

#### 4. CONCLUSIONS

- Multiple-crack-type fiber reinforced air mortar was produced by adding a large amount of prefoamed bubbles to PVA fiber reinforced mortar.
- The strength and Young's modulus of the fiber reinforced air mortar decreased with an increase in the air content. The strength and Young's modulus were improved by using fiber reinforced mortar with a low W/C.
- As the air content increased, the number of cracks and the displacement from the initial cracking point to the peak point increased, whereas both the initial cracking load and peak load decreased.
- Almost all PVA-fibers penetrating the air bubbles were covered with cement matrix and hardly any naked fibers were observed. The effect of foam addition on the bond between fibers and matrix was presumably small
- Digital microscope observation revealed that PVA fibers tended to rupture at a lower air content but the matrix tended to fail at a higher air content.

The achievement of this study is useful for improving the properties of both air mortar and fiber reinforced mortar. Large size cracks on air mortar due to shrinkage can be dispersed into multiple fine cracks by adding fibers. This material can be applied to joint-free structures such as continuous pavement and walls. Optimum combinations of strength, ductility, density, workability and also cost can be obtained by selecting a suitable fiber type, air content and W/C of base mortar.

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## RATE DEPENDENCE IN ENGINEERED CEMENTITIOUS COMPOSITES

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### Abstract

This paper examines the rate dependence in engineered cementitious composite (ECC), a promising material for seismic, impact, and blast-applications. Research focus has been placed on uncovering the source of rate dependence in ECC and composite re-engineering. Test results show a strong decrease in tensile strain capacity with increasing strain rate in particular versions of ECC. Single fiber pullout test reveals that change in the interface chemical bond with rate is responsible for the loss of composite tensile ductility. Preliminary results in composite re-engineering confirm that extreme ductility of ECC can be retained under seismic loading rate.

### 1. INTRODUCTION

High performance fiber reinforced cementitious composites (HPFRCC) with high tensile ductility, toughness, and damage-tolerance are potential material solutions for seismic applications [1] and impact- and blast-resistant structures [2]. Under these high-rate loading scenarios; however, it is possible that HPFRCC properties may change and unexpected structural failure could happen. Unfortunately, most available knowledge is limited to HPFRCC quasi-static behavior. Rate dependence of HPFRCC properties has received little attention so far. If HPFRCC were to be applied to high-rate loading applications successfully, a better understanding of its rate dependence is needed.

There are two purposes in the study of the loading rate effects in HPFRCC. The first purpose is to quantify the rate dependence in order to establish a rate dependent constitutive model of HPFRCC for structural analysis and design. The second purpose is to derive knowledge of the sources of rate dependence in HPFRCC. For material

engineers, this knowledge provides important guidance for composite engineering. In this paper, the material engineering approach is adopted. A preliminary study has focused on quantifying rate dependence of composite tensile stress-strain behavior, understanding the sources of rate dependence, and redesigning the composite with desired high rate properties.

## 2. ENGINEERED CEMENTITIOUS COMPOSITE

Engineered cementitious composite (ECC), a special type of HPRCC with extreme tensile ductility, is used in this study to investigate the loading rate effects. Figure 1 shows the typical tensile stress-strain curve of ECC under quasi-static monotonic loading. As can be seen, ECC exhibits a tensile strain-hardening behavior similar to that of ductile metals. The "yield point" corresponds to the composite first cracking; subsequent strain-hardening is achieved by a continuous formation of multiple cracks. The ultimate tensile strain capacity of ECC ranges from 3 - 5% which is several hundred times that of normal concrete (~0.01%). The fracture toughness of ECC is similar to that of aluminum alloys [3]. Furthermore, the material remains ductile even when subjected to high shear stresses [4]. The compressive strength of ECC ranges from 40-80 MPa depending on mix composition, the high end similar to that of high strength concrete.

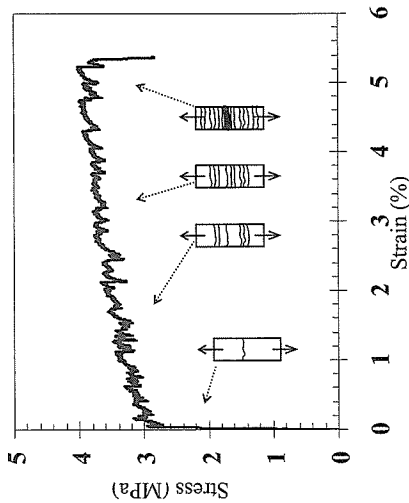


Figure 1: Typical ECC tensile stress-strain curve

The ingredients in ECC are cement, water, sand, fly ash, fiber, and other chemical additives commonly used in fiber reinforced concrete (FRC). PVA-ECC utilizes short (8 or 12 mm), randomly distributed polymer fibers (e.g. Polyvinyl Alcohol) with a moderate volume fraction (2% or less). With a relatively small amount of short fibers and appropriate particle-size grading, the mixing procedure of ECC is similar to that of normal concrete and

can be produced in regular or self-consolidating [5, 6] processes. The high performance, moderate fiber content combination is attained by micromechanics-based composite optimization [7, 8].

It has been observed experimentally that ECC structural members, such as beams [9], columns [10], walls [11], and connections [12], show superior structural ductility, structural strength, energy absorption and extreme high damage tolerance under monotonic and cyclic loading, when compared with normal R/C structures, even when the ECC members do not contain seismic detailing. This significantly enhanced performance of ECC structural elements is a direct result of the ultra-ductility of ECC, which suppresses the brittle failure mode and promotes synergistic interaction between reinforcement and surrounding ECC. It is plausible that this high-energy absorption feature of R/ECC may be exploited in members subjected to seismic, impact, and blast loading, as long as the tensile ductility of ECC could be retained under high rate loading.

## 3. REVIEW OF RATE DEPENDENCE IN ECC

Maaiej et al [2] investigated the strain rate effect in a hybrid-fiber ECC (1.5 vol.% polyethylene and 0.5 vol.% steel fibers) and concluded that the tensile strain capacity shows almost no rate dependence for strain rate ranging from  $2 \times 10^6$  to  $2 \times 10^{-1}$  1/s (figure 2). At higher strain rates, the strain capacity (~3.2%) and multiple cracking behavior were found to be similar to those in quasi-static tests. A remarkable increase in the ultimate tensile strength (from 3.1 MPa to 6 MPa) with increasing strain rate was also reported. Conversely, Douglas and Billington [13] reported strong rate dependence of tensile ductility in a PVA-ECC (ECC with 2 vol.% polyvinyl alcohol fiber). At the highest strain rate ( $2 \times 10^{-1}$  1/s), the tensile ductility decreased by 50% (from 0.5% to 0.25%), while the ultimate tensile strength doubled that at quasi-static strain rate ( $2 \times 10^{-5}$  s<sup>-1</sup>).

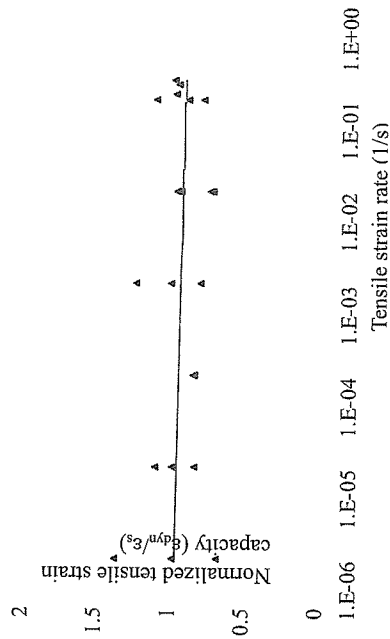


Figure 2: Rate dependency in hybrid-fiber ECC tensile ductility (After Maaiej et al [2])

These results reveal several interesting observations. First, ECC tensile properties may exhibit rate dependence. Second, the magnitude and tendency of this rate dependence will likely depend on the microstructure/material composition. These observations suggest a need to understand the source of rate dependence, in order to design an ECC with extreme tensile ductility under higher strain-rate loading.

#### 4. EXPERIMENTS

##### 4.1 Material

A reference ECC, M45 [14], for general applications is used as a control to investigate the rate dependence in ECC. Table 1 shows the mix proportions of M45. The matrix of M45 is comprised of standard mortar components, including type I Portland cement (C), water (W), fly ash (FA, class F), sand (S, 0.11 mm nominal grain size), and superplasticizer (SP). The PVA (REC-15) fiber is produced by Kuraray Co. and mechanical properties are provided in table 2.

Table 1: Mix proportions of ECC-M45 by weight

Material	C	W	FA	S	SP	PVA (vol.%)
ECC-M45	1.0	0.53	1.2	0.8	0.03	0.02

Table 2: Mechanical properties of PVA fiber REC15

Material	Length (mm)	Diameter ( $\mu\text{m}$ )	Tensile Strength (MPa)	Tensile Modulus (GPa)
PVA-REC15	12	40	1600	40

##### 4.2 Composite uniaxial tensile test

A uniaxial tensile test is conducted to quantify the magnitude of rate dependence in ECC tensile stress-strain behavior. Coupon specimen (220mm x 75mm x 12.7mm) aged 28 days with 100mm gage length is tested in uniaxial tensile configuration. A servo-hydraulic material test machine is used in a displacement control mode and the test strain rate ranges from  $10^{-5}$  to  $10^{-1}$  1/s (corresponding cross head speed is from  $10^{-3}$  to 10 mm/s). The low end represents the quasi-static test and the high end is the condition for seismic loading.

##### 4.3 Single fiber pullout test

To uncover the source of rate dependence, a single fiber pullout test (figure 3) is conducted to examine the rate dependence in fiber/matrix interface properties. Three interface micromechanics parameters, namely the chemical bond strength,  $G_d$  ( $\text{J/m}^2$ ), frictional bond strength,  $\tau_0$  (MPa), and slip hardening coefficient,  $\beta$ , were determined from the pullout curve [15]. The pullout speed ranges from  $10^{-3}$  to 10 mm/s, which is identical with that in composite uniaxial tensile test.

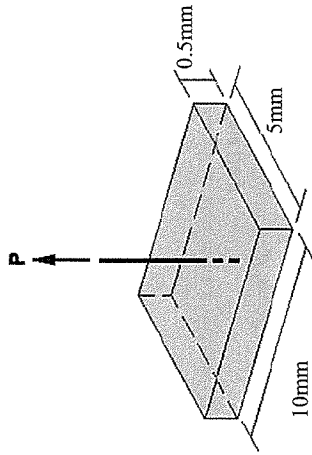


Figure 3: Geometry for a single fiber pullout specimen

#### 5. RESULTS

##### 5.1 Rate dependence in composite tensile behavior

Preliminary results show strong rate dependence in PVA-ECC M45 tensile properties. Figure 5(a) plots the tensile stress-strain curve of M45 in different strain rates. A descending trend of tensile ductility with increasing strain rate is found for M45 as depicted in figure 5(b). Tensile ductility reduces from 3% to 0.5% at the highest strain rate. Both first cracking strength and ultimate tensile strength were found to increase with increasing strain rate.

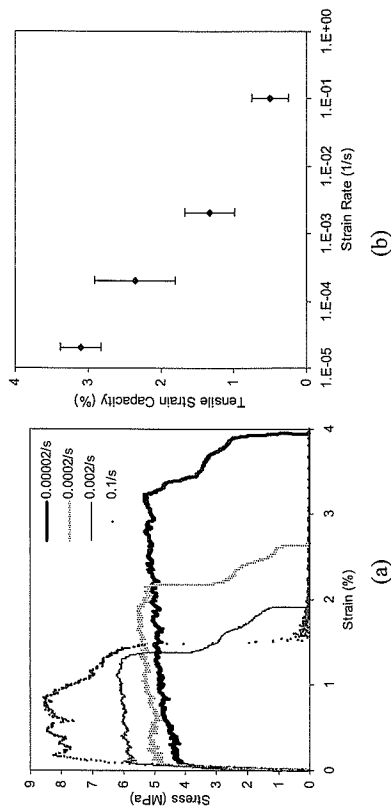


Figure 4: Rate dependency in ECC-M45: (a) tensile stress-strain curve and (b) tensile ductility versus strain rate relation

### 5.2 Rate dependencies in interface properties

Figure 5 presents the rate dependence of interface chemical bond strength,  $G_d$ , in M45. A strong rate dependency in  $G_d$  is evident. At the highest pullout speed,  $G_d$  can be 5 times higher than the static value (from 1.1 to 5.1 J/m<sup>2</sup>). However, the interface frictional bond strength and slip hardening coefficient show almost no rate dependence at the present pullout speed.

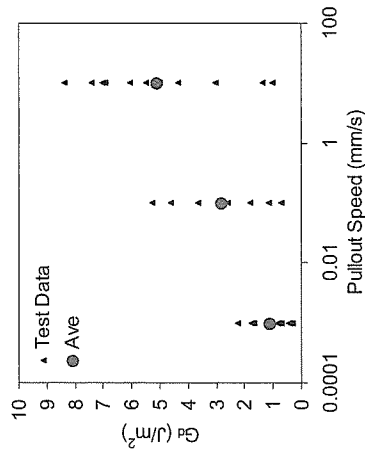


Figure 5: Rate dependence in interface chemical bond strength,  $G_d$   
ECC RE-ENGINEERING FOR HIGH RATE APPLICATIONS –  
PRELIMINARY RESULTS

From the result of micro-scale investigation, specifically rate dependencies in fiber/matrix interface properties, it is concluded that interface chemical bond strength increase is responsible for the low tensile ductility in M45 composite behavior at higher loading rate. The chemical bond increase tends to cause premature fiber rupture, which can lead to drastic loss of tensile ductility. Although it has been tested and recognized that other properties, such as fiber modulus and strength and matrix toughness and strength, may also exhibit rate dependence, not much can be done in terms of modifying rate dependence in these parameters. Therefore, attention is given to modifying interface properties in general, and chemical bond strength in particular. Several attempts have been made to re-tailor ECC for high rate applications and preliminary results are summarized here.

One approach is to eliminate chemical bond between fiber and matrix. If no chemical bond exists, no rate dependence can exist in chemical bond strength. It is well known that PE (polyethylene) fibers show no chemical bond in cement-based composite due to its hydrophobic nature. Hence, a lower rate dependency in PE-ECC is expected when compared with PVA-ECC. This concept is supported by the observations in the test results of Maalej et al [2].

As increase in chemical bond tends to promote fiber breakage, another approach would be to use a shorter fiber length. Figure 6 shows the tensile stress-strain curve of M45 with 8mm PVA fiber at the highest strain rate (0.1/s). The mix proportion of this ECC is exactly the same with M45 except the PVA fiber only has 8mm in length (12mm in M45). As can be seen, the average tensile strain capacity can reach 1.5% which is 3 times higher than 12mm PVA-ECC M45 at the same loading rate.

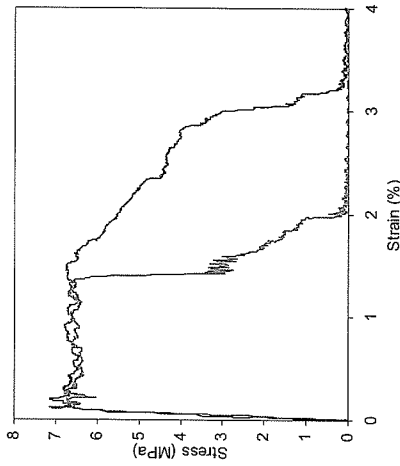


Figure 6: Stress-strain curve of ECC M45 with 8mm PVA fiber at the highest strain-rate loading (0.1/s)

It is recognized that increase of chemical bond strength can cause a higher matrix cracking strength and a lower bridging complementary energy. This leads to a smaller margin between peak bridging strength ( $\sigma_{b,peak}$ ) and matrix cracking strength ( $\sigma_c$ ) and between bridging complementary energy ( $J_b$ ) and matrix toughness ( $J_{ip}$ ). Both tendencies are unfavorable to strain-hardening. The third approach to material re-engineering is to delay the rate dependency by imposing a larger margin between  $\sigma_{b,peak}$  and  $\sigma_c$  and between  $J_b$  and  $J_{ip}$  in advance.

Lightweight ECC [16] provides a larger margin for strain-hardening condition and has desirable features for seismic applications. By introducing light-weight aggregate, it may also weaken the interface chemical bond, which has a positive effect in delaying rate dependence of PVA-ECC. Table 3 gives the mix proportions of a lightweight PVA-ECC. Lightweight aggregate, glass bubble S60, is produced by 3M Co. Figure 7 shows the tensile stress-strain curve of lightweight ECC at different loading rate (10<sup>-2</sup> to 10<sup>-1</sup> 1/s). It is found that tensile strain capacity can be retained (~3.5%) at the highest strain rate.

Table 3: Mix proportions of lightweight ECC by weight

C	*LA	W	**MC	SP	PVA (Vol. %)
1.0	0.2	0.45	0.0015	0.03	0.02

\* LA: Lightweight Aggregate (Glass Bubble S60)

\*\* MC: Methyl Cellulose

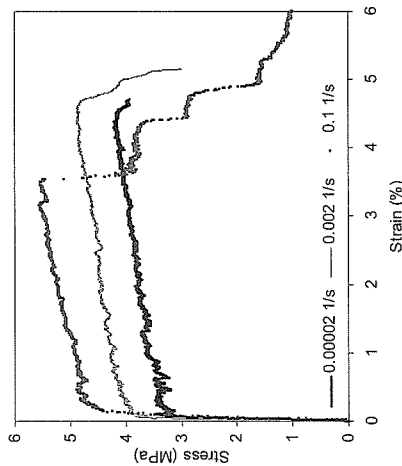


Figure 7: Stress-strain curve of lightweight ECC at different loading rates

## 7. CONCLUSION

This study investigates the rate dependence of ECC and explores the underlying micromechanical sources responsible for the rate effect. This knowledge provides insights for ECC re-engineering. Several preliminary attempts have been made to redesign a new generation of ECC for high rate applications. The following specific conclusions may be drawn:

- The tensile properties of PVA-ECC M45 exhibit strong rate dependence. The tensile strain capacity decreases from 3% to 0.5% when the loading rate increases from quasi-static to seismic strain rate.
- The interfacial chemical bond strength,  $G_a$ , of M45 shows a strong rate dependence which contributes to the composite rate dependency.  $G_a$  at the highest pullout speed is found to be 5 times that in quasi-static loading.
- Extreme ductility of ECC under higher loading rate could be retained, if properly designed. At seismic loading rate, the tensile strain capacity is 3.2% for ECC with PE fiber, 1.5% for PVA-ECC M45 with 8mm fiber, and 3.5% for lightweight ECC with a

light-weight matrix.

- This research demonstrates that ECC can be engineered with high ductility suitable for high rate loading applications.

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## INVESTIGATION OF THE FIBER BRIDGING STRESS- CRACK OPENING RELATIONSHIP OF FIBER REINFORCED CEMENTITIOUS COMPOSITES

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### Abstract

High performance fiber reinforced cementitious composites (HPFRCC) are characterized by multiple cracking and pseudo strain hardening under direct tensile loading. Designing for these properties of HPFRCC and prediction of the tensile behavior is essential for structural applications. In this study, experimentally obtained information on the fiber bridging stress-crack opening relationship is used to assess the potential for multiple cracking and strain hardening behavior of HPFRCC in uniaxial tension.

This paper proposes a method to simulate the displacement-controlled uniaxial tension test of HPFRCC using information on stress-crack opening relationship. The multiple cracking phenomenon in the strain hardening stage is captured in the simulation results and characteristics of multiple cracking such as width and spacing can be obtained.

### 1. INTRODUCTION

Concrete is one of the fundamental materials used in civil engineering and has many beneficial features such as high compressive strength, relatively low cost, convenient production and placement, and good durability. However, due to its brittle nature, it tends to crack under tensile loading, resulting in loss of tensile strength in the post-cracking deformation regime. For reinforced concrete, the lack of ductility of concrete has implications on the structural performance as well as long term durability. Internal fiber reinforcement can improve the tensile strength and ductility of concrete beyond the elastic limit. Fiber reinforced concrete can be categorized into conventional Fiber Reinforced Cementitious Composite (FRCC) and High Performance Fiber Reinforced Cementitious Composite (HPFRCC). The former shows a tension softening behavior