structure to crack width as a controlling property of structural durability (Figure 3).

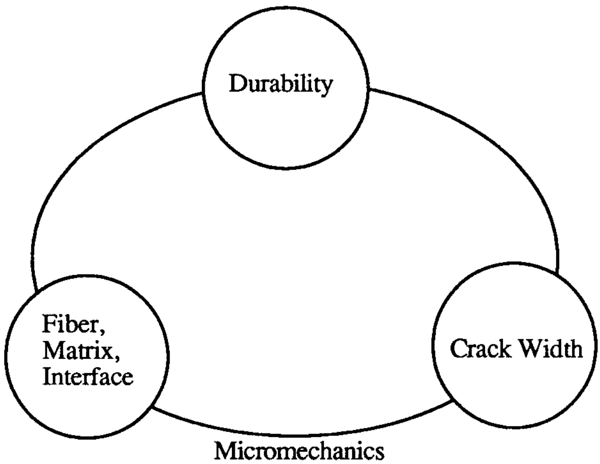

Figure 3: The Performance Driven Design Approach for FRCC Targeted for Structural Durability

4 Relationship Between Water Penetration And Crack Width

Two types of experimental tests which relate water penetration and crack width in FRCC are reviewed here. Although the experimental approaches and investigation emphasizes are different in these investigations, they both suggest that: 1) crack width governs water penetration, and 2) fiber addition has beneficial effects in reducing water penetration.

Keer et al (1989) studied the influence of chemical treatments of cracked and uncracked FRCC cement sheets on water absorption. The cement sheets reinforced with polypropylene networks between 3.0 and 4.7 % undergoes pseudo strain-hardening when loaded beyond its first crack strain. The FRCC sheets were precracked to predetermined strain-levels, resulting in controlled crack widths of .02 - .06 mm in the unloaded state. (However, the number of cracks is likely to be different for the different specimens.) Specimens kept wet on one side by sponges were weighted at fixed time intervals up to 96 hours. Water absorption was calculated as the weight difference (with respect to initial weight) and normalized by the dry weight. For our present purpose, we show in Figure 4 the water absorption as a function of crack width for the untreated specimens. The 1 hour measurement shows a stronger dependence of water absorption on crack width than the 96 hour ones. Hannant and Keer (1983) reported (for the same series of tests) that when crack widths are small, autogenous healing of the concrete could take place under natural weathering conditions. This mechanism will further limit the migration of aggressive agents into the concrete.

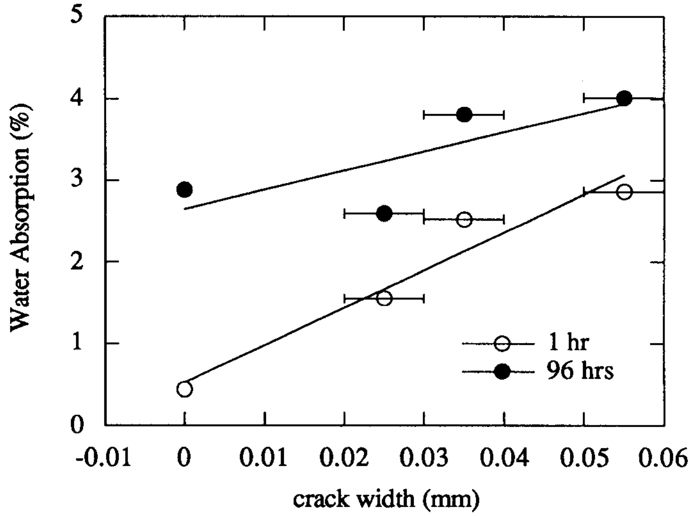

Figure 4: Measured Water Absorption Into Polypropylene FRCC with Controlled Crack Widths (after Keer et al, 1989).

Tsukamoto (1990) studied water tightness of FRCC with less than 2.5 % volume fraction of polymer and steel fibers. The water flow rate on one side of a precracked specimen of controlled crack width was measured while the opposite side was subjected to fluid pressure created by a water column. The results confirm previous findings that the flow rate scales with the third power of crack width (Figure 5) with a threshold value which depends on the fluid pressure. Tsukamoto found that for a given crack width, the presence of fibers appears to reduce the flow rate significantly. This is apparently due to the roughening effect of the fracture surface in the presence of fibers. In addition, because the fibers likely bridge the crack faces after the crack is introduced, the effective crack width felt by the fluid flow may be smaller than that indicated by specimen surface measurements.

The above studies indicate that the water flow rate is highly sensitive to crack width, while the water absorption as measured by Keer et al is less sensitive, at least for long term measurements. In both cases, they found positive influence of fibers on reducing water penetration into cementitious materials. The flow rate test under steady state condition can be considered as measuring the effective permeability of the concrete with a crack (so that Figure 5 may be read as effective permeability as a function of crack width for the various materials, since the pressure head is fixed), whereas the water absorption test is likely measuring a different material property related to moisture migration, presumably via capillary action. These properties may independently or in combination govern structural durability, depending on the given environment.

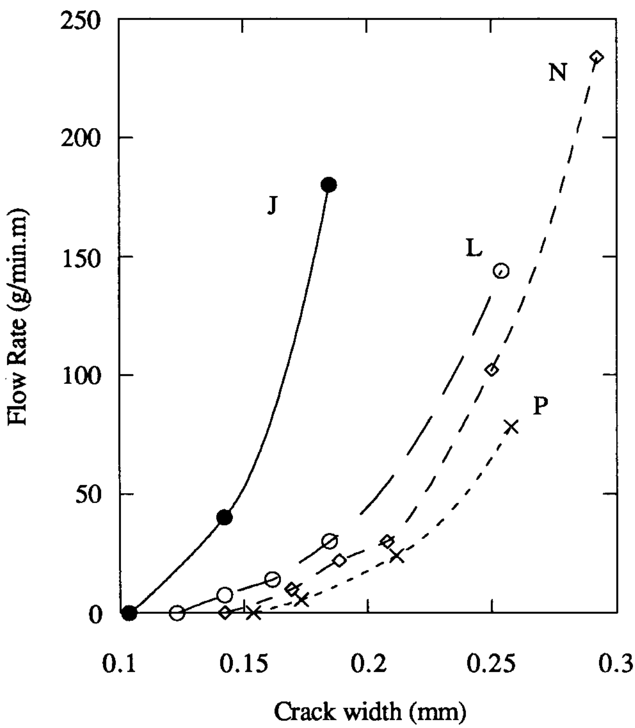

Figure 5: Measured Flow Rate Through FRCCs with Controlled Crack Widths (after Tsukamoto, 1990).
J = Plain Concrete; L = Polyacrylonitril FRC (d_f = 0.1 mm, L_f = 6 mm; V_f = 1.7%); N = Steel FRC (d_f = 0.5 mm, L_f = 30 mm; V_f = 1.0%); P = Polyvinylalcohol FRC (L_f = 24 mm; V_f = 0.8%). Pressure head = 7 mWS/m; Temperature = 20°C.

5 Crack Width Control By Fibers

In conventional concrete structures, crack widths are controlled by the steel re-bars. Crack width in such structures coupled with an ordinary fiber reinforced concrete has been studied by Kanazu et al. (1982), Stang (1991) and Stang and Aarre (1991). Stang showed that crack widths can be controlled to within 0.25 mm, depending on stress in the reinforcing bar. In the following, our attention is placed on FRCCs which exhibit pseudo strain-hardening such that crack widths in the FRCCs are controlled by the reinforcing fibers, to within 0.05 mm and less, without the benefit of the reinforcing steel bar. An idealized tensile stress-strain curve in a pseudo strain-hardening cementitious composite is shown in Figure 6. This curve may be divided into four regions of straining. In region I, the composite is deforming linear elastically and no through-thickness crack occurs. In region II, multiple cracking occurs and the strain increases with additional cracks while the crack width remains constant. In region III, multiple cracking has been completed and further straining results in direct loading of fibers. In region IV, pull-out or failure of fibers occur. In typical design, it seems prudent to limit the strain below ε_{mc}. Our interest in crack width control therefore lies in region II.

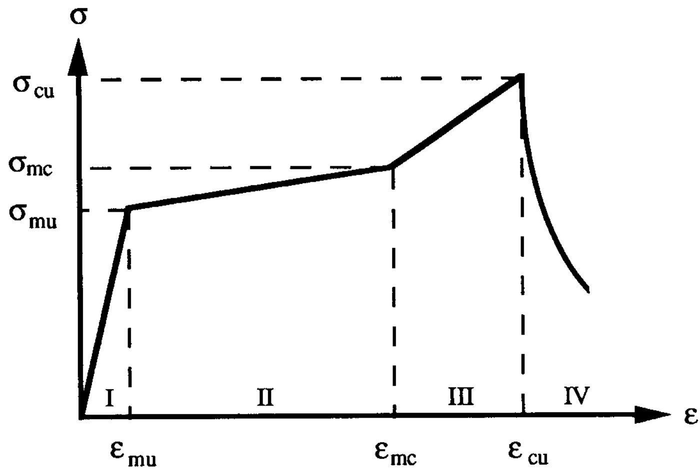

Figure 6: Schematics of Tensile Behavior of a Pseudo Strain-Hardening FRCC

In continuous aligned fiber composites, multiple cracks will be spaced between x' and 2x', where x' is given by (Naaman, 1970; Aveston et al, 1971):

$$x' = \frac{E_m d_f \varepsilon_{mu} V_m}{4\tau V_f} \tag{1}$$

The first crack strain ε_{mu} has also been derived by Aveston et al, and is given as:

$$\varepsilon_{mu} = \left[\frac{24V_f^2\tau\gamma_m E_f}{E_c E_m^2 d_f V_m}\right]^{\frac{1}{3}} \tag{2}$$

In (1) and (2), E and V are the modulus and volume fractions, respectively. Subscripts m, f and c denote matrix, fiber and composites. d_f and τ are the fiber diameter and interface frictional bond strength. The maximum crack width w can be calculated by integrating the difference in strain between the fiber and the matrix over a matrix block, so that

$$w = \varepsilon_{mu}(1+\alpha)x' \tag{3}$$

where $\alpha = E_m V_m / E_f V_f$.

In practical applications, it is more likely that short random fibers will be used in cementitious composites. However, the above procedure does not apply to this type of composites because of fiber discontinuity. Recently the ascending branch of the crack bridging stress σ_B has been derived as a function of crack opening δ for 3-D random short fiber composites (Li, 1992):

$$\tilde{\sigma}_B(\tilde{\delta}) = \left[2\left(\frac{\tilde{\delta}}{\tilde{\delta}^*}\right)^{1/2} - \frac{\tilde{\delta}}{\tilde{\delta}^*}\right]g \qquad \textit{for } \tilde{\delta} \le \tilde{\delta}^* \tag{4}$$

where $\tilde{\sigma}_B \equiv \frac{\sigma_B}{\sigma_o}$ and $\sigma_o \equiv \frac{1}{2}V_f\tau\left(\frac{L_f}{d_f}\right)$, $\tilde{\delta} \equiv \frac{\delta}{L_f/2}$ and $\tilde{\delta}^* \equiv \left(\frac{2\alpha\tau}{(1+\alpha)E_f}\right)\left(\frac{L_f}{d_f}\right)$. L_f is the fiber length and g is a snubbing factor included to take into account the friction pulley effect for bridging fibers inclined at an angle to the principal tensile stress direction. $\tilde{\delta}^*$ corresponds approximately to the crack opening at the peak bridging stress. The crack opening in region II may be computed if the load at first cracking is known. For a pseudo strain-hardening material, this corresponds to the state when a matrix crack propagates steadily at essentially no increasing remote load, i.e. at the steady state crack strength σ_{ss}, and (Li and Leung, 1992; Li and Wu, 1992),

$$\tilde{\sigma}_{ss} = \left(2\sqrt{\bar{c}_s} - \bar{c}_s\right)g \tag{5}$$

$\bar{c}_s$ is the non-dimensional crack length at initiation of steady state cracking and is defined in terms of a non-dimensionalized material parameter $\overline{K}$:

$$\bar{K} = \frac{2}{\sqrt{\pi}}\bar{c}_s\left(\frac{2}{3}\sqrt{\bar{c}_s} - \frac{1}{2}\bar{c}_s\right) \qquad 0 \le \bar{c}_s \le 1 \tag{6}$$

Li and Leung showed that $\bar{K}$ may be interpreted as a ratio of crack tip fracture energy absorption rate G_{tip} to the energy absorption rate in the fiber bridging zone G_r behind the crack front, hence:

$$\bar{K} = \frac{10}{3\sqrt{\pi}}\left(\frac{G_{tip}}{G_r}\right) \tag{7}$$

These fracture energy terms can be written as a function of material structural parameters:

$$G_r = \frac{5}{24}g\tau V_f d_f\left(\frac{L_f}{d_f}\right)^2 \tilde{\delta}^* \tag{8}$$

and

$$G_{tip} = (E_c / E_m)G_m \tag{9}$$

and G_m is the matrix fracture energy. Once $\bar{K}$ is determined from material structure parameters, it is then possible to calculate the steady state crack width $\tilde{\delta}'$ from (4)-(6). [Indeed, by requiring $\sigma_B = \sigma_{ss}$, it can be seen from (4) and (5) that $\tilde{\delta} / \tilde{\delta}^* = \bar{c}_s \equiv \tilde{\delta}' / \tilde{\delta}^*$.] In (9), the composite modulus E_c has been related to the fiber and matrix moduli and volume fractions in the form:

$$E_c = V_m E_m + \eta V_f E_f \tag{10}$$

where η is a fiber efficiency factor used to reduce the contribution of the fibers to the composite modulus because of fiber randomness to load direction and fiber finite length. A variety of values for η (for a succinct review of efficiency factors, see Bentur and Mindess, 1990) has been derived. Naaman et al (1991) suggested that an arithmetic average of the lower and upper bound for continuous aligned composites, such as derived by Halpin and Tsai (1969) serves to fit experimental data (of steel FRCC) well. More accurate representations of E_c in terms of fiber and matrix parameters can be found in Tandon and Weng (1986), and Wakashima and Tsukamoto (1991). However, given the cumbersome character of these representations, and the relatively forgiving nature of modulus representation at fiber volume fractions (typically less than 10% and usually just a few percent) expected in cementitious composites, the simple form of (10) with $\eta=1$ (upper bound) is employed for the calculations presented here.

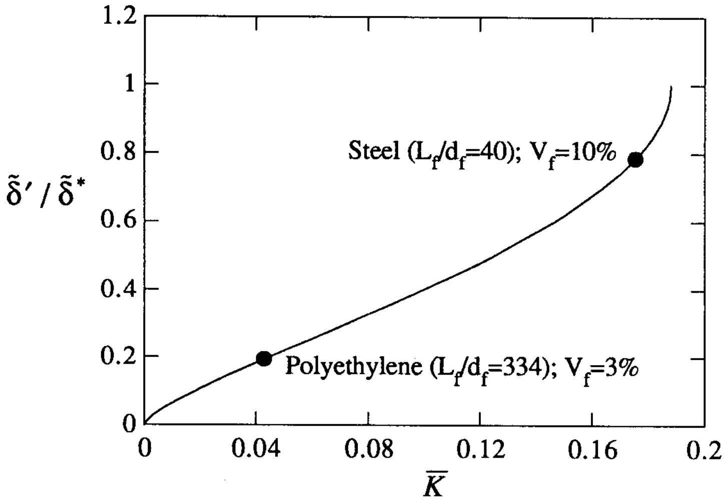

Figure 7: Normalized Crack Width Controlled by $\overline{K}$

Table 1: Fiber, Matrix and Interface Properties used in Composite Crack Width Opening

	Fiber				**Matrix**			**Interface**	
Type	E_f (GPa)	L_f (mm)	d_f (mm)	V_f	E_m (GPa)	K_m (MPa$\sqrt{m}$)	ν	g	τ (MPa)
Steel	200	6	0.15	0.1	15	0.2	0.2	2	6.5
Polyethylene	120	12.7	.038	.03	15	0.2	0.2	2	1

Figure 7 shows a plot of $\tilde{\delta}' / \tilde{\delta}^*$ as a function of $\overline{K}$. The non-dimensional form of this plot allows the inclusion of any material (fiber, matrix and interface properties), geometries (fiber length and diameter) and fiber volume fraction to be represented on a single curve. Two specific composites, reinforced with commercially available steel and polymeric fibers, are located on this curve. Properties of these fibers, as well as mortar matrix and interface properties, are tabulated in Table 1. An interesting point about Figure 7 is that when $\overline{K}$ exceeds 0.188, the crack opening is predicted to approach infinity. This $\overline{K}$ value corresponds to $\overline{K}_{crit}$ discussed in Li and Leung (1992) who showed that when $\overline{K} > \overline{K}_{crit}$, multiple cracking cannot be achieved. Thus softening occurs as soon as the first crack appears so that a finite crack width cannot be maintained at the failure load. Details of conditions for multiple cracking can be found in Li and Wu (1992).

While Figure 7 is empowered with dealing with a wide range of material structures, its physical meaning may be obscured by the non-dimensionalization. Figure 8 shows two physical plots for crack width. In Figure 8a, the influences of fiber modulus and interface bond strength on crack width are examined, for a fiber of fixed aspect ratio of 100. Other fiber and matrix parametric values are given in the figure caption. As expected, increasing interface bond reduces the crack width. For each bond strength, choosing a fiber with higher modulus tends to lower the crack width, at least initially. At higher modulus, the crack width tends to increase again. These curves are terminated at a fiber modulus which causes $\overline{K}$ to reach its critical value, at which state no multiple cracking can occur, and the composite once again fail catastrophically with a single large fracture. Figure 8b examines the influence of fiber aspect ratio on crack width, for a fixed fiber modulus, chosen for a steel. For each interface bond strength, the crack width is shown to decrease with aspect ratio. When the aspect ratio is too low, however, conditions on multiple cracking are again not met and these curves indicate crack widths going to infinity. For the range of parametric values covered, Figure 8 seems to suggest that as long as multiple cracking conditions are met, the crack widths are likely limited to less than 0.02 mm. Even smaller crack widths can be achieved with higher fiber volume fractions. These figures are useful for designing composites with controlled crack widths and hence structural durability as we described in the previous section.

For comparison purpose, eqns. (1)-(3) and (4)-(6) have been used to compute the crack widths for the composites with microstructural parameters described in Table 1, for both the continuous aligned case and the short random case. The results are summarized in Table 2.

Table 2: Computed Composite Crack Width in mm x 10^{-3}

Fiber	Continuous Aligned	Discontinuous Random
Steel	0.72	2.5
Polyethylene	1.13	5.7

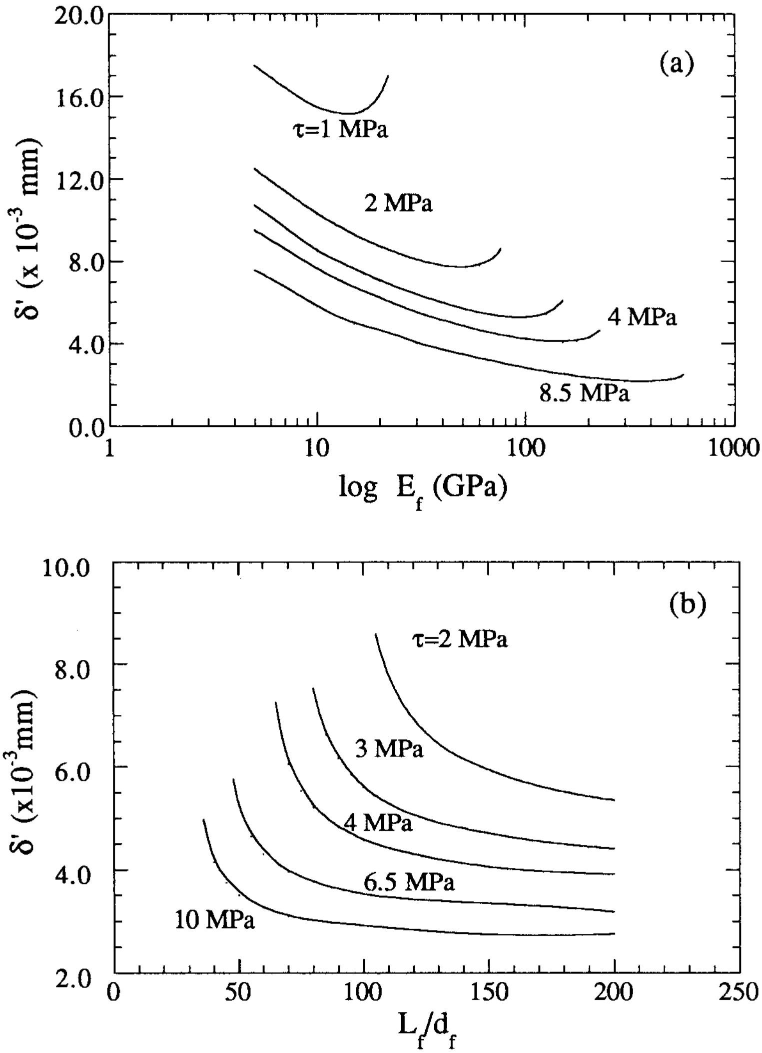

Figure 8: Dependence of Crack Width on (a) Fiber Modulus and Bond Strength, for L_f = 5 mm; d_f = .05 mm; and (b) Fiber Aspect Ratio and Bond Strength, for E_f = 200 GPa; d_f = .15 mm. For both cases E_m = 15 GPa; K_m = 0.2 MPa$\sqrt{}$m; g = 1; and V_f = 3%.

The calculations confirm that the stiffer steel fiber provides smaller crack widths than the polymer fiber, and that for each fiber type, the continuous aligned case provides smaller crack widths than the short random case. In all cases, these composites provide crack widths of less than 0.01 mm. This is much smaller than the mm scale cracks typically encountered in reinforced concrete structures. The small crack width of such composites more than meets the code specifications, or recommendations of ACI 224R-80, the CEB Model Code and the FIP (0.1 -0.3 mm allowable crack width depending on concrete cover, see, e.g. Mehta, 1986) for reinforced or prestressed concrete structures exposed to aggressive environments. Based on Figure 5, the flow rate and therefore the effective permeability could be expected to be much smaller when this type of material is used in comparison to ordinary concrete.

6 Discussions And Conclusions

In this paper, we present the performance driven design framework for FRCC. This approach links a desired structural performance to specific FRCC properties which in turn are linked to the material structure of the composite. The material structure can then be tailored for specific structural performance in mind. The advantage of the performance driven design approach is that FRCCs with optimized properties can be developed for a given application. In recent years, (see, e.g. Reinhardt and Naaman, 1991) there has been a debate as to the definition of *high performance* FRCC. The present discussion, (in particular Figure 1), suggests that high performance implies different meanings according to the performance requirements of different structures or different structural components. Indeed, it is not feasible, nor economically sensible, to design FRCCs to be high performance for all applications.

The example of structural durability is chosen to illustrate the performance driven design concept. One specific FRCC property, namely the crack width, has been identified as a controlling property for fluid flow and hence structural durability. This addresses only one dimension of a very complex problem. A more complete solution will include at least the first cracking strength which reflects stabilization of microcracks induced by processing and during curing, and the fracture energy of the composite which reflects stabilization of macrocracks induced by loading. Nevertheless, through micromechanical analyses, it is illustrated that specific micromechanical parameters can be chosen to control crack widths to within 0.05 mm and less, such that water penetration will be kept to a minimal, hence lengthening the service life of the structure. Further research, combined with experimental verifications in the field, will be required to validate these ideas. Specifically, additional work will be necessary to identify structural life in a given environment and its relationship to crack widths. Figure 8 (or more generally figure 7) can then be used to locate combinations of micromechanical parameters associated with fiber, matrix and/or interface, and the corresponding composite can be designed for this particular application.

The micromechanical model for crack width described in this paper has assumed that the composite has been properly reinforced so that pseudo strain-hardening behavior results. The detailed conditions for pseudo strain-hardening for continuously aligned and discontinuous random fiber reinforced brittle matrix composites can be found in a review by Li and Wu (1992). Also it should be noted that because a real composite is populated with defects of various sizes and inhomogeneous matrix and interface properties, the various regions (I-IV) indicated in Figure 6 are likely to merge together continuously, rather than sharply divided as shown. The predicted crack widths therefore serve as rough order-of-magnitude estimates, and more detailed experimental verifications are now planned at the University of Michigan.

Although the performance-property-material structure linkages represented in Figure 1 provide a useful framework for FRCC development, it is recognized that many elements of this framework must be strengthened. For example, certain material properties may not be well defined for a given performance. The micromechanisms associated with these properties can be even less understood. Impact resistance and fatigue resistance in FRCC are just two such examples. To successfully utilize performance driven design of FRCC, it will be necessary to clarify the properties associated with the desired structural performance and micromechanical models must be developed to relate such properties to the material microstructures. The significant amount of work on the micromechanics and micromechanisms of important composite properties, such as fracture toughness (see, e.g. Shah, 1990), accomplished over the last decade, sets an excellent platform from which successful development of FRCCs based on the performance driven design approach can be launched.

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