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Design of Engineered Cementitious Composite Suitable for Wet-Mixture Shotcreting

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An engineered cementitious composite (ECC) suitable for wet-mixture shotcreting (sprayable ECC) in the fresh state, while maintaining tensile strain-hardening behavior in the hardened state, has been developed by employing a parallel control of micromechanics- and rheology-based 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. Within the predetermined micromechanical constraints, the fluid properties are controlled by the rheological process design to develop flocculations between cementitious particles at a proper rate. The pumpability and sprayability of the ECC mixture are then realized by the controlled rheological properties of fresh matrix and the uniform dispersion of fibers. A series of spray and deformability tests show the excellent pumpability, sprayability, and rebound property of the sprayable ECC. Subsequent uniaxial tensile tests demonstrate that the mechanical performance of sprayed ECC using wet-mixture shotcreting process is comparable with that of ECC cast with external consolidation for the same mixture design.

Keywords: cementitious; fiber; matrix; rheology; shotcrete.

INTRODUCTION

An engineered cementitious composite (ECC) is a micromechanically designed cementitious composite that 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 special type of polyvinyl alcohol (PVA) fiber was developed specifically for ECC reinforcement.[1] A variety of applications of this material ranging from repair and retrofit of structures, cast-in-place structures, to precast structural elements requiring high ductility are being developed.[2-3]

ECC suitable for wet-mixture shotcreting (sprayable ECC) can be defined as the ECC conveyed through a hose and pneumatically projected at a high velocity from a nozzle onto place. The rheological properties of the fresh mixture in the wet-mixture shotcreting are obviously crucial. The fresh mixture should be moderately deformable, that is, pumpable under the pumping and conveying pressure, so it can 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 mixture while embodying the ductile performance of ECC, the method to control the processing parameters and micromechancial parameters in a parallel manner was adopted. Previous works on development of the self-compacting PVA-ECC material confirmed that this approach is highly beneficial to achieving the desired properties of both fresh mixture and hardened material.[4] In addition, the previous studies demonstrated that the rheological design, which determines optimal dosage of the chemical admixtures and appropriate mixing procedure with given chemical admixtures, was a very powerful tool to modify the fluid properties of fresh cementitious mixture.

The objective of this study is to develop a sprayable ECC to exhibit fluid properties suitable for wet-mixture shotcreting process with comparable ductility with ordinary ECC. The parallel control methodology adopted involves the following steps. Within the predetermined matrix, fiber, and interface properties based on micromechanical tailoring, the focus is on modulating flocculation between cement particles under the hypothesis that adjusting interactions between cement particles greatly alter the fluid properties of fresh ECC mixture. For this purpose, the effects of organic and inorganic admixtures on the rheological properties of cement pastes were investigated to determine the optimal dosages. Then, the effectiveness of the designed cement pastes on realizing the desired fluid properties of fresh ECC mixture with various fluid tests including deformability tests, pump-out test, fill-up test, and spray-on test were examined. Uniaxial tensile tests were also performed to demonstrate that the sprayed ECC using wet-mixture shotcreting process retains strain-hardening behavior comparable with ordinary ECC cast with external consolidation, with the same mixture proportion.

RESEARCH SIGNIFICANCE

This paper presents the development of a sprayable ECC in the context of material design under the guidance of micromechanical principles and rheological tools. Specifically, this study illustrates how the fresh properties suitable for wet-mixture shotcreting may be realized, while accommodating the strain-hardening requirements imposed by micromechanical tailoring. Results from spray tests show that the fluid properties of predetermined ECC mixture are effectively modified by adopting rheological control parameters. Subsequent uniaxial tensile tests demonstrate the strain-hardening behavior comparable to that of cast ECC, for the same mixture design. One class of applications expected to benefit from sprayable ECC is repair of deteriorated infrastructures by wet-mixture shotcreting process. Sprayable ECC provides the large deformability often required in the repair material.

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Table 1—Properties of PVA fiber used in ECC material

Diameter, μm	Length, mm	Nominal strength, MPa	Elongation, %	Oiling agent content, %	Young's modulus, GPa
39	8.12	1620	6	0.8	42.8

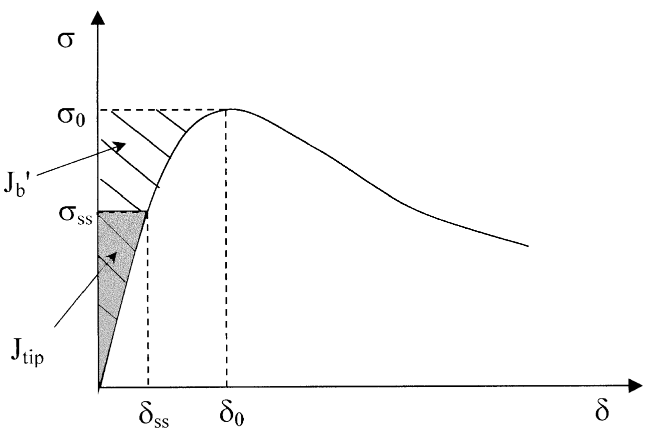


Fig. 1—Typical s(d) curve for strain-hardening composite. Hatched area represents complementary energy J_b'*. Shaded area represents the crack tip toughness* J_{tip}.

DESIGN FRAMEWORK OF SPRAYABLE ECC

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 used herein is mainly focused on achieving strain hardening in tension because 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 versus crack opening δ curve, as illustrated in Fig. 1[5]

$$J_{tip} \leq \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J'_b \qquad (1)$$

$$J_{tip} = \frac{K_m^2}{E_c} \qquad (2)$$

where σ_0 is the maximum bridging stress corresponding to the opening δ_0, and E_c is the composite elastic modulus. Equation (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,

$$\sigma_{fc} < \sigma_0 \qquad (3)$$

where σ_{fc} is determined by the maximum preexisting flaw size max a_0 and the matrix fracture toughness K_m. Details of these micromechanical analyses can be found in Li and Leung[6] and Li and Wu.[7] Satisfaction of Eq. (1) and (3) is necessary to achieve ECC behavior. Otherwise, normal tensile softening fiber-reinforced concrete (FRC) behavior results.

Thus, the ECC theory provides an analytical tool for composite design without going through numerous experiments as required by the traditional trial-and-error approach in the development of new FRCs. Furthermore, it allows one to maximize the fiber efficiency for composite performance as well as to minimize the fiber content. The small content of discontinuous fibers allows for flexible processing for spray procedure as well as normal on-site cast construction. 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.

Two-stage rheological control

To develop a satisfactory wet-mixture shotcreting process, the fresh properties of ECC mixture are controlled to have a two-stage behavior. In the first stage, a highly deformable ECC mixture is desirable for ease of pumpability for transporting the material from the mixer to the 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 mixture sprayed onto a substrate.

These contrasting fluid properties need to be achieved at given concentrations of ingredients determined by the micromechanics-based design. Therefore, the focus is on adjusting the flocculation rate of cement particles for the two stages because moderate flocculation leading to low viscosity may be advantageous for the transport of fresh mixture, while strong flocculation leading to high viscosity provides good adhesion and cohesion. To achieve a moderate flocculation, a proper concentration of chemical 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 used. Although reactivity of particles may enhance the viscosity of particles over time, the 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 because it governs the competitive contributions between the particle size effect and reactivity to the viscosity of the mixture.

MATERIALS

Sprayable ECC

ECC material is composed of common mortar matrix and fibers. In this study, a micromechanically designed PVA fiber was used as the reinforcing fiber.[8] The fiber dimensions and mechanical properties are given in Table 1. ASTM Type 1 ordinary portland cement (OPC), (average particle diameter = 11.7 ± 6.8 μm), silica sand (average particle diameter = 110 ± 14.8 μm), fly ash (FA) (average particle diameter = 26.9 ± 7.0 μm), and calcium aluminate cement (CA) (average particle diameter = 5.5 ± 1.5 μm) were used as the major ingredients in the matrix. All of the cementitious raw materials were used as received. Chemical admixtures comprised of high-range water-reducing admixture (HRWRA) and hydroxypropylmethylcellulose (HPMC) were used to modify the fluid properties.

Prepackaged mortars (PMs)

There are several hundred commercially available shotcreting mortars for repair work, which can be categorized into a few generic types.[9] Of these, the most widely used type is OPC/sand shotcreting mortar. As a reference material for sprayable ECC, two kinds of OPC/sand PMs were used in this investigation. One (PM-1) is a kind of polymer-modified mortar for wet and dry shotcreting. The other (PM-2) is a kind of synthetic fiber-reinforced shotcreting mortar with silica fume. The details of these products, however, are not available due to the proprietary nature of their formulations.

EXPERIMENTAL PROGRAM

Rheological measurements for fresh cement paste

A controlled stress rheometer was used to monitor changes in the storage modulus of fresh cement pastes over time. Using a concentrated cylinder geometry, pastes were 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. Following the Cox-Mertz rule,[10] it was presumed that dynamic viscosity is equal to the viscosity measured under a steady shear mode.

Deformability test for fresh mortar matrix mixture using flow cone

The small flow cone (diameter d_0 = 10 cm) for conventional flow table test was used to quantify the deformability of fresh mortar matrix mixture Γ^F. Flow table tests were performed twice, immediately after mixing, and after resting for a fixed time (every 15 min), so that the effect of fluidity consistency could be incorporated into the deformability performance. No external means (for example, vibration) were applied to consolidate the fresh cementitious mixture. Once the test cones were lifted, the fresh cementitious mixture tended to collapse and spread. The maximum diameter of the spread d_1 and the diameter perpendicular to it d_2 were measured. Indexes for deformability Γ^F were then calculated by

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

where superscript F stands for the deformability of mortar matrix mixture measured by flow table test, and subscript *rest* means the rest time after mixing in minutes.

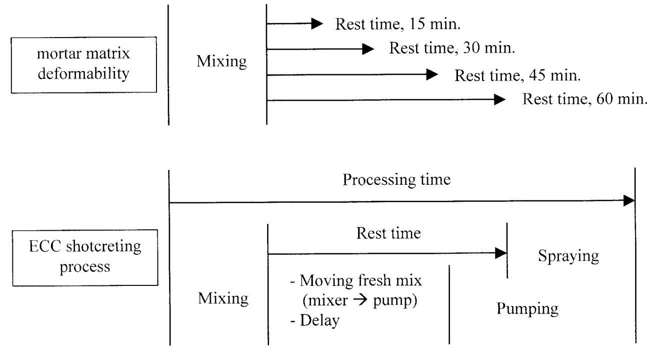


Fig. 2—Schematic comparison between definitions of rest time in mortar matrix deformability test and in ECC shotcreting process.

Deformability test for fresh ECC mixture using slump cone

To quantify the pumpability and sprayability of fresh ECC mixture, a deformability test using a slump cone was conducted. A regular slump cone (diameter D_0 = 20 cm) for the conventional slump test was employed to measure the deformability Γ of the sprayable ECC mixture. Deformabiltity Γ was calculated by Eq. (5) with the measured maximum diameter of the spread D_1 and the diameter perpendicular to it D_2

$$\Gamma_{rest} = \frac{(D_1 \times D_2) - D_0^2}{D_0^2} \tag{5}$$

where subscript *rest* means also the rest time after mixing in minutes.

Spray test for fresh ECC and PM mixture

A spiral pump was used for the wet-mixture shotcreting process in this study. This system was known to be particularly suitable for premixed liquids and mortar with the maximum grain size of 3 mm. Fresh ECC and PMs mixed in a 40 L-capacity drum mixer were pumped through this spiral pump and then down a 25 mm-diameter rubber hose to a spray gun, from where it was sprayed pneumatically with an air pressure of approximately 700 kPa onto a substrate. The pumping pressure was observed during the shotcreting process. Once the pumping pressure reached 4 MPa, the maximum pumping pressure permitted by the pump manufacturer, all tests were aborted. The mixture design was then considered unsuitable for wet-mixture shotcreting.

To characterize the pumpability in terms of pumping pressure, pump-out tests were performed by documenting pumping pressure during conveyance of the fresh mixture through the open hose without a nozzle. The deformability Γ_0 was also measured just after mixing to quantify the ECC fresh properties suitable for pumping.

Two types of spray tests were introduced to demonstrate sprayability. The fill-up test was performed for all fresh mixtures by spraying onto a vertically positioned substrate in the form of a wood box of 356 x 362 mm bottom area and 51 mm depth. The rest time between the end of mixing and the beginning of spraying, as illustrated in Fig. 2, required for the fresh mixture to attain an appropriate viscosity to fill the box without any flowing down in one continuous spraying operation was measured. To quantify the sprayable fresh

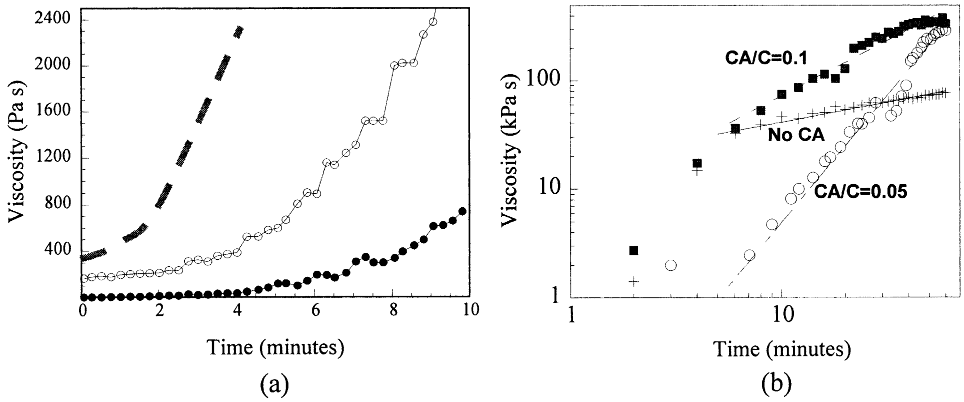


Fig. 3—Changes in cement paste viscosity over time for: (a) effects of mixing sequence on viscosity change (---) no stabilization, ● addition of HPMC prior to HRWRA, and ❍ addition of HRWRA prior to HPMC; and (b) effects of CA particles on the viscosity change, + cement suspension without CA particles, ❍ cement suspension with CA particles (CA/C = 0.05), and ■ cement suspension with CA particles (CA/C = 0.1).

properties, in terms of deformability Γ_{rest}, slump tests were performed when spraying. The minimum rest time was set with 15 min as a target, assuming in-place batch plant mixing.

Sprayability was also assessed quantitatively in terms of the thickness of fresh mixture that could be sprayed onto a substrate prior to failure under its own gravitational force, which can be named spray-on test. The fresh mixture was sprayed horizontally onto a vertical surface and vertically onto an overhead surface to try and obtain as large a thickness of the sprayed layer build as possible, in one continuous spraying operation, without dripping or sagging, especially in overhead sprays.

For subsequent uniaxial tensile tests, sprayed ECC coupons (305 x 76 x 13 mm) were sawn from panels sprayed into 305 x 300 x 13 mm wood molds positioned vertically. Companion ECC coupons were prepared by casting into tensile coupon molds, for the same mixture proportion.

RESULTS AND DISCUSSION

Determination of micromechanical constraints

For a parallel design of fresh ECC mixture and hardened PVA-ECC, first, an appropriate range of ingredients loading from extensive micromechanical analyses and experiments was determined. They disclosed that a water-cementitious material ratio (*w/c*) ranging from 0.45 to 0.47 and a sand-cement ratio (*s/c*) ratio of 0.8 would be appropriate to achieve satisfactory matrix properties as well as interfacial frictional stress τ_0.[1] A 0.8% oiling agent content for fiber coating, suitable for attaining appropriate interfacial bond properties, was chosen in this study to obtain sufficient strain-hardening behavior and robust composite performance.

The adjustments of the interfacial properties would set the fiber volume fraction V_f of 2.0% (26 kg per m^3 ECC), which is above the critical V_f. The fiber volume fraction, however, is also limited by fresh mixture properties, that is, workability, pumpability, and sprayability considerations. In general, increasing the V_f tends to increase the viscosity of the suspension. In spraying ECC, the fibers as well as fresh mortar have to be conveyed through the pump and hose. Higher fiber content can lead to high internal friction during conveyance and require excessive pumping pressure. Therefore, fiber volume fractions ranging from 1.5 to 2.0% were selected to satisfy both ductile performance in the hardened state and desirable pumpability during shotcreting process.

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.[11] For the PVA fiber (V_f = 1.5, 2, 3%; L_f = 6 to 12 mm), the average workable aspect ratio was chosen to be approximately 300.[12] In particular, fiber length is also limited by pumpability consideration, which means that increasing the L_f hinders conveying the fresh mixture through the spiral pump. The fiber lengths of 12 and 8 mm, therefore, were selected based on average workable aspect ratio (300) and the more processible aspect ratio (200) in this investigation.

Determination of rheological control parameters

For successful use of the chemical admixtures, the effects of mixing sequence on the viscosity change over time were investigated. As confirmed with studies on the preparation of self-compacting ECC,[4] HRWRA 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 chemical admixtures additions. Addition of HPMC prior to HRWRA leads to the formation of electrosteric layers on the particle surfaces, resulting in a much slower increase in the viscosity over time than when HRWRA is added first (Fig. 3(a)). Because the shotcreting process requires fast increase in the viscosity after a certain time period, possessing too high resistance against the buildup of flocculated microstructure may not be desirable. Therefore, the mixing procedure was adopted to add HPMC following the addition of HRWRA, so that HPMC can act only as viscosity agent to prevent the segregation between the ingredients.

To enhance the cohesiveness of the fresh ECC mixture and adhesiveness of ECC to concrete substrate after shotcreting, a technique to enhance the time-dependent flocculation between cement particles stabilized with chemical admixtures at a proper rate was investigated. For this purpose, the CA particles were incorporated to cement pastes stabilized with HRWRA and HPMC at CA dosages (in terms of the mass fraction of cement particles replaced with CA particles) ranging from 0 to 10%. Incorporation of CA particles contributed to enhancing the viscosity increase over time (Fig. 3(b)). Introduction of CA particles at 5% CA results in a slower increase in the viscosity compared with the plain cement pastes for the first 10 min, which is due to the particle size effect of CA particles. The particle size effect is a role of CA to free the water between cement particles, resulting in a lower viscosity compared with plain pastes. As time goes on, reactivity of CA particles to enhance the aggregation becomes dominant over the particle size effect, thus activating the increase of the viscosity. This activation of viscosity increase, which starts at approximately 10 min, makes the viscosity of cement pastes including 5% CA particles much higher than that of plain pastes after 30 minutes. In contrast, further increase of CA dosages to 10% results in a rapid increase of viscosity for the first 10 min, similar to the plain pastes. It is most likely due to the fact that the contribution of high reactivity at high CA contents overwhelms the contribution of particle size effect of CA particles.

Therefore, it is proposed that adopting a 5% CA content is an optimal point to prepare fresh ECC mixtures suitable for the shotcreting process. This is expected to provide a slow increase of the viscosity in the beginning to facilitate the pumping and conveyance, and the subsequent activation in the viscosity increase to make fresh ECC mixtures readily adhere to the substrates at a proper time point. In addition, excessive CA contents may be detrimental to achieving the desired hardened mechanical properties, that is, matrix toughness and fiber-matrix interfacial properties, which were designed micromechanically without consideration of CA. Thus, a CA dosage of 5% is expected to be preferable to a high CA content (that is, 10%).

Deformability characteristics of fresh mortar matrix mixture

Based on the rheological studies with cement pastes, an appropriate mixing sequence was determined to add HRWRA, HPMC, and CA particles. To control initial viscosity by changing HRWRA concentration and to reconfirm the optimal dosage of CA particles, deformability tests on fresh mortar matrix mixtures using a flow cone were performed.

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

Figure 4(b) illustrates the effect of the CA on the rate of deformability loss of fresh mortar mixture Γ^F. The amount of cement replaced by CA was 0, 3, and 5% based on the mass of cement particles with constant HPMC and HRWRA concentrations. Figure 4(b) shows a difference in Γ^F_0 just after mixing with the dosage of CA because of the particle size effect as discussed in the previous section. The addition of CA, however, accelerates the setting of mortar mixture and induces the flocculation between the stabilized particles, leading to a fast decrease in the deformability over time. The effects become stronger with an increasing dosage of CA. These test results reconfirm that replacing 5% of cement with CA particles is the optimal dosage of CA particles because this mortar matrix mixture exhibits more moderate

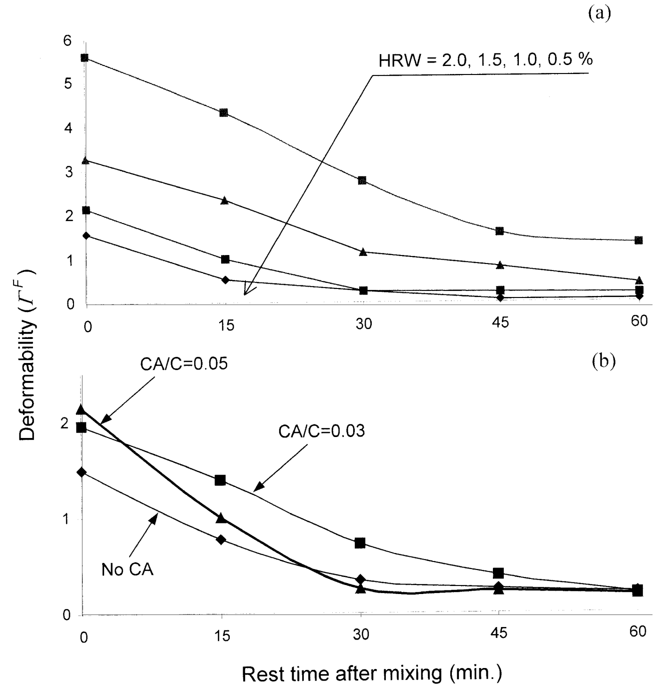


Fig. 4—Changes in deformability G^F of mortar matrix mixture, as function of rest time for: (a) effect of HRWRA concentration (HPMC = 0.05%, CA = 5.0%); and (b) effects of CA dosage (HRWRA = 1.0%, HPMC = 0.05%).

Table 2—Mixture proportions of ECC for spray test

Mixture	Cement	Water	Sand	Fly ash	HPMC*	HRWRA†	CA‡	V_f§
S-0	1.00	0.47	0.80	0.30	0.0005	0.020	0	0.015
S-1	0.95	0.47	0.80	0.30	0.0005	0.015	0.05	0.015
S-2	0.95	0.47	0.80	0.30	0.0005	0.015	0.05	0.020
S-3‖	0.95	0.46	0.80	0.30	0.0005	0.0075	0.05	0.020

*Hydroxypropylmethylcellulose.
†High-range water-reducing admixture.
‡ Calcium aluminate cement.
§Fiber-volume fraction.
‖Fiber length = 8 mm.
Note: All numbers are mass ratios except for V_f.

initial deformability as well as faster decrease of deformability over time, compared with other mixtures. Consequently, it is demonstrated that the rest time during the shotcreting process, as illustrated in Fig. 2, can be controlled by adjustment of HRWRA and CA dosages.

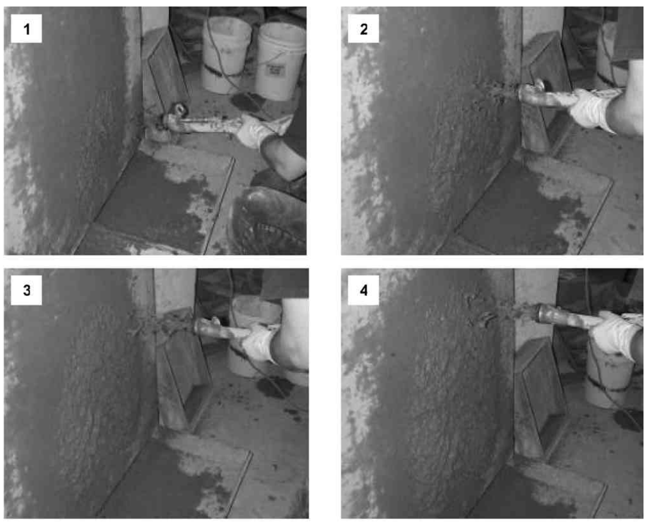
Therefore, it is proposed that changes in HRWRA concentration strongly impact initial deformability, while varying concentrations of CA particles significantly affect the deformability loss over time. In addition, it supports the concept that interaction between cement particles is the important factor to control the fluid properties of fresh mortar mixture.

Pumpability and sprayability of fresh ECC mixture

Based on the rheological studies with cement paste and mortar matrix, several ECC mixtures were designed (Table 2) and sprayed to determine suitable fresh properties for the shotcreting process in terms of ECC mixture deformability Γ.

To assess pumpability, the pump-out tests were performed just before spraying. As displayed in Table 3, no excess

Fig. 5—Fill-up test (Mixture S-3).



(a) spraying sequence onto vertical surface

(b) 45 mm thickness of sprayed ECC layer

Fig. 6—Spray-on test to vertical surface (Mixture S-3) for: (a) spraying sequence onto vertical surface; and (b) 45 mm thickness of sprayed ECC layer.

pumping pressure was observed for ECC not only during the pump-out tests but also during the spraying procedure. These observations revealed that all the fresh ECC mixtures, of which Γ_0 was more than 3.0, were properly pumpable for this spiral pump system. In contrast, slightly high pumping pressure (2 MPa) was observed during the test on PM-1. The pump-out test on PM-2 with a 25 mm length of synthetic fibers with V_f of less than 1%, however, was aborted because

Table 3—Results of spray tests

Mixture	Slump test		Pump-out test	Fill-up test	Spray-on test (thickness)	
	Γ_0	Γ_{rest}	Pumping pressure	Rest time*	Vertical surface	Overhead surface
S-0	6.5	†	< 1 MPa	> 90 min	†	†
S-1	5.0	2.7	< 1 MPa	30 min	40 mm	N/A
S-2	5.1	†	2 MPa	†	†	†
S-3	3.1	2.3	< 1 MPa	15 min	45 mm	25 mm
PM-1	13 cm‡	N/A	2 MPa	N/A	10 mm	N/A
PM-2	8 cm‡	†	> 4 MPa	†	†	†

*Rest time demanded for fresh mixture to attain viscosity to meet requirement of fill-up test.
†Improper fresh mixture to test.
‡Slump of fresh PM.

the pumping pressure reached the maximum value (4 MPa) and kept going up.

During the test on Mixture S-2 (L_f = 12 mm; V_f = 2%), the pump went down due to fibers stuck inside the twister. The role played by twister is to transport mortar from hopper to hose, rushing fresh ECC through the narrow passage between rotor and stator. It was likely that V_f of 2% was too high to pass through the twister because the length of fiber (12 mm) was much larger than the maximum grain size (3 mm) recommended by the pump manufacturer. Following the spray test on Mixture S-2, more processible fibers with 8mm length were adopted for the next Mixture S-3 to reach the critical fiber volume fraction (V_f = 2%). The HRWRA concentration was also optimized at 0.75% to set the rest time at 15 min. As can be seen in Table 3, Mixture S-3 (L_f = 8 mm; V_f = 2%) was pumpable enough to display moderate pumping pressure less than 1 MPa. This demonstrates that fiber length as well as fiber volume fraction are critical material parameters for pumpability when using a spiral pump system.

To verify the sprayability of the fresh ECC mixture, the fill-up test (Fig. 5) and spray-on test (Fig. 6 and 7) were performed. As compared in Table 3, the suitable deformability when spraying, in terms of Γ_{rest}, was revealed to be in the range of 2.0 to 3.0 regardless of the initial deformability Γ_0. Mixture S-0 (without CA addition), however, was too flowable to fill the box even after the rest time of 90 min while it was moderately deformable under pumping pressure (Γ_0 = 6.5), that is, pumpable. It is most likely due to the absence of CA particles and excessive initial deformability as well. This clearly demonstrates that the fluid properties of ECC mixtures were effectively modified by introducing a small amount of CA particles (5%) and by optimizing chemical admixtures concentrations. These results also reconfirm that the rest time from after mixing to spraying is controlled by adjustments of the CA and HRWRA dosage.

Based on the pump-out and fill-up tests performed on ECC fresh mixtures, Mixture S-3 was determined to be the optimized ECC mixture able to satisfy micromechanical constraint (V_f = 2%) as well as to exhibit moderate pumpability with desired rest time (15 min) demanded to satisfy the fill-up test requirement. If the freshly sprayed ECC stays adhered to the substrate, its dead weight should not exceed the internal cohesion force or the adhesion force to the substrate. As shown in Fig. 6, the sprayability was assessed quantitatively to obtain as large a thickness of sprayed ECC as possible. Processing a continuous spray onto a vertical surface, the maximum thickness of 40 and 45 mm were obtained for S-1 and S-3 mixtures, respectively. Spraying Mixture S-3 onto an overhead surface, the maximum thickness of 25 mm was achieved, as shown in Fig. 7. These values of 25 and 45 mm are comparable with the usually applied thickness of shotcrete layer, ranging from 25 to 50 mm, in repair work.[13,14] The fresh PM-1 mixture was flowing down after shotcreting about 10 mm thickness layer onto a vertical surface, which is the thickness of a sprayed layer in one continuous spraying operation, recommended by the manufacturer.

It should be noted that almost no rebound was observed in spraying ECC. In contrast, the sands (several mm size in diameter) were extensively rebounded from the substrate during the spraying of PM-1. It is most likely because all ingredients in the fresh ECC mixture are strongly integrated by the viscous cement suspensions due to the smaller size of sand and lower stiffness of fiber in ECC, compared with PMs or typical steel fiber-reinforced shotcrete (SFRS). Such a low rebound of sprayable ECC should be beneficial to cost and mechanical performance. First, the amount of rebound in shotcrete typically demands an additional 5 to 8% increase in cost.[15] Second, it is generally agreed that the amount of fiber rebound seriously affects the toughness of the resulting in-place fiber-reinforced shotcrete. Highly toughened shotcrete can be obtained by the use of ECC material.

Tensile performance of the sprayed ECC

To confirm the ductile strain-hardening behavior of the sprayed ECC and to compare it with the test results of cast ECC coupons, direct tensile tests were performed at 28 days. As shown in Fig. 8, the strain capacity and tensile strength of the sprayed ECC (Mixture S-3) is comparable with that of ECC specimens cast with external consolidation. Such consistent material property is likely due to the sufficient compaction during the wet-mixture shotcreting process. Figure 8 shows that the ultimate tensile strain of the sprayed ECC ranges from 1.5 to 2.0%. During loading, a large number of microcracks and a small average crack width less than 100 μm were formed. Details of the hardened properties of sprayed ECC are discussed in a follow-up paper.

CONCLUSIONS

An ECC suitable for wet-mixture shotcreting that 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 experimental results:

1. The optimal composition of ECC based on micromechanical tailoring was determined. The *w/c* of 0.46 and *s/c* of 0.8 were employed to obtain matrix and fiber-matrix interface suitable for achieving strain-hardening behavior. Given the fiber diameter (d_f = 39 μm) and fiber volume fraction (V_f = 2%), 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;

2. Desired fresh properties within the limited range of loading of solid ingredients were achieved by mediating the interactions between cement particles with the proper admixtures (that is, HRWRA, HPMC, and CA particles). Specifically, adopting the appropriate mixing sequence and optimal doses of admixtures made the viscosity of fresh mixture increase at the desired rate, resulting in a target of two-stage rheological properties. Thus, the desired pumpability at the first stage and sufficient adhesion to the substrates and

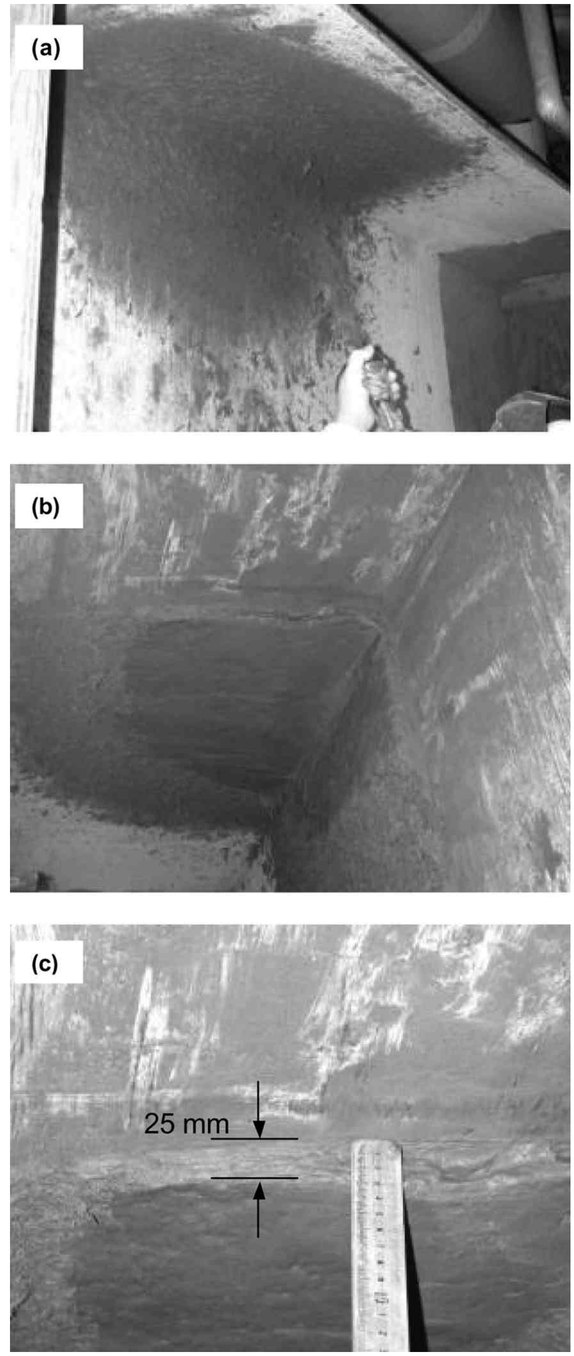


Fig. 7—Spray-on test to overhead surface (Mixture S-3) for: (a) spraying ECC onto overhead surface; (b) sprayed layer of ECC; and (c) 25 mm thickness of sprayed ECC layer.

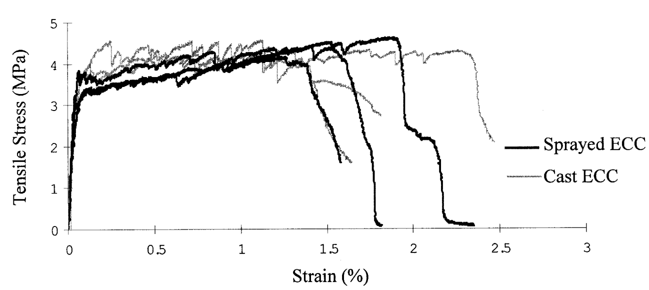


Fig. 8—Uniaxial tensile stress versus strain curves of Mixture S-3 ECC at 28 days.

cohesion between ingredients at the second stage were achieved. Such excellent workability was illustrated with a series of spray tests;

3. Spray tests revealed that the deformabilities suitable for the shotcreting process, in terms of Γ_0 and Γ_{rest}, were more than 3.0 when pumping and roughly 2.5 when spraying. Comparison of the spray test results between ECC mixtures indicates that the fluid properties of optimized mixture (Mixture S-3) were effectively designed by the two-stage rheological control. The maximum thicknesses of 45 and 25 mm were obtained, spraying onto the vertical surface and overhead surface, respectively. In contrast, the maximum thickness of 10 mm was achieved for PM-1 from the spray-on test onto vertical surface. Very low rebounds were observed in spraying ECC while several mm size sands were extensively rebounded during the spray of PM-1. It is most likely due to the smaller size of sand and lower stiffness of fiber in ECC, compared to PMs or typical SFRS; and

4. Uniaxial tensile test results revealed strain-hardening behavior of sprayed ECC. Ultimate strain capacities comparable with those of ECC (with the same mixture proportion) cast with external consolidation were obtained from sprayed specimens. Sprayed ECC using wet-mixture shotcreting process was found to exhibit tensile strain capacity of about 100 times that of SFRS.

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