17 DEVELOPMENT OF SPRAYABLE ENGINEERED CEMENTITIOUS COMPOSITES

Y.Y. Kim[1], H.J. Kong[2] and V.C. Li[1]
[1] ACE-MRL, Department of Civil and Environmental Engineering, University of Michigan, USA
[2] Department of Macromolecular Science and Engineering, University of Michigan, USA

Abstract

Sprayable engineered cementitious composite (ECC), which exhibits tensile strain-hardening behavior in the hardened state, while maintaining sprayable properties in the fresh state, has been developed by employing parallel control of micromechanical design and rheological process design. In the development concept of sprayable ECC, micromechanics is adopted to properly select the matrix, fiber, and interface properties to exhibit strain-hardening and multiple cracking behaviors in the composites. With the selected ingredient materials, the pumpability and sprayability of ECC are then realized by the controlled rheological properties of fresh matrix and the uniform dispersion of fibers. A series of spray test and deformability test reveals that the sprayable ECC developed in this study exhibits superior pumpability, sprayability and rebound property. Uniaxial tensile tests demonstrate that the mechanical performance of sprayed ECC is comparable to that of ECC cast with external consolidation.

1. Introduction

Engineered Cementitious Composites (ECC) is a micromechanically designed cementitious composite which exhibits extreme tensile strain capacity while using a moderate amount of fiber, typically less than 2% in terms of fiber volume fraction (V_f). Recently, a variety of applications of this material ranging from repair and retrofit of structures, cast-in-place structures to pre-cast structural elements requiring high ductility are being developed [1].

Sprayable ECC can be defined as the ECC conveyed through a hose and pneumatically projected at high velocity from a nozzle onto place. The rheological properties of the fresh mix in the wet spray processing are obviously crucial. The fresh mix should be moderately deformable, i.e., pumpable under the pumping and conveying pressure, so it would efficiently move through the hose to the nozzle. Once it is sprayed onto the surface of the substrates, however, it should be viscous enough to stay adhered to the substrate and to remain cohesive without composite ingredient segregation.

To attain such different fluid properties of the fresh mix, while embodying the ductile performance of ECC, we adopt the method to control the processing parameters and micromechancial parameters in a parallel manner. At given concentrations of ingredients determined by micromechanical design, we focus on modulating flocculation between cement particles under the hypothesis that adjusting interactions between cement particles greatly alter the fluid properties of fresh ECC mix. For this purpose, we investigate the effects of organic and inorganic admixtures on the rheological properties of cement pastes to determine the optimal dosages. Then, we examine the validity of cement pastes on realizing the desired fluid properties of fresh ECC mix with various fluid tests including deformability tests and spray tests. Subsequent uniaxial tensile tests demonstrate that the mechanical performance of sprayed ECC is comparable to that of ECC cast with external consolidation, for the same mix design.

2. Material design framework

2.1 Micromechanical design

Micromechanical design is a technique to tailor the microstructure of the composite based on the understanding of the mechanical interactions between the matrix, fiber, and interface phases under load. This technique utilized herein is mainly focused on achieving strain-hardening in tension since the tensile ductility is representative of the structural performance as well as material ductility.

A fundamental requirement for strain-hardening is that steady state cracking occurs, which requires the crack tip toughness J_{tip} to be less than the complementary energy J_b' calculated from the bridging stress σ vs. crack opening δ curve, as illustrated in Fig. 1 [2],

$$J_{tip} \le \sigma_o \delta_o - \int_0^{\delta_o} \sigma(\delta)\, d\delta \equiv J'_b \tag{1}$$

$$J_{tip} = \frac{K_m^2}{E_c} \tag{2}$$

where σ_0 is the maximum bridging stress corresponding to the opening δ_0, and E_c is the composite elastic modulus. Eq. (1) is obtained by considering the balance of energy changes during extension of the steady state flat crack. Another condition for strain-hardening is that the tensile first crack strength σ_{fc} must not exceed the maximum bridging stress σ_0,

$$\sigma_{fc} < \sigma_o \tag{3}$$

where σ_{fc} is determined by the maximum preexisting flaw size max a_0 and the matrix fracture toughness K_m. Satisfaction of Eqs. (1) and (3) is necessary to achieve ECC behavior. Otherwise, normal tensile softening FRC behavior results.

Thus, the ECC theory provides an analytical tool for minimizing the fiber content. The small content of discontinuous fibers allows for flexible processing for spray procedure. Additionally, the processing design focuses on the control of aggregated microstructure in the fresh state. The microstructural adjustment, however, must ensure compatibility with micromechanical design.

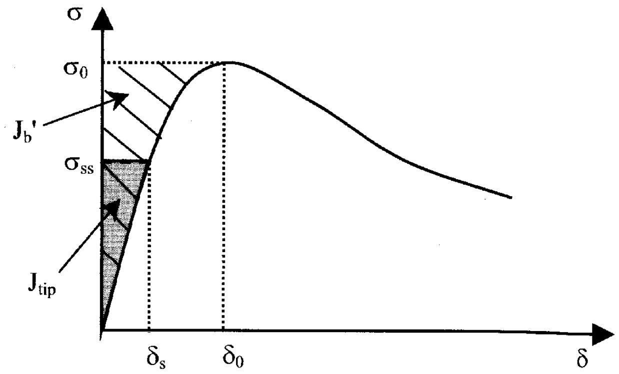


Fig. 1: A typical σ(δ) curve for strain hardening composite. Hatched area represents the complementary energy J_b'. Shaded area represents the crack tip toughness J_{tip}

2.2 Two-stage rheological control

To develop a satisfactory spray process, the fresh properties of ECC mix are controlled to have a two-stage behavior. In the first stage, a highly deformable ECC mix is desirable for ease of pumpability for transporting the material from the mixer to the spray nozzle via a flexible hose. During this stage, low viscosity is necessary. In the second stage, the viscosity should rise rapidly to facilitate the adhesion of fresh mix sprayed onto a substrate.

These contrasting fluid properties need to be achieved at given concentrations of ingredients determined by micromechanics-based design. Therefore, we focus on adjusting the flocculation rate of cement particles, since moderate flocculation leading to low viscosity may be advantageous for the transport of fresh mix, while strong flocculation leading to high viscosity provides the good adhesion and cohesion. To achieve a moderate flocculation, a proper concentration of polymeric admixtures to disperse/stabilize the cement particles will first be determined. To induce the aggregation to develop at the desired rate, reactive particles, which are smaller than cement particles by one order of magnitude, will also be utilized. Although reactivity of particles may enhance the viscosity of particles over time, small size of particles will contribute to reduction of the viscosity in the first stage by freeing the water between the cement particles. Therefore, an appropriate concentration of the reactive particles will be determined, since it governs the competitive contributions between the particle size effect and reactivity to the viscosity of the mix.

3. Experimental program

3.1 Material

PVA fiber REC tailored based on the framework outlined in the previous section and produced by Kuraray Co., Japan, is adopted in this study [3]. ASTM Type 1 ordinary Portland cement (OPC, average particle diameter = 11.7 ± 6.8 μm, LaFarge Co.), silica sand (average particle diameter = 110 ± 14.8 μm, U.S. Silica Co.), fly ash (FA, average particle diameter = 26.9 ± 7.0 μm, Boral Material Technologies Inc.), and calcium aluminate cement (CA, average particle diameter = 5.5 ± 1.5 μm, Alcoa Chemicals Co.) were used as the major ingredients in the matrix. All of the cementitious raw materials were used as received. All of the cementitious raw materials were used as received. Melamine formaldehyde sulfonate (MFS, W. R. Grace Chemical Co.) and hydroxypropylmethylcellulose (HPMC, DOW Chemical Co.) were used as admixtures to modify the fluid properties.

3.2 Rheological measurements for fresh cement paste

A Bohlin controlled stress rheometer (CS-50) was used to measure the change in the storage modulus of fresh cement pastes over time. Using a concentrated cylinder geometry, the paste was deformed at a constant stress within the linear viscoelastic region and the resulting strain was measured at frequency of 1 Hz. The storage modulus and the dynamic viscosity were then directly determined from this measurement.

3.3 Deformability test for mortar matrix and ECC mix

To quantify the deformability, flow table tests for mortar matrix and slump tests for ECC mix were conducted, respectively. A regular flow cone (diameter = 10 cm) and a conventional slump cone (diameter = 20 cm) were employed to measure the deformability of the fresh mix.

The deformability test was performed twice, immediately after mixing, and after resting for a certain amount of time. No external means (e.g. vibration) were applied to consolidate the fresh ECC mix. Deformabiltity Γ were calculated using Eq. (4) with the measured maximum diameter of the spread d_1 and the diameter perpendicular to it d_2,

$$\Gamma_{rest} = \frac{(d_1 \times d_2) - d_0^2}{d_0^2} \tag{4}$$

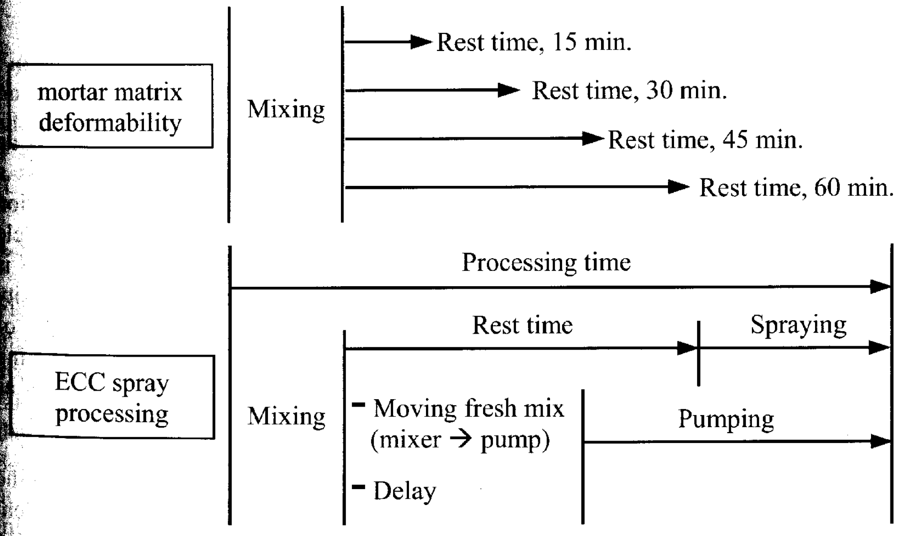
where the d_0 is the diameter of flow cone or slump cone, and subscript "rest" means the rest time after mixing in minutes. When the deformability test is performed for the mortar matrix using the flow cone, the resulting deformability measurement is denoted as Γ_{rest}^{F}.

.4 Spray test

resh ECC mixed in a 40 liters capacity drum mixer was pumped through a spiral pump d then down a 25 mm diameter rubber hose to a spray gun, from where it was sprayed eumatically with an air pressure of approximately 700 kPa onto a substrate. The umping pressure was observed during spray processing. Once the pumping pressure ached 4 MPa, the maximum pumping pressure permitted by the pump manufacturer, tests were aborted. The mix design is then considered unsuitable for spray processing.

characterize the pumpability in terms of pumping pressure, the pump-out tests were rformed by documenting pumping pressure during conveyance of the fresh ECC mix ough the open hose without nozzle. The deformability Γ_0 was also measured just after ixing to quantify the ECC fresh properties suitable for pumping.

he fill-up test was conducted for all ECC mixes by spraying onto a vertically sitioned substrate in the form of a wood box of 356×362 mm bottom area and 51 mm pth. The rest time between the end of mixing and the beginning of spraying, as ustrated in Fig. 2, required for the fresh mix to attain an appropriate viscosity to fill the x without any flowing down in one continuous spraying operation was measured. The lation between deformability Γ_{rest} and rest time was obtained from slump test and fill- test. We set the optimum rest time of 15 minutes as a target assuming in-situ batch nt mixing.



ig. 2: Schematic comparison between the definitions of rest time in mortar matrix eformability test and in ECC spray processing

prayability was also assessed quantitatively in terms of the thickness of fresh ECC that uld be sprayed onto a substrate prior to failure under its own gravitational force pray-on test). The fresh ECC was sprayed horizontally onto a vertical surface and vertically onto an overhead surface to try and obtain as large a thickness of sprayed ECC layer as possible in one continuous spray processing.

4. Results and discussion

4.1 Determination of micromechanical constraints

PVA fiber tailored based on the framework outlined in section 2.1 was adopted in this investigation. Extensive micromechanical analyses and experiments have disclosed that a W/C ratios ranging from 0.45 to 0.47 and a S/C ratio of 0.8 would be appropriate to achieve satisfactory matrix properties as well as interfacial frictional stress τ_0 [4]. To obtain sufficient strain-hardening behavior, 0.8% oiling agent content suitable for attaining appropriate interfacial bond properties was chosen. Such adjustments of the interfacial properties would set the fiber volume fraction (V_f) of 2.0% which is known as the critical V_f.

Given the diameter of selected fiber(d_f = 39 μm), proper aspect ratio, that is the ratio of fiber length (L_f) to fiber diameter, must be chosen on the basis of interfacial properties of fibers and composite processibility [5]. For the PVA fiber (V_f = 1.5, 2, 3%, L_f = 6-12 mm), the average workable aspect ratio was chosen to be approximately 300 [6]. In particular, fiber length is also limited by pumpability consideration, which means that increasing the L_f hinders from conveying fresh mix through the spiral pump. The fiber length of 8 mm was selected based on the more processible aspect ratio (200) than the average workable aspect ratio.

4.2 Determination of rheological control parameters

As confirmed on the processing of self-compacting ECC [7], MFS can be used as an electrostatic dispersant, and HPMC can be used as a steric stabilizer as well as a viscosity agent, depending on the sequence of polymeric admixtures additions. Addition of HPMC prior to MFS leads to the formation of electrosteric layers on the particle surfaces, resulting in much slower increase in the viscosity over time than when MFS is added first (Fig. 3a). Since the spray processing requires fast increase in the viscosity after a certain time period, possessing too high resistance against the built-up of flocculated microstructure may not be desirable. Therefore, we adopted the mixing procedure to add HPMC following the addition of MFS, so that HPMC can act only as viscosity agent to prevent the segregation between the ingredients.

To enhance the cohesiveness of the fresh ECC mix and the adhesiveness of ECC to the substrates after spraying, we investigated a technique to enhance the time-dependent flocculation between cement particles stabilized with polymers at a proper rate. Adding 3% of CA particles based on the weight of cement particles retarded the increase in the viscosity over time (Fig. 3b). However, when the ratio between CA and cement particles are increased to 5%, we could observe a slower increase in the viscosity than the plain cement pastes for the first 10 minutes, followed by an acceleration of viscosity increase. The reduction in the viscosity for the first 10 minutes in the presence of CA particles is attributed to the particle size effect to free the water between cement particles. As time goes on, reactivity of CA particles to enhance the aggregation becomes dominant over

the particle size effect, thus accelerating the increase of the viscosity. Therefore, we propose that use of appropriate amount of CA particles slow increase of the viscosity in the beginning in order to facilitate the mixing and spray process, and the subsequent acceleration in the viscosity increase in order to make fresh mix readily adhere to the substrates.

Excessive CA contents may be detrimental to achieving the desired hardened mechanical properties, i.e., matrix toughness and fiber/matrix interfacial properties, which were designed micromechanically without consideration of CA. Thus, CA dosages up to 5% were introduced in the present study. The effect of the higher CA content will be further investigated.

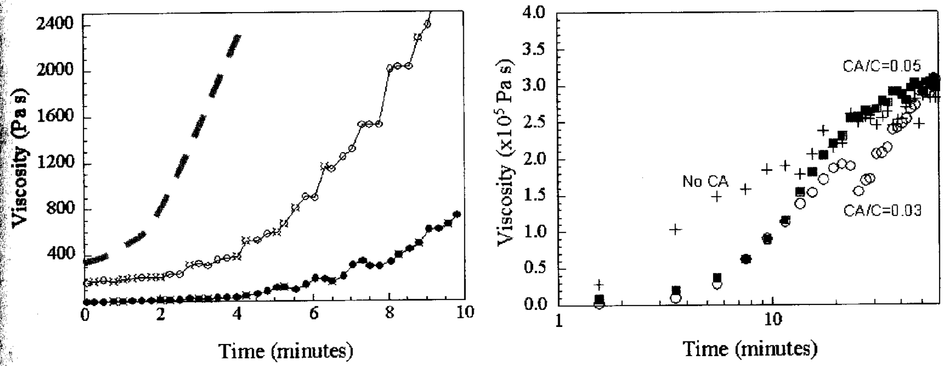


Fig. 3: Changes in cement paste viscosity over time for (a) Effects of mixing sequence on the viscosity change (---) no stabilization, ● addition of HPMC prior to MFS, ○ addition of MFS prior to HPMC; and (b) Effects of CA particles on the viscosity change, + cement suspension without CA particles, ○ cement suspension with CA particles (CA/C=0.03), ■ cement suspension with CA particles (CA/C=0.05).

4.3 Fluid properties of fresh mortar matrix mix

Fig. 4a illustrates the effect of MFS concentration on the deformability of fresh mortar mix Γ^F. Based on the rheological studies with cement pastes, mortar matrix was mixed according to the sequence to add MFS, HPMC, and CA particles. MFS concentration ranges from 0.5% to 2.0%, with constant HPMC concentration of 0.05%. Fig. 4a shows that decreasing the MFS concentration from 2.0 to 0.5% (w/w) significantly reduces the deformability from 5.6 to 1.6 in terms of Γ^F_0 while the deformability changes over time at almost same rate despite the varying MFS concentrations. This indicates that the initial deformability of ECC mix is strongly dependent on the concentration of MFS.

Fig. 4b illustrates the effect of the CA on the rate of deformability loss of fresh mortar mix Γ^F measured by the flow table test. The amount of cement replaced by CA was 0, 3, and 5% based on the weight of cement particles with constant HPMC, and MFS concentrations. Fig. 4b shows a difference in Γ^F_0 just after mixing with the dosage of CA because of particle size effect as discussed in the previous section. However, the addition of CA accelerates the setting of mortar mix and induces the flocculation between the stabilized particles, leading to a fast decrease in the deformability over time.

The effects become stronger with increasing dosage of CA. These test results reconfirm that replacing 5% of cement with CA particles is the optimal dosage of CA particles since this mortar matrix mix exhibits more moderate initial deformability as well as faster decrease of deformability over time, compared to other mixes. Consequently, it is demonstrated that the rest time during spray processing, as illustrated in Fig. 2, can be controlled by adjustment of MFS and CA dosages.

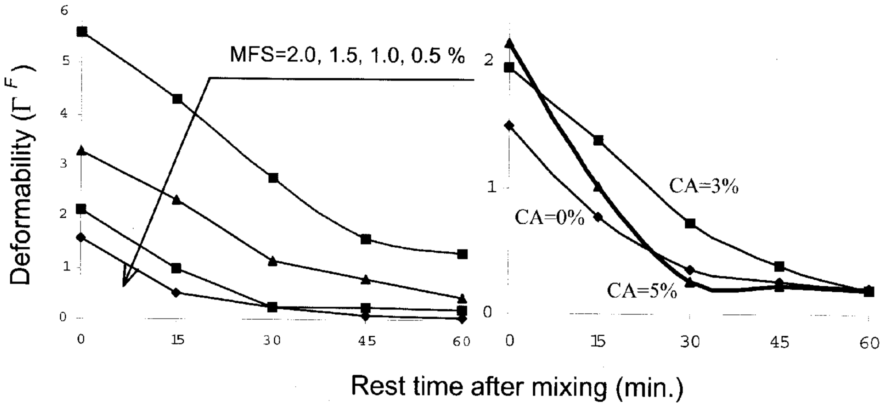


Fig. 4: Changes in deformability of the mortar matrix, as a function of rest time for (a) Effect of MFS concentration (HPMC = 0.05%, CA = 5.0%) and (b) Effects of CA dosage (MFS = 1.0%, HPMC = 0.05%).

4.4 Deformability, pumpability and sprayability of fresh ECC mix

From the results obtained in the previous sections, several kinds of ECC mix were designed and sprayed to determine suitable fresh properties for spraying in terms of deformability Γ. To demonstrate pumpability, the pump-out tests were performed just before spraying. It was found that pumping pressures were kept below 1 MPa not only during the pump-out tests but also during the spraying procedure. These observations revealed that ECC mix, of which Γ_0 was more than 3.0, was properly pumpable for this spiral pump system. It was demonstrated by fill-up test (Fig. 5) that the suitable deformability of fresh ECC mix when spraying (Γ_{rest}) ranged from 2.0 to 3.0. The rest time demanded for the fresh mix to attain a viscosity to fill the box in a continuous spray processing, and the deformability when spraying was measured by fill-up test and slump test. Based on those tests, we employed MFS dosage of 0.75% to optimize the rest time at 15 minutes.

As shown in Fig. 6, we assessed the sprayability quantitatively to obtain as large a thickness of sprayed ECC as possible, in a continuous spray processing. Spraying onto a vertical surface and onto an overhead surface, the maximum thickness of 45 mm and 25 mm were achieved. These values of 25 and 45 mm are comparable to the recommended thickness of spray layer, ranging from 25 mm to 50 mm, for spraying of concrete in repair work [8, 9].

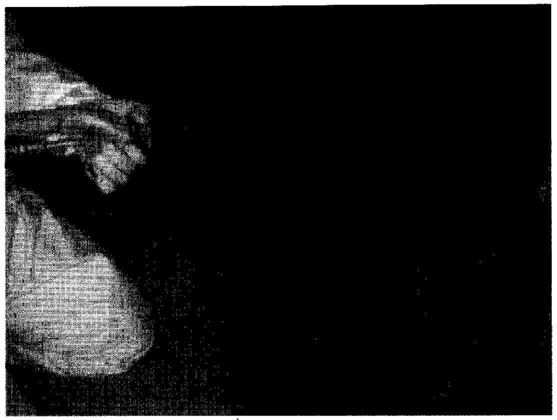


Fig. 5: Fill-up test

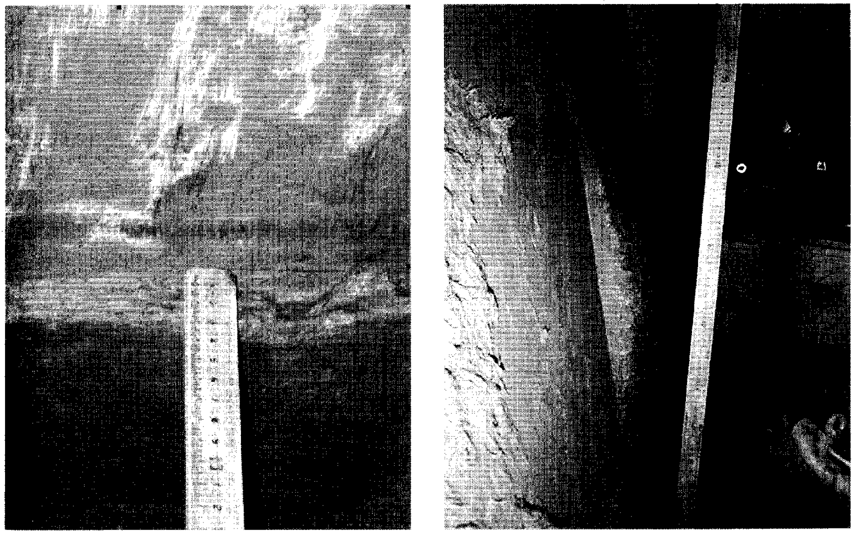


Fig. 6: Demonstrations by spray-on test for (a) 45 mm thickness of sprayed ECC layer on vertical surface and (b) 25 mm thickness of sprayed ECC layer on overhead surface

It was particularly noted that almost no rebounds were observed in spraying ECC. It is most likely because all ingredients in the sprayed ECC are strongly integrated by the viscous cement suspensions due to the smaller size of sand and lower stiffness of fiber in ECC, compared to commercial prepackged mortars or typical steel fiber reinforced shotcrete. Such a low rebound of sprayed ECC should be beneficial to cost and mechanical performance. First, the amount of rebound in sprayed concrete material typically demands an additional 5 to 8% increase in cost [10]. Second, it is generally agreed that the amount of fiber rebound seriously affects the toughness of the resulting in-situ fiber reinforced shotcrete. Highly toughened shotcrete can be obtained by the use of the ECC in spray processing.

4.5 Tensile performance of the sprayed ECC

To verify the strain-hardening behavior of the sprayed ECC and to compare it with the test results of cast ECC coupons, direct tensile tests were performed. Sprayed ECC coupons (305 mm × 76 mm × 13 mm) were sawn from the ECC panels sprayed in a wood mold positioned vertically. Additional ECC specimens were prepared by casting into tensile coupon molds, for the same mix design.

As compared in Fig. 7 the strain capacity and tensile strength of the sprayed ECC is comparable to that of ECC specimens cast with external consolidation. Such consistent material property is likely due to the sufficient compaction during the spray processing. Fig. 7 shows that the ultimate tensile strain of the sprayed ECC ranges from 1.5 to 2.5%. During loading, a large number of microcracks and small average crack width less than 100μm were formed.

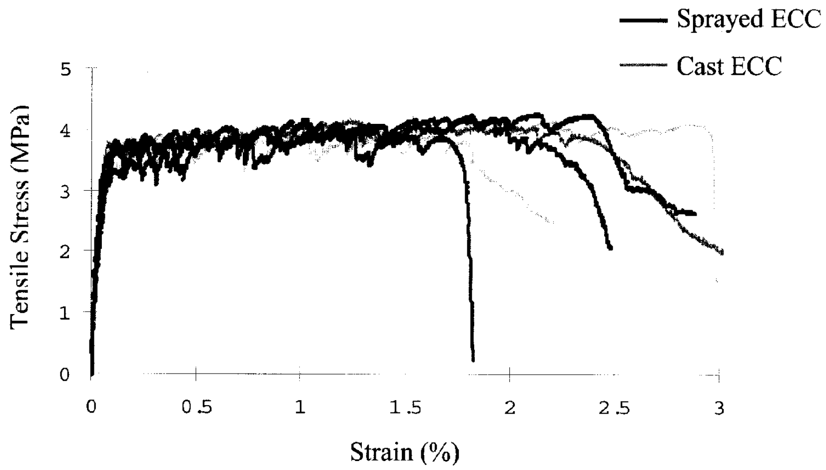


Fig. 7: Uniaxial tensile stress versus strain curves

5. Conclusions

A sprayable ECC which exhibits proper pumpability and sprayability in the fresh state and strain-hardening behavior in the hardened state has been successfully developed by employing parallel control of micromechanical design and rheological process design. The following conclusions can be drawn from the current experiments.

We determined the optimal composition of ECC for spray processing. W/C ratio of 0.46 and S/C ratio of 0.8 were employed to obtain matrix and fiber/matrix interface suitable for achieving strain-hardening behavior. Given the fiber diameter (d_f = 39μm) and fiber volume fraction (V_f = 2.0%), fiber length was chosen to be 8 mm on the basis of pumpability in the fresh state and fiber/matrix interfacial properties in the hardened state.

The fresh performance of ECC suitable for spray processing was accomplished by adjustments of dosages of HPMC (0.05%), MFS (0.75%) and CA particles (5%). Appropriate mixing procedure was determined to create a two-stage rheological property. Water and cement were added to form the basic mortar matrix to the dry ingredients, i.e., fly ash and silica sand. Thereafter, MFS was first added prior to the addition of the PVA fibers, followed by the HPMC. CA particles were finally added to the fresh ECC mix.

Spray tests revealed that the suitable deformability when spraying, in terms of Γ_{rest} was in the range of 2.0 to 3.0. The maximum ECC layer thickness of 45 mm and 25 mm were obtained, spraying onto vertical surface and overhead surface, respectively. These are comparable to the recommended thickness of spray layer, ranging 25 mm to 50 mm, in repair work. Very low rebounds were observed in spraying ECC. It is most likely due to the smaller size of sand and lower stiffness of fiber in ECC, compared to commercial prepackaged mortars or typical steel fiber reinforced shotcrete.

Subsequent uniaxial tests demonstrated that the mechanical performance of sprayed ECC is comparable to that of cast ECC with the same mix proportions.

6. References

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