Fiber Reinforced High Performance Concrete Material

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1. Introduction

In recent years, it has become popular to use the terms "high performance" to describe certain concrete materials (concrete, mortar, cementitious composites). Indeed, major advances have been made in various performances addressing one or more deficiencies of traditional concrete. Table 1 lists the advantages and disadvantages of concrete as a structural material. The advantages of concrete are what make this material so ubiquitous. The disadvantages of concrete, however, are responsible for problems in infrastructure deterioration and collapse of reinforced concrete structures under severe loading.

Table 1. Advantages and disadvantages of concrete
(adapted from Mindess and Young, 1981)

Advantages	Disadvantages
Ability to be cast Economical Durable Fire Resistant Energy efficient On-site fabrication Aesthetic properties	Low tensile strength Low ductility Volume instability Low strength-to-weight ratio Low reliability

Phenomena such as cracking and spalling are often associated with deterioration in a wide variety of constructed facilities. Shear fracture has been observed in building columns and viaduct piers in a number of major earthquakes. These phenomena of cracking, spalling and fracture can be traced to the intrinsic brittle nature of concrete, even though concrete is typically reinforced with steel in structural applications. The most successful remediation of the intrinsic brittle nature of concrete is by means of fiber reinforcement. High performance fiber reinforced cementitious materials (HPFRC) can lead to drastically altered stress-strain response. Instead of elastic–brittle, or elastic–tension-softening, HPFRC can behave as elastic–strain-hardening (Naaman and Reinhardt, 1996).

The brittleness problem of concrete is exacerbated by the presence of defects, in the form of microcracks or pores. These defects are rendered more difficult to eliminate since concrete is typically cast on-site and requires proper vibration for compaction, so that quality control is difficult especially in light of the shortage of skilled labor. The recognition that the reliability of concrete and concrete structures can be improved if the fresh concrete can self-compact under gravity leads to the development of high performance self-compacting concrete (Ozawa et al, 1992).

Table 2 shows the nature of high performance and limitations in High Performance High Strength Concrete (HPC), High Performance Fiber Reinforced Cementitious Materials (HPFRC), and High Performance Self-Compacting Concrete (HPSCC). High strength concrete typically has two to three times the compressive strength of normal concrete, and because of the denser packing, typically has lower porosity and improved durability. Unfortunately, high strength concrete is often extremely brittle. Failure under compression can be explosive. High performance fiber reinforced concrete often refers to concrete reinforced with a large amount of fibers, from 4% to 20%, and attains tensile strain-hardening behavior with a tensile ductility of around 1%. The large amount of fibers used significantly increases cost and reduces the workability of this material, sometimes leading to the requirement of a different type of processing other than conventional casting. High performance self-compacting concrete has the advantage of self-compactability in the fresh state. However, it remains a brittle material in the hardened state as in normal concrete.

Table 2. High performances and limitations of HPC, HPFRC, and HPSCC

Materials	**High Performance**	**Limitations**
HPC	Compressive strength,	Very brittle
HPFRC	Ductile	Poor workability
HPSCC	Self-compacting	Brittle

It should be pointed out that to attain the performance of the respective materials, modifications of the aggregate component, among other aspects of the mix design, are necessary. For example, HPSCC often utilizes a type of grading of aggregate to achieve improved flowability, and HPC often utilizes a smaller aggregate size to limit intrinsic flaw size, while HPFRC often employs sand without coarse aggregates to allow proper dispersion of fibers in the cementitious matrix.

It is desirable to embody the combined merits of strength, ductility and self-compactability in a single material. In this paper, we describe the preliminary development of such a material – a self-compacting ECC material.

2. Engineered Cementitious Composites (ECC)

A brief introduction of ECC is given here. Detailed information can be found in Li (1998), Li and Kanda (1998).

The high performance of ECC is due to its ultra-ductility. The material strain-hardens after first cracking, reaching a tensile strain capacity of 3-6%. During strain-hardening, the material undergoes an inelastic damage process in the form of sub-parallel microcracking with crack planes lying normal to the principal tensile stress direction. Localization into fracture occurs only after peak load is reached (at 3-6% strain). Prior to this, the microcrack damage is analogous to dislocation damage in plastic yielding of ductile metals. Hence, microcrack damage in an ECC material is entirely different from cracks in concrete or FRCs (Li, 2000). This metal-like behavior of ECC can be significantly beneficial to structural integrity under normal service loads as well as under extreme loads. Closely associated with the strain-hardening behavior is the high fracture toughness of ECC, reaching around 30 kJ/m^2, similar to those of aluminum alloys (Maalej et al, 1995). In addition, the material shows excellent damage tolerance (Li, 1997), and remains ductile even in severe shear loading conditions (Li et al, 1994, Fukuyama et al, 1999). The compressive strength of ECC varies from 30 to 90 MPa, depending on the matrix composition. Compressive strain capacity is approximately 0.4 – 0.65% (Li, 1998). Most data so far have been collected on PVA-ECC (reinforced with poly (vinyl alcohol) fibers) and PE-ECC (reinforced with high modulus polyethylene fibers).

The ultra ductility of ECC and its influence on structural member response have been extensively studied with a variety of specimen types, including beams under flexural and/or shear loads (Kanda et al, 1998; Fukuyama et al, 1999; Fischer and Li, 2000; Li and Wang, 2000), columns (Fischer and Li, 2000; Fukuyama et al, 2000), connection joints (Kanda et al, 1998; Parra-Montesinos and Wight, 2000), and slabs under indentation load (Kanda et al, 1998). As an illustration of the ductility of an ECC material, Figure 1 shows the deformed shape of a 12 mm thick ECC plate subjected to a flexural load. Figure 2 shows the large deformation capacity of a steel reinforced (reinforcement ratio = 3.1%) ECC column (500x100x100 mm) subjected to fully reversed cyclic loading. Even at 10% drift and with no stirrups, this column shows only minor damage without fracture localization. These behaviors appear to be scale invariant, confirmed by specimens with sizes ranging from cms. to meters (maximum 1.5 m longest dimension).

In terms of material constituents, ECC utilizes the common ingredients of water, cement, sand, fiber, and small amounts of chemical additives. Only very fine sand is used in the mix. A typical composition employs a water/cement ratio of 0.25-0.45

and a sand/cement ratio of 1.0 or lower. Unlike most HPFRC, ECC does not utilize large amounts of fiber. In general 2% or less by volume of discontinuous fiber is adequate, even though the composite is designed for structural applications. The high performance of ECC derives from knowledge of the mechanical interactions between fiber, matrix and interface. This knowledge is translated into micromechanical design guidelines (Li, 1998; Kanda et al, 1998). This means that the three sets of parameters associated with fiber, matrix and interface must be of a correct combination to attain the unique behavior of ECCs. Thus, ECCs can be considered cementitious composites with embedded design knowledge.

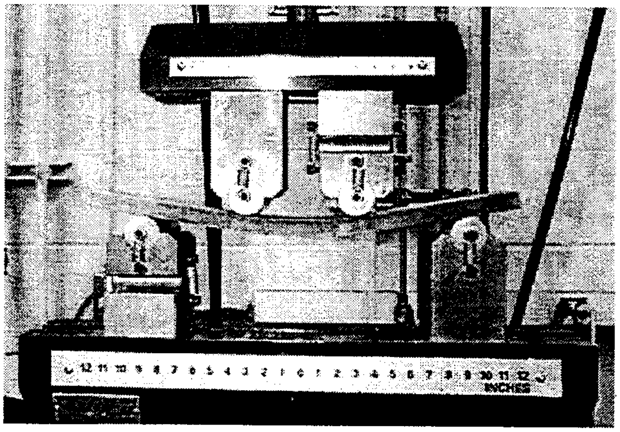
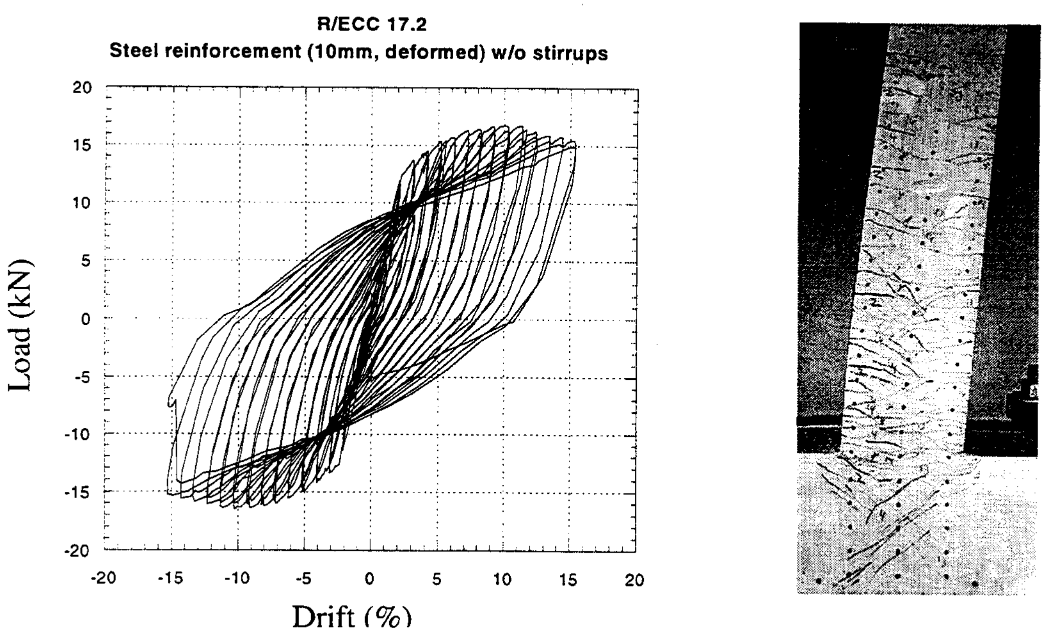


Figure 1. Flexural specimen showing high ductility of ECC.



(a) (b)

Figure 2. (a) Stable hysteresis loops of a steel reinforced PE-ECC column subjected to fully reversed cyclic loading. Deformed shape shown in (b) is at 10% drift, with crack pattern marked.

To illustrate the composite design concept, Figure 3 shows the computed critical fiber volume fraction V_f^{crit} for a PVA fiber which has a chemical as well as frictional bond interface with the cementitious matrix. This computation is based on a micromechanical model described in Lin et al (1999). All micromechanical parameters except the interface properties are fixed in this calculation. The meaning of V_f^{crit} can be interpreted in the following manner. For a fiber volume fraction above V_f^{crit}, the resulting composite will exhibit the ultra ductile behavior of ECC. Below V_f^{crit}, the resulting composite will exhibit the tension-softening behavior typical of FRCs. Naturally, a small value of V_f^{crit} is desired. Figure 3 indicates that V_f^{crit} is strongly dependent on the magnitudes of the interfacial fracture energy G_d and friction τ_o. For a given value of G_d, increasing τ_o first leads to a decrease in V_f^{crit}, since the fiber bridging properties are improved. However, a further increase in τ_o leads to a rise in V_f^{crit}. This phenomenon occurs because a greater amount of fiber rupture occurs at high bond values, deteriorating the fiber bridging properties. A similar argument applies to the influence of G_d. This implies an optimal window of τ_o for which V_f^{crit} is minimized. For example, for $G_d = 5$ J/m^2, the optimal window of τ_o is 1-3 MPa, if V_f^{crit} were to be kept below 1.5%. If all other micromechanical parameters were fixed, then control of the interface properties, through tailoring of the fiber surface or interphazal zone control (Li and Stang, 1997) becomes the primary concern. Micromechanical modeling, as illustrated in Figure 3, together with an interface property test (e.g. single fiber pull-out test, Katz and Li, 1996), can systematically lead to the development of an ECC material. Conversely, it is also possible to use the micromechanical model to guide fiber mechanical and geometric property design.

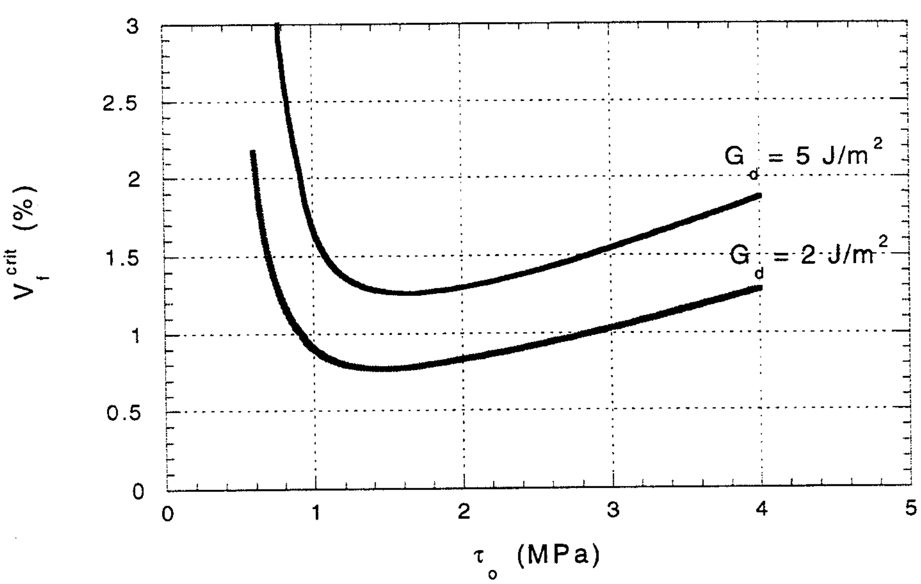


Figure 3. Computed V_f^{crit} showing dependence on interface properties.

3. Designing ECC with Self-Compactability

3.1 Overall design approach

As in the design for strain-hardening, the design for self-compactability also follows a microstructural approach (Figure 4). For ECC design, the most fundamental properties governing strain-hardening and multiple cracking are the fiber bridging and the mortar matrix properties. These properties are in turn related to micromechanical parameters associated with the fiber, matrix, and interface as discussed in Section 2. The matrix parameters can be controlled by the mortar mix design, including the Water/Cement (W/C) ratio and size and content of sand particles and other admixtures. The fiber mechanical and geometric properties as well as its coating can be tailored to provide the appropriate bridging response. For design of self-compactability, the concept of rheological control of a concentrated suspension is utilized. The objective is to achieve well-stabilized cementitious microstructure with uniform fiber dispersion, directly leading to the self-compacting properties. Focus is placed on the fundamental behavior of the mortar matrix deformability and segregation resistance, and on the interactions between matrix flow and fiber dynamics. These behaviors are in turn controlled by appropriate fiber, matrix and interface microstructural tailoring. Since these microstructures tuned for fresh state performance are the same as those tuned for hardened state performance, it is necessary that they satisfy both requirements simultaneously.

The development of self-compacting ECC necessitates compatible microstructural design. This implies that contradictory design should be avoided. For example, while a low fiber aspect ratio is desirable for self-compactability, it must not be so low as to compromise the requirement for strain-hardening, which favors a high fiber aspect ratio. The approach adopted emphasizes the development of a highly deformable fresh mortar matrix mix since this provides the main driving force for a self-compacting composite and for good fiber dispersion, and the resulting matrix remains consistent with that required for strain-hardening. Fiber dynamics (not discussed in this article) are then considered to ensure minimum disturbance of the fresh properties of the mortar matrix mix.

For development of a highly deformable matrix without particle segregation and with high consistency, the interactions between cement particles at constant solids concentration, including fixed W/C and Sand/Cement (S/C) ratios, are considered. The deformability performance of a fresh cementitious mix is governed by its rheological properties, represented by the yield stress and especially the viscosity; the consistency performance relates to the change of the deformability performance with time. The rheological properties of cement pastes are in turn governed by the microstructure and its change (due to hydration and particularly flocculation between particles) with time. It is therefore important to establish a means of controlling the cement paste microstructure in the fresh state, such as by the addition of optimal amount and types of stabilizing polymers and ensuring their complete adsorption onto the cement grains. The effectiveness of microstructural control of cement paste on mortar matrix deformability and consistency is then assessed via flow table tests.

Deformability, consistency, and self-compactability of the fresh ECC mix (i.e. including fibers) are subsequently assessed via slump and box-vessel tests.

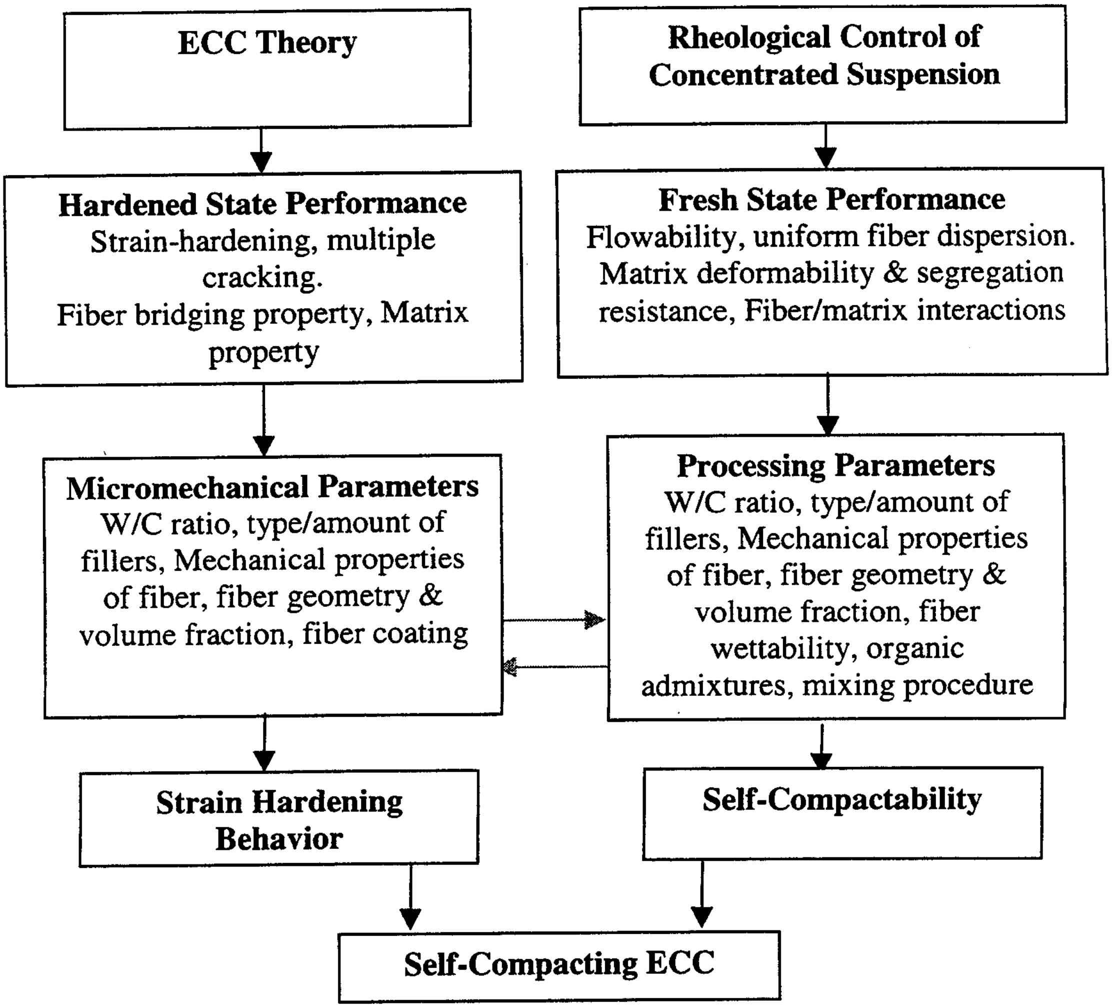


Figure 4. Design approach of self-compacting ECC.

3.2 Microstructural design of cement pastes

While the steady shear viscosity ($\eta(\dot{\gamma})$) at steady shear rate ($\dot{\gamma}$) is considered the rheological property governing the deformability of a concentrated suspension, the viscoelasticity responding to low-amplitude oscillatory shear deformation is considered the rheological property most directly associated with the microstructural characteristics of the suspension. According to the Cox-Merz rule (Bird et al, 1987), the product of the steady shear viscosity and the shear rate is equivalent to the product of the complex viscosity ($\eta^*(\omega)$) responding to the oscillatory shear deformation, the frequency (ω) and the shear strain (γ_0), as described in equation (1):

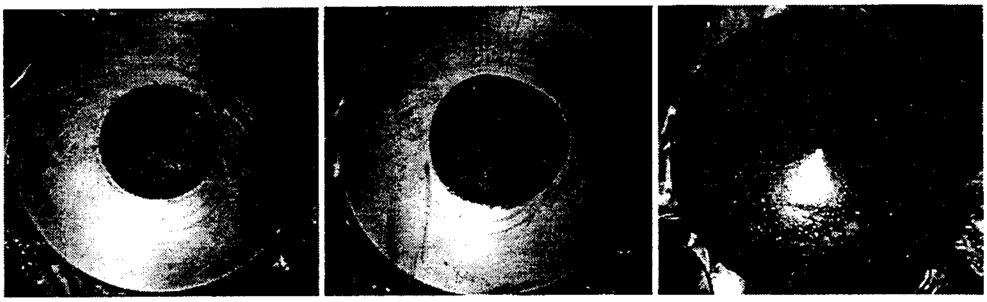
$$\eta(\gamma^{\cdot})\gamma^{\cdot} \approx \eta^{*}(\omega)\omega\gamma_0 = \left[(G'(\omega))^2 + i\ (G''(\omega))^2\right]^{1/2}\gamma_0$$
$$= \eta_{medium}\left[(G'_{red}(\omega))^2 + i\ (G''_{red}(\omega))^2\right]^{1/2}\gamma_0 \qquad (1)$$

Under oscillatory shear deformation at low strain γ_0, low enough so that the flocculated microstructure is not disrupted, the storage modulus ($G'(\omega)$) represents deformation energy storage while the loss modulus ($G''(\omega)$) represents energy dissipation. The storage modulus at high frequency is related to the attractive energy between the particles and the loss modulus at infinitesimally low frequency is comparable to steady shear viscosity at zero shear rate (Larson, 1999). These shear moduli also include the effect of medium viscosity η_{medium}. To normalize for changes in the medium viscosity, the shear moduli can be divided by η_{medium} to obtain the reduced storage modulus G'_{red} and reduced loss modulus G''_{red}. Then, any increase in the reduced storage modulus, for example, can be attributed to a stronger microstructure, due particularly to increased flocculation between the particles and also to hydration. This also leads to an increase in the steady shear viscosity with time. Thus, this equation suggests that flocculation between cement particles should be limited to decrease the storage and loss moduli. Consequently, the shear viscosity (and yield stress) of cement pastes would be decreased, leading to the desirable condition for high deformability of a fresh cementitious mix. In addition, retarding the microstructural growth with time will maintain the initial low shear viscosity, and thus produce a high consistency. One means to retard the microstructural growth is to maintain repulsion between particles over time.

3.3 Control of deformability of fresh matrix mix at low W/C ratio

We have combined a superplasticizer (melamine formaldehyde sulfonate, SP) and a non-ionic water-soluble polymer (hydroxypropylmethylcellulose, HPMC) to provide the repulsive forces between particles in the fresh cementitious mix. The effects of these polymers on the shear viscosity of the cement pastes mixed at low W/C ratio of 0.3 and a constant S/C ratio of 0.5 were confirmed in a previous study (Li et al, 1998). These solids contents are suggested by micromechanical studies to obtain the desirable strain-hardening behavior of ECC reinforced with polyethylene fibers.

In this study, we observed the effect of the polymer admixture on the consistency of fresh mortar matrix mix by performing the flow table test to quantify the deformability (Γ_1). Γ_1 is measured as $[d^2-d_0^2]/d_0^2$, where d is the final spread diameter and d_0 is the flow cone diameter (equal to 10 cm). Prior to the test, the fresh mortar mix was allowed to rest in the flow cone for 10 minutes. The concentrations of SP and HPMC employed here were found in another study (Li et al, 1998) to be optimal for promoting a low shear viscosity. Figure 5 (a) shows that the fresh mix dispersed only with SP became rigid in the flow cone, thus producing low deformability. Figure 5 (b) shows that a combination of HPMC of 0.013 %, based on cement weight, with SP of 1.00 % slightly increases Γ_1. It is suggested that the adsorption of the two polymers onto the cement grains provides electrosteric stabilization, which is the desired stabilization method for cementitious suspensions (Uchigawa et al, 1997). Figure 5 (c) exhibits that extension of the mixing time increases Γ_1 by more than an order of magnitude. This result arises because the extension of the mixing time from 2 to 10 minutes increases the adsorbed amount of the HPMC, even though the polymer concentrations are unchanged. Thus, two factors—optimal HPMC and SP concentrations and optimal mixing time—are considered important processing parameters to prevent the growth of the flocculated microstructure in cement pastes.



(a) (b) (c)

Figure 5. Improvements of the deformability of the fresh matrix mix at low W/C ratio (0.30). (a) Stabilized only with SP of 1.00 % (Γ_1 = 0.24), (b) SP of 1.00 %, HPMC of 0.013 % (Γ_1 = 0.32), (c) Same as (b), but with extension of the mixing time for the HPMC from 2 minutes to 10 minutes (Γ_1 = 5.76).

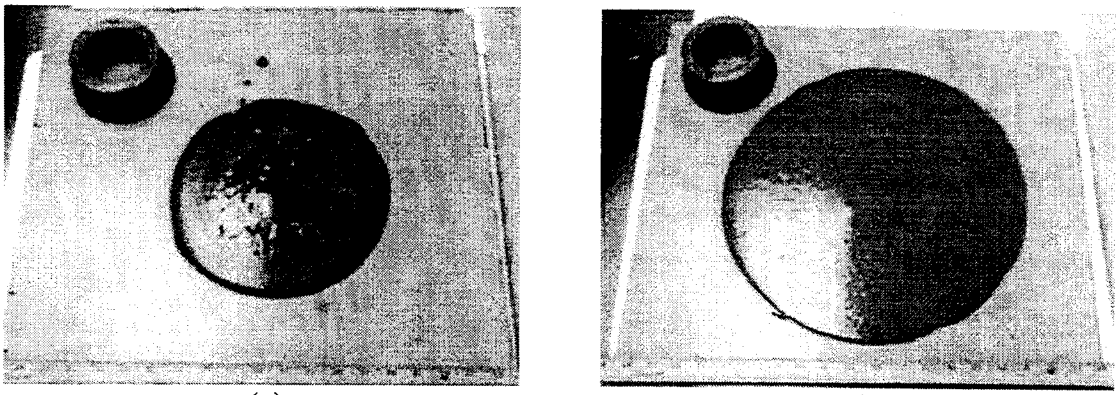
3.4 Control of the deformability of a fresh matrix mix at high W/C ratio

To obtain high ductility of ECC reinforced with PVA fibers, higher W/C ratios are required.

At high W/C ratios, it is critical to optimize the concentrations of SP and HPMC to achieve the desired deformability in the fresh matrix mix. The minimum content of SP (much less than 1%) is typically recommended for concrete with a high W/C ratio, to avoid segregation. Adsorption tests, however, indicate that the maximum amount of adsorbed SP onto cement particle surfaces is 1.00 % in the presence of adsorbed HPMC. In other words, SP concentrations lower than 1.00 % would lead to bare regions on the particle surfaces, enhancing the attraction between the particles and leading to incomplete dispersion of particles. Consequently, the fluidity loss with time would be faster with use of low SP concentrations, even though the initial deformability is high.

To overcome both the segregation tendency and fast fluidity loss, the microstructure should be designed so that segregation is prohibited by the appropriate medium viscosity and flocculation is prevented by sufficient adsorption of polymer onto the cement particles. Equation (1) indicates that the decrease in the reduced moduli at higher SP levels can be compensated by an increase in the medium viscosity to maintain the total viscosity above the critical level necessary to prevent segregation. In practice, it is known that addition of a viscosity agent, such as HPMC, avoids segregation induced by SP (Khayat and Guizani, 1994). That is, at higher SP concentrations, HPMC can be added to increase the suspension viscosity above a critical level necessary to prevent segregation in a cement paste. This would achieve the desired microstructure to produce slow fluidity loss, accompanying high resistance to segregation. However, at lower-than-optimal SP concentrations, the addition of HPMC may produce a microstructure that fails to prevent fast fluidity loss, even though segregation is avoided. In addition, non-adsorbed HPMC chains purely increase the medium viscosity and thus adjust the viscosity to above the critical level to cause segregation; the suggestion that the non-adsorbed HPMC chains directly affect the consistency of fresh mortar mix has not been proven. This highlights the need to optimize both the SP and HPMC concentrations to minimize segregation while slowing fluidity loss in the suspension.

In this work, a W/C ratio of 0.45 and a S/C ratio of 0.6 were required to achieve high ductility of ECC reinforced with PVA fibers. In addition, fine particles, such as fly ash, were incorporated at a FA/C ratio of 0.15 to improve the cohesiveness between the fresh matrix and the PVA fibers. Results of the deformability of the fresh mixes with varying SP and HPMC concentrations are shown in Figure 6. A SP concentration of 1.00% and a HPMC concentration of 0.13 % improve the deformability by 150 %, compared with that of a fresh mix stabilized with lower concentrations of SP (0.33 %) and HPMC (0.05 %). In these tests, the deformability is measured after allowing the fresh mix to rest for 10 minutes following loading into the flow cone.



(a) (b)

Figure 6. Effect of polymer concentration on the deformability of the fresh matrix mix prepared at a high W/C ratio of 0.45, (a) SP of 0.33 %, HPMC of 0.05 %, Γ_1 = 4.3, (b) SP of 1.00 %, HPMC of 0.13 %, Γ_1 = 10.6.

3.5. Effect of the deformability of the fresh matrix mix on that of the fresh ECC mix

Figure 7 plots the measured deformability of fresh ECC mix, made from the mortar matrix mixes (as described in the previous Section 3.4) with the indicated polymer concentrations, together with PVA fibers. This figure demonstrates how the deformability of the fresh matrix mix (Γ_l) affects that of a fresh ECC mix. Two volume percent of PVA fibers (type K-II REC manufactured by Kuraray Co. Ltd., Japan) was adopted to satisfy the micromechanical requirements for strain-hardening. Deformability of the fresh ECC mix was quantified using a half slump cone (cut in half to save materials). Higher deformability of the fresh matrix mix obtained at higher SP concentrations also led to higher deformability of the fresh ECC mix. The consistency of the fresh mix was also improved with an increase in the SP concentration.

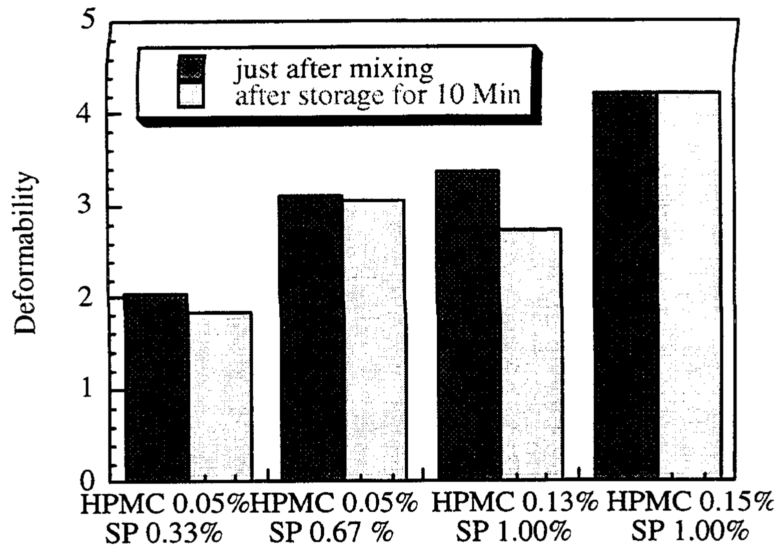


Figure 7. Effect of polymer concentrations on the deformability of fresh ECC mix.

In fact, the combination of HPMC at 0.13 % with SP at 1.00 % resulted in higher deformability of the fresh mortar mix (Γ_l = 10.6) than the combination of HPMC at 0.15 % with SP at 1.00 % (Γ_l = 9.4). No segregation was observed in the fresh mortar mix with HPMC at 0.13 % and SP at 1.00 %. The fresh ECC mix made with this matrix mix, however, showed segregation at the interfaces between the fresh matrix mix and the fibers. This segregation is attributed to too high of a deformability in the fresh mortar matrix, leading to inhomogeneous flow with the fibers. Therefore, this necessitates tuning the deformability of the fresh matrix mix to ensure homogeneous flow. The increase in the HPMC concentration to 0.15 % enhances the deformability of the fresh ECC mix, despite a small reduction in Γ_l from 10.6 to 9.4. This result emphasizes the importance of adjusting the flow of the fresh matrix mix in the presence of fibers on obtaining high deformability. The detailed adjustment, which depends on the characteristics of the fiber, is outside the scope of this article.

4. Properties of the Self-Compacting PVA-ECC

4.1 Composition

Based on the composite design approach described in the previous sections, we have determined a feasible composition for a self-compacting ECC, as shown in Table 3.

Table 3. Composition for a self-compacting ECC

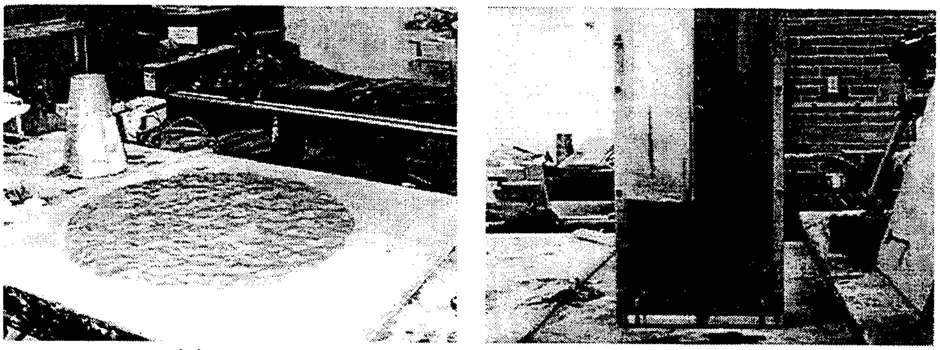
Cement	Sand	Fly ash	Water	HPMC	SP	Fiber (vol%)
1.00	0.60	0.15	0.45	0.0015	0.01	2.00

Compositions (except for fiber) expressed as weight fractions of cement

The PVA K-II REC fiber has a length 12 mm. This fiber has been designed for ECC reinforcement using micromechanics modeling. The sand size is 150 μm average diameter.

4.2 Self-compactability of fresh PVA-ECC mix

To demonstrate self-compactability, we performed the deformability test (with a full size slump cone) and the box test utilized in self-compacting concrete (Ozawa et al, 1995; Nagamoto and Ozawa, 1997). The deformability Γ_2 of the fresh PVA-ECC mix is 12 (Figure 8(a)). This value of the deformability is comparable to the deformability of self-compacting concrete, which ranges from 8 to 12. Figure 8(b) shows that self-compactability L of the fresh ECC mix is 0.82; L is defined as $h/(h_0/2)$, where h is the final height of the mix which flowed from the right compartment through the gate (with vertically placed reinforcement bars spaced 12 mm apart) into the left compartment, and h_0 is the initial height filled into the right compartment before gate lift). This value of self-compactability is also comparable to that of self-compacting concrete, which ranges from 0.73 to 1.00 (Okamura and Ozawa, 1995; Ozawa et al, 1995; Nagamoto and Ozawa, 1997).



(a) (b)

Figure 8. Field tests showing the high deformability and self-compactability of the fresh PVA-ECC mix. (a) Slump test, $\Gamma_2 = 12$; and (b) Box test, $L = 0.82$.

4.3 Tensile properties of self-compacting ECC

Tensile test were performed on ECC specimens to demonstrate the strain-hardening behavior of self-compacting ECC. The tensile specimens were cast without applying vibration, and were cured in water for four weeks.

Figure 9 shows that the ultimate tensile strain of the self-compacting ECC ranges from 3 to 7.5% for three different test specimens (two specimens failed at grip). During loading, a large number of microcracks with very fine crack spacing (2 to 5 mm) and small average crack width of 0.08 mm were formed, as observed in Figure 10. Crack closure, though incomplete, was observed on unloading, suggesting that the fibers bridge the cracks, without catastrophic fiber rupture during strain-hardening of the composite.

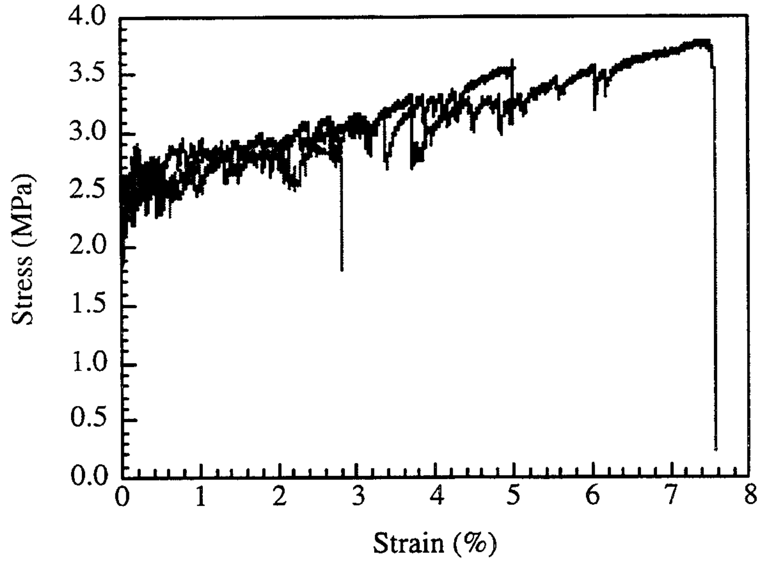


Figure 9. Tensile stress-strain curve of self-compacting PVA-ECC.

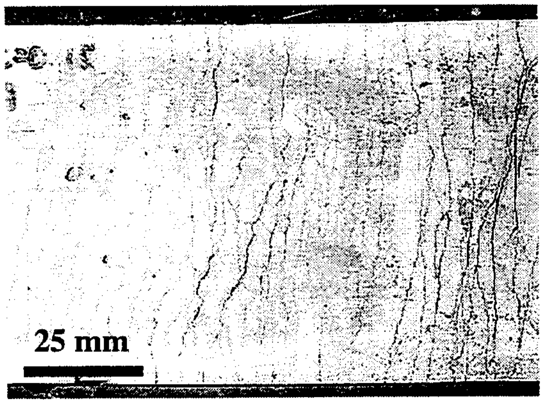


Figure 10. Closely spaced multiple cracks on self-compacting ECC specimen, tested to beyond peak load.

5. Conclusions

This article describes the development of a self-compacting ECC that exhibits self-compacting behavior in the fresh state and strain-hardening behavior in the hardened state. The emphasis is on microstructure tailoring in achieving targeted macroscopic properties. Micromechanics is utilized to design for strain-hardening behavior with saturated multiple cracking by controlling the fiber, matrix and interface properties. The relationship between self-compacting performance, rheological properties and microstructure development of a concentrated suspension of solid particles is employed to guide the use of organic admixtures for microstructure control. The optimal concentrations of the polymers are determined with the aid of adsorption, viscosity, and deformability measurements of the cement paste. By observing the compatibility between the requirements for fresh and hardened properties of the composite, a suitable composition of a self-compacting ECC with a PVA fiber is established. (A composition of a self-compacting ECC with PE fibers was described in Li et al, 1998). The resulting composite reveals self-compacting performance achieving Γ_2 and L values considered satisfactory for self-compacting concrete. The tensile strain capacity attained is in excess of three percent under a uniaxial tension test. It is concluded that the approach of microstructure control can be employed successfully in designing a self-compacting ECC.

6. Acknowledgements

The research on self-compactability of ECC described in this article has been sponsored by Kuraray Company, Ltd., Osaka, Japan. This paper was completed while V. Li was a Knud Højgaard Visiting Professor at the Technical University of Denmark. Support of Kuraray Company, the Knud Højgaard Foundation, and the Technical University of Denmark is gratefully acknowledged.

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