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Microstructure variability and macroscopic composite properties of high performance fiber reinforced cementitious composites

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Abstract

High performance fiber reinforced cementitious composites have made major advances in recent years, to the point where they are being adopted in building and bridge constructions. The most significant advantage of HPFRCC over conventional concrete is their high tensile ductility. However, the tensile strain capacity has been observed to vary, most likely as a result of the variability of the microstructure derived from the processing of these materials.

This paper describes the composite property variability, as well as the variability of the material microstructure. Scale linkage is discussed. In particular, the tensile stress–strain curves, and the crack pattern on uniaxially loaded specimens are presented. The treatment of random fibers in micromechanical models, and tailoring of matrix flaw size distribution for saturated multiple cracking are examined. It is suggested that robust composite properties can be achieved by deliberate control of microstructure variability. Some open issues concerning the randomness of microstructures and possibly related macroscopic behavior are also identified. Further gains in composite property control may be expected from improvements in characterization and modeling of the microstructure randomness.

Keywords: Composite properties; Microstructure randomness; Fiber reinforced concrete; Tensile ductility; Micromechanics

1. Introduction

Great strides have been made in the past decade in developing high performance fiber reinforced cementitious composites (HPFRCC) with significant strain-hardening behavior. Advances in HPFRCC have been so rapid that large-scale application of HPFRCC is now emerging in the field. In particular, Engineered Cementitious Composites (ECC), a special class of HPFRCC, received broad attention due to their high performance to cost ratio and easy execution in practice. The material has been successfully applied to dam repair, bridge deck overlay, coupling beam in high-rise building, and other structural elements and systems [2].

The most significant advantage of HPFRCC is their high tensile ductility resulted from multiple cracking, in contrast to the single-cracking and tension softening behavior of concrete and conventional fiber reinforced concrete. High ductility has been recognized, gradually, as having a close association with structure durability [3]. Many deterioration and premature failures of infrastructure can be traced back to the brittle nature of concrete, and hence HPFRCC are considered a promising solution to the global infrastructure deterioration problem.

The majority of HPFRCC are reinforced by short discontinuous fibers. The fiber orientation is determined by processing details as well as fiber content. In most cases, fibers are randomly distributed to some extent. Once a crack is formed in a uniaxial tensile specimen, the bridging fibers across the crack determine the load carrying capacity of the composite. Cracking of the brittle matrix composites is typically initiated at a dominant flaw of the section inherited from processing. In that sense, the composite performance is largely governed by the random nature of fiber location and orientation and flaw size distribution in the cementitious matrix.

Despite the apparent similarity in composition of various HPFRCC, e.g. short discontinuous fiber, cementitious binders, aggregates and of course water, the design principles embodied in these materials are rather distinct. For ECC, micromechanics links between microstructure and composite performance are emphasized and the links are used to guide the tailoring of

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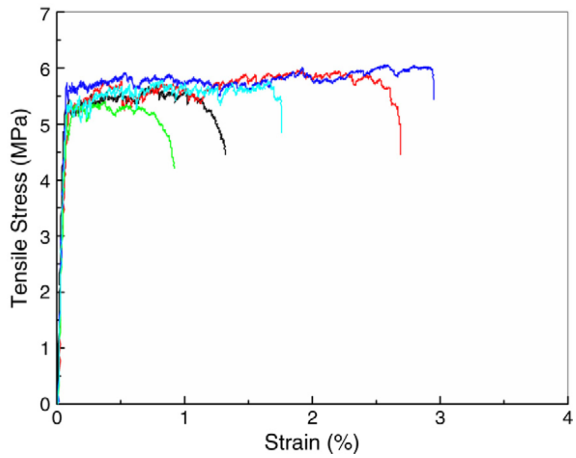


Fig. 1. Extreme variability case of strain capacity within same set of ECC specimens. This phenomenon is common in HPFRCC materials.

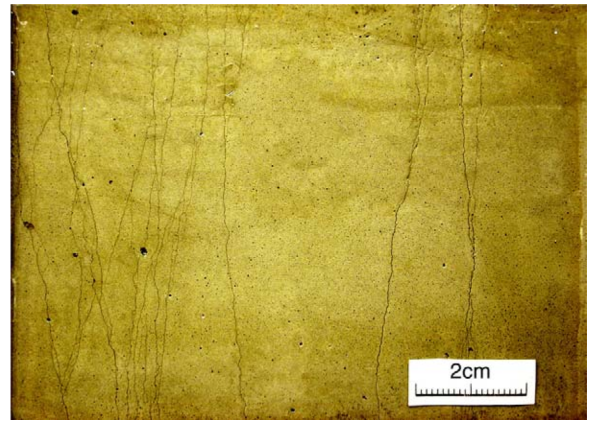


Fig. 2. Unsaturated multiple cracking. Large crack spacing implies inefficient utilization of the reinforcing fibers.

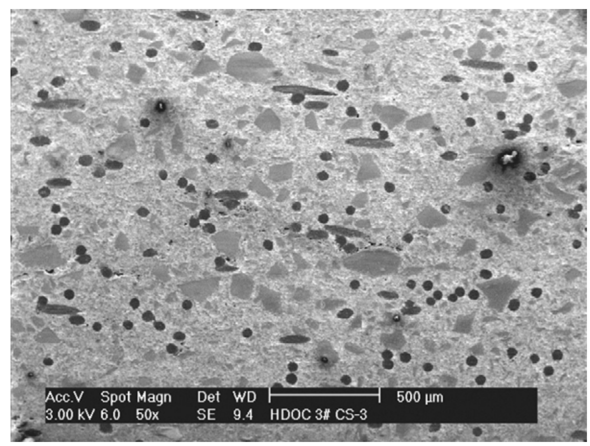


Fig. 3. SEM photo of an ECC section. PVA fibers (black dot) and sand (irregular gray phase) are surrounded by cementitious binder. Due to fiber orientation, the fiber intersection shape may be elliptical.

Fig. 4. Voids with various sizes in four ECC sections sampled from a coupon specimen.

individual components for overall performance. The design of ECC materials is driven by micromechanics modeling of the key components, i.e. fiber, matrix and interface interaction.

This paper focuses on the connections between microstructure variability and macroscopic composite properties, in particular the ductility of ECC materials. Variation of composite tensile behavior is first described, followed by modeling of random fibers for bridging properties and matrix flaw size for cracking strength. As a demonstration of such a connection, experimental observations of the effect of matrix flaw size distribution on multiple-cracking saturation are presented. Although the discussion is based on ECC, the methodology and conclusion are believed to be also applicable to other HPFRCCs.

2. Variation of tensile behavior

Multiple-cracking behavior is commonly observed in HPFRCC materials; however, the density of cracks or the crack spacing varies significantly from material to material, at times even within different specimens of the same batch. To illustrate, Fig. 1 shows an extreme case of tensile strain variability. Such high variability limits the full usage of the tensile ductility in structural design, so that the full potential of the HPFRCC material is not fully utilized.

According to Aveston et al. and Wu and Li, [1,6], the maximum crack spacing of fiber reinforced composites under uniaxial tension should be no more than twice the minimum crack spacing. This minimum crack spacing is defined as the distance necessary to transfer load from the bridging fibers of one crack back into the matrix through the fiber/matrix interface shear in order to create the next matrix crack, assuming uniform fiber distribution and homogeneous matrix strength. In this paper, multiple cracks with this minimum crack spacing in uniaxial tension specimens at failure are referred to as fully saturated. However, this may not be readily observed in most HPFRCC materials. Fig. 2 illustrates a typical pattern of unsaturated multiple cracking, showing a wide distribution of crack spacing far exceeding twice the minimum crack spacing. The average spacing of the multiple cracks, or inversely, the density of multiple cracks, is directly linked to the tensile strain capacity since the inelastic deformation derives from the opening magnitude and the number of multiple cracks in a representative volume element.

Microstructure imperfections, including non-uniform fiber distribution (e.g. Fig. 3) and matrix flaws (e.g. Fig. 4), are likely sources of the variations observed in crack spacing and

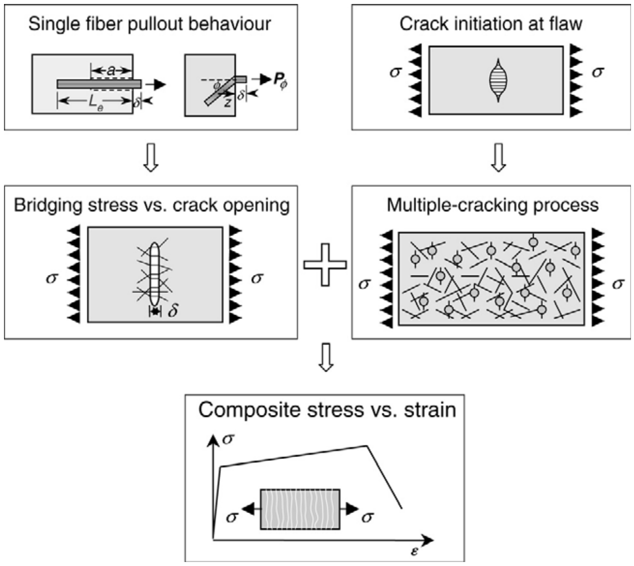


Fig. 5. Scale linking of microstructure of ECC to its tensile performance.

tensile strain capacity. Robust material performance calls for uniformity of the related microstructure.

3. Scale linking

Two aspects of microstructure variation pertaining to multiple-cracking behavior are of particular interest, i.e. fiber distribution and matrix flaw size distribution. The former governs the bridging behavior of fibers at a particular crack, while the latter determines the number of cracks that can be developed prior to reaching the peak bridging stress.

Fig. 5 illustrates the scale linking between microstructure and composite tensile behavior. For individual fibers, the pullout behavior is largely governed by the fiber and interface properties. Integration of the bridging force contributed by the fibers crossing the crack yields the fiber bridging stress versus crack opening relation, which describes the single-crack behavior. The *propagation* of cracks is influenced by the characteristics of the fiber bridging force. If steady state cracking occurs with a flat crack formed under constant ambient stress, and the cracking stress is also below the peak bridging stress, then the composite has strain-hardening potential, i.e. there exists a margin of load carrying capacity for developing sequential multiple cracking. To form these multiple flat cracks, however, it is necessary to first initiate them from pre-existing flaw sites. The *initiation* of cracks is determined by the matrix fracture toughness and critical flaw sizes. The evolution of multiple cracking does indeed reflect the size and spatial distribution of matrix flaws, until the bridging force capacity is exhausted. The modeling of micromechanisms at each material length scale and their linkages forms the theoretical framework of ECC material design.

4. Modeling of fiber randomness

The randomness of fiber location and orientation is accounted for in the modeling of the fiber bridging stress

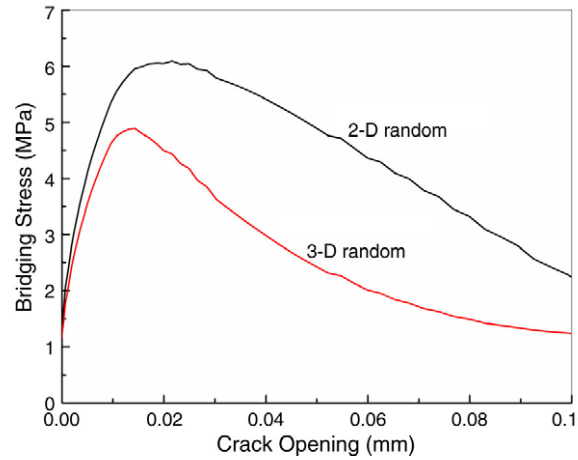


Fig. 6. Fiber bridging stress versus crack opening relation theoretically predicted for 2-D and 3-D random distribution for a typical PVA-ECC.

versus crack opening relation by adopting probability density functions that describe the spatial variability of the fibers [7]. Eq. (1) shows the formulation of the bridging stress versus crack opening relation. P is the bridging force contributed by a single fiber with centroidal distance z and orientation angle ϕ relative to the crack plane. Expressions for P can be found in [4] for the simple case of fiber pull-out with only frictional bonding, and in [5] for the case where fiber fracture and chemical bonding are allowed. p is the probability density function for fiber with distance z and orientation ϕ. A_f, l_f and V_f are the cross-sectional area, length, and volume fraction of fiber respectively.

$$\sigma(\delta) = \frac{1}{A_f V_f} \int P(z,\phi)\, p(z,\phi) \mathrm{d}z\, \mathrm{d}\phi. \tag{1}$$

For the simplest case, e.g. 3-D uniform randomly distributed fibers, $p(z,\phi)$ can be decoupled and expressed as follows:

$$p(z,\phi) = p(z)p(\phi) \tag{2}$$

$$p(z) = \frac{1}{l_f} \qquad -\frac{l_f}{2} \le z \le \frac{l_f}{2} \tag{3}$$

$$p(\phi) = \sin(\phi) \qquad 0 \le \phi \le \frac{\pi}{2}. \tag{4}$$

The uniform random distribution assumption rests on the observations that the fibers used in ECC are both short (8–12 mm), and of low volume fraction (typically no more than 2%), and that the rheology of ECC in the fresh state is also engineered to avoid fiber clustering. The fiber orientation however may be constrained, for instance in a spray process where the ECC is applied layer by layer. In the case of 2-D random distribution, the orientation probability of the fiber can be expressed as

$$p(\phi) = \frac{2}{\pi} \qquad 0 \le \phi \le \frac{\pi}{2}. \tag{5}$$

Fiber orientation has a significant effect on fiber bridging behavior, e.g. $\sigma(\delta)$ curve, both due to fiber counts, and also since the bridging force is a function of the fiber inclination

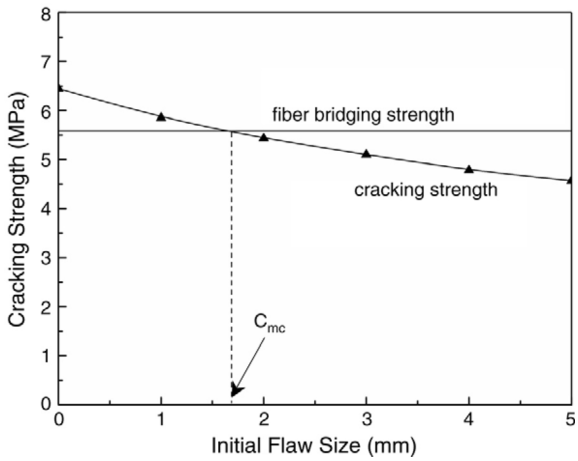


Fig. 7. Theoretically predicted effect of initial crack size on the cracking strength of PVA-ECC containing 2% by volume PVA fiber. The maximum fiber bridging stress is also shown in the plot.

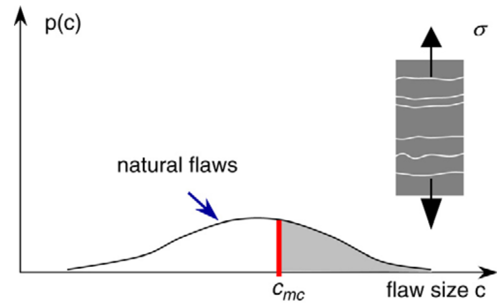
angle. Fig. 6 shows the theoretical σ–δ relations of PVA-ECC with 2-D and 3-D random fiber orientation, using Eq. (1). The difference in peak bridging stress is evident.

In practice, uniformity of fiber distribution is never perfect, and this may contribute to the variability of the σ–δ relation from one crack plane to another. The variability of the σ–δ relation is supported by the fact that the final failures in uniaxial tension always occur on a single crack plane, most likely the one with the lowest peak strength in the σ–δ relation among all the multiple crack planes. However, experimental stress–strain curves from the same batch of specimens indicate that this lowest peak strength is fairly consistent from one specimen to another, since the variations in first cracking and peak bridging strengths in uniaxial tension testing are considerably less than the fluctuation in strain capacity (e.g. Fig. 1).

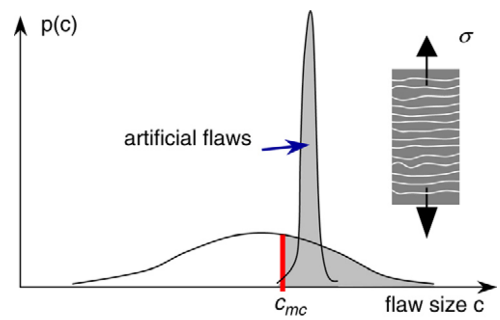
5. Flaws—matrix randomness

The inhomogeneity of brittle matrix, i.e. flaws from the micromechanical point of view, plays a significant role in the multiple-cracking behavior of ECC. ECC does not use coarse aggregates so they do not represent a source of randomness.

In a quasi-brittle matrix composite like ECC, flaws are typically the sites where cracks are initiated. Most flaws inherent from the mixing process have sizes below 4 mm, and their existence considerably reduces the cracking strength from the intrinsic material strength. Fig. 7 illustrates the effect of initial flaw size on the theoretical cracking strength of an infinite 2-D ECC plate under uniaxial tension. 2% by volume of polyvinyl alcohol (PVA) fiber is used. In this case, the theoretical tensile strength of the composite without macrodefects is assumed to be 6.5 MPa. For a crack with 1 mm width, the critical cracking stress is reduced to 5.4 MPa, and for 4 mm initial crack width the critical cracking strength can be further lowered to 4.8 MPa. Such reduction is important in developing strain-hardening behavior since the cracking strength must be lower than the peak bridging strength that the fiber can provide, which is 5.5 MPa for this particular PVA-ECC.



(a) Size distribution of natural flaws inherent from processing.



(b) Size distribution of the superimposed artificial flaws.

Fig. 8. Scheme of the flaw size tailoring for saturated multiple cracking in fiber reinforced brittle matrix composites [8].

High ductility is closely associated with the density of multiple cracking, and saturated multiple cracking can only be reached when a sufficient number of large flaws exist. However, the inherent flaws in cementitious matrix, e.g. pores, weak boundaries between phases, and cracks induced by shrinkage, possess a random nature and strongly depend on processing details and environmental effects. The number of cracks that can be activated before reaching peak bridging stress therefore may be limited and can vary significantly from batch to batch.

A practical approach to ensuring availability of large initial flaws is by introducing artificial flaws with prescribed size distribution. Fig. 8 illustrates the concept of a matrix flaw tailoring scheme for saturated multiple cracking. In composites without explicit flaw size control, the distribution exhibits a random nature and spans over a large range. c_{mc} is the critical initial flaw size that separates inert and active flaws (Fig. 8(a)). Only flaws larger than c_{mc} can contribute to multiple cracking. The value of c_{mc} can be determined by micromechanics models (e.g., as shown in Fig. 7). The tailoring process superposes a large number of artificial flaws with a narrow size distribution to overwhelm the natural flaw system by providing a sufficient large crack initiator pool (Fig. 8(b)). The artificial flaws can be any particles with weak bonds to the matrix or with low tensile strength. Expandable particles that can actively create microcracks are preferred.

Illustrations of the aforementioned tailoring approach are presented below. Fig. 9 shows the flaw size distribution in a normal casting PVA-ECC mix before and after adding artificial flaws. The flaws were determined by section sampling, and only large flaws exceeding 1 mm were counted. Low strength lightweight aggregates made from expanded shale were used

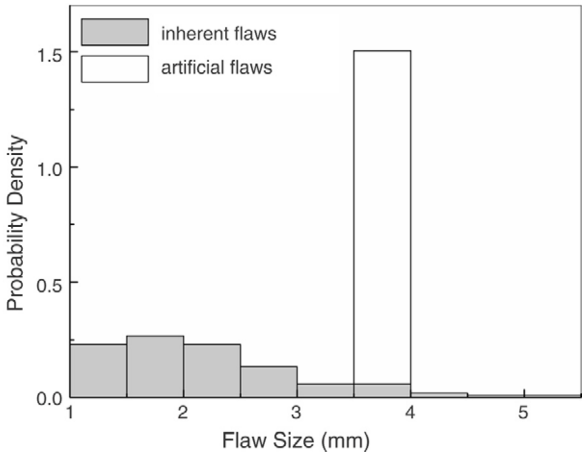


Fig. 9. Large flaw (> 1 mm) size distribution in a normal PVA-ECC mix (gray histogram) and superposition of artificial flaws (white histogram).

as the artificial flaws. The aggregates have a graded size of 3.5 ± 0.2 mm and the volume fraction is 7%. The superposition creates a concentration at the large size end of the flaw distribution. The effect of the tailoring on tensile ductility is clearly shown in Fig. 10, as the strain capacity of this mix increase from about 0.4% to 2.5% on average [8]. Such increase is achieved by developing more closely spaced microcracks. As shown in Fig. 11, near saturated multiple cracking prevails after adding artificial flaws, compared to the very uneven seen pattern previously. Control of flaw size distribution also improves the robustness of ECC tensile behavior. As shown in Fig. 12, the variation of strain capacity of the PVA-ECC presented in Fig. 1 diminishes after adding 7 vol% of plastic beads with 4 mm diameter as artificial flaws.

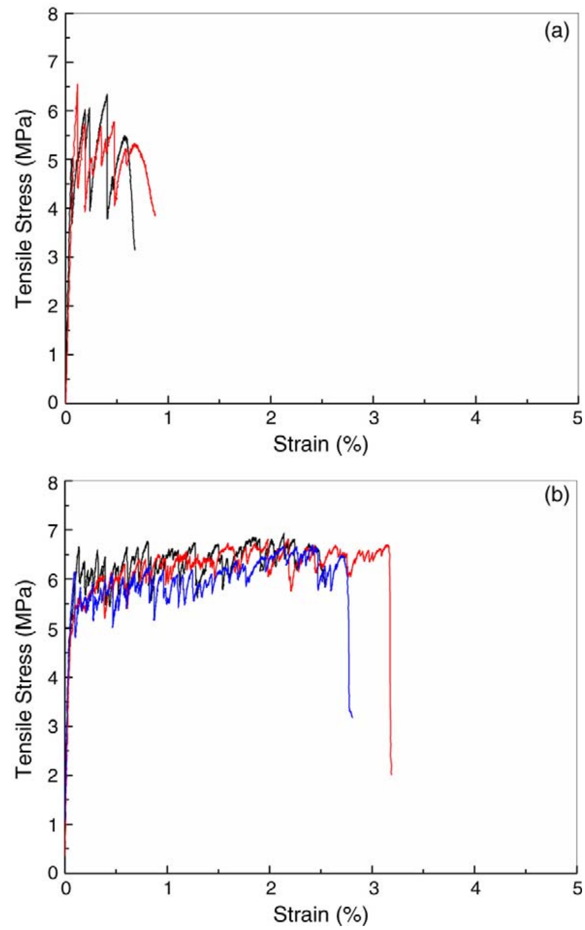


Fig. 10. Tensile behavior of PVA-ECC: (a) w/o artificial flaws and (b) with 7 vol% artificial flaws in the form of lightweight shale [8].

6. Discussion

The significance of the randomness of critical microstructures for the performance variability of ECC is evident in the examples illustrated above. At present, limited accounting for the microstructure randomness is included in the micromechanics models. Further efforts are needed to better understand the linkages between the randomness of microstructures and variability in composite behaviors. For instance, it is often observed in unsaturated multiple cracking that the distribution of microcracks tends to be clustered, i.e. banding of the microcracks (e.g. see Figs. 1 and 11(a)). Within those bands the cracking may approach saturation while outside the bands few cracks are developed. It is believed that such a phenomenon is closely related to the fluctuation of either fiber or flaw distribution but proof has not yet been established.

In attempts to understand the micromechanics linkages, it is vital to accurately capture and quantify the randomness of the critical microstructures at various material length scales. The characterization involves microstructure feature recognition and 3-D reconstruction, e.g. fiber and flaw spatial distributions. In particular, the flaws have sizes spanning over a few orders of length magnitude from submicron to millimeter and may have irregular shapes. Effective characterization of such a system

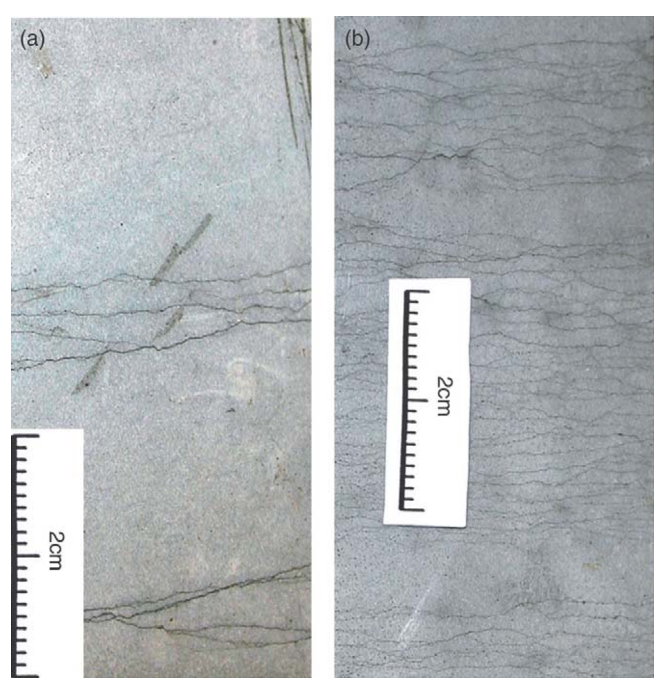


Fig. 11. Multiple-cracking pattern of PVA-ECC: (a) w/o artificial flaws and (b) with 7 vol% artificial flaws in the form of lightweight shale [8].

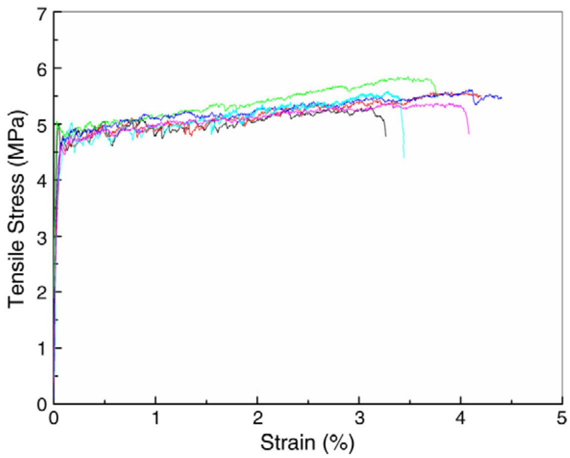


Fig. 12. Robust tensile behavior of PVA-ECC with controlled flaw size distribution and tailored interface properties. Plastic beads with 4 mm diameter were added at 7 vol%. The proportion otherwise is same as the mix in Fig. 1.

may require a combination of various imaging and analysis techniques.

Recognizing the random nature of the microstructure, it is appealing to incorporate probabilistic models in an ECC theoretical framework to explicitly account for the variation caused by processing. Key parameters may be extracted from the distribution information obtained from microstructure characterization. Such quantitative linkages could provide useful guides in ECC material design for further robust performance and economics gains.

7. Conclusion

Microstructure variability, in particular fiber and flaw size distribution, significantly influences the ductility of ECC materials. While the current micromechanics models suggest a powerful and effective means of composite design, their limitations are apparent in dealing with the microstructure variability. Even so, experimental results demonstrate that robust composite ductility can be achieved by controlling the variability of the key microstructure parameters. Further gains in composite property control may be expected from improvements in characterization and modeling of the microstructure randomness.

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