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Cement & Concrete Composites 25 (2003) 301–309

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Development of a self-consolidating engineered cementitious composite employing electrosteric dispersion/stabilization

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Received 15 February 2002; accepted 15 May 2002

Abstract

A self-consolidating engineered cementitious composite (ECC) reinforced with hydrophobic polyethylene fibers has been developed by combining micromechanics based design and rheological design, in a compatible manner. The previously developed micromechanics based design selects material ingredients for tensile ductility in the hardened state. The rheological design, which is the focus in this paper, modifies the material ingredients for self-consolidation behavior in the fresh state. For this purpose, the rheological design adopts a complementary electrosteric dispersion and stabilization technique to obtain cement pastes with desirable flow properties at constant particle concentrations dictated by the micromechanics based design. Such stabilization is realized by optimizing the dosages of strong polyelectrolyte and non-ionic polymer and by controlling the mixing procedure of the polymers. The fresh cement paste designed thereby leads to fresh mortar mix with desirable deformability, cohesiveness, and high consistency, and thus satisfies the self-consolidating performance of fresh ECC mix. In addition, ductile strain-hardening performance of the self-consolidating ECC is confirmed through uniaxial tensile test. This ductile composite with excellent fluidity can be broadly utilized for a variety of applications, e.g. in repair of deteriorated infrastructures requiring horizontal formworks, or in seismic-resistant structures with dense reinforcements and requiring high ductility.

Keywords: Self-consolidating ECC; Strong polyelectrolyte; Non-ionic polymer; Electrosteric stabilization; Rheological design

1. Introduction

Normal concrete has been widely used as a construction material with the advantages of durability, resistance to fire, energy efficiency, and on-site fabrication, for example [1]. In contrast, it has the disadvantages of low tensile strength, low ductility, volume instability, and inconsistent reliability due to variable vibration application skills on the job site. To improve its performance, several modified materials, such as high performance high strength concrete (HPC) and high performance fiber-reinforced concrete (HPFRC), have been developed. In the case of HPC, it has a higher compressive strength and possibly improved durability. However, it is extremely brittle. Most HPFRCs incorporate large amounts of fiber ranging from 4% to 20%, and attain tensile strain-hardening behavior with a tensile ductility of about 1% [2]. The large amount of fibers used reduces the workability of the HPFRC, sometimes leading to the necessity to employ different types of processing other than conventional casting, and thus limiting the application of the material, especially for on-site fabrication.

Engineered cementitious composites (ECCs) are cement mortar-based fiber-reinforced composites (FRCs) with superior ductility (about 600 times of the ductility of normal concrete in tension) [3–5]. These composites are composed of cement, sand, water, a small amount of admixtures, and an optimal amount of fibers. Although ECCs essentially utilize the same ingredients as most FRCs except without coarse aggregates and employ a

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0958-9465/03/$ - see front matter
PII: S0958-9465(02)00057-4

much smaller amount of fibers than most HPFRCs, ECCs have a tensile strain capacity of up to 6% and exhibit pseudo-strain-hardening behavior. This strain capacity is much higher than that of a commercial fiber-reinforced cementitious composite known as DUCTAL (<0.5%) [6]. The unique material properties of ECCs derive from its micromechanical approach in material design, which serves to establish the link between properties of the material constituents—the matrix, fiber, and interface properties [7–10].

In recent years, self-consolidation of fresh concrete mix has been recognized as a means to improve the quality and constructability of concrete infrastructures. High performance self-consolidating concrete (HPSCC), which requires no consolidation on job sites, has been successfully developed and commercialized in the construction of tall buildings [11,12] and bridges [13]. The self-consolidating properties are generally achieved by high deformability of the fresh concrete mix, good resistance against segregation, and low slump loss. The use of new polymeric admixtures, like poly(carboxylate) copolymers, to provide electrosteric stabilization (i.e., combination of electrostatic stabilization to disperse the cement particles flocculated by electrostatic attraction and steric stabilization to reduce the van der Waals attraction between particles), optimization of the cement component by using supplementary cementitious materials and fillers (e.g., belite phase) [14], and proper grading of aggregates have been considered key factors to achieving the properties of self-consolidation [15]. However, the HPSCC is still a brittle material in the hardened state.

Thus, self-consolidating ECC materials, defined as materials which retain the self-consolidating properties of HPSCC in the fresh state, while exhibiting extreme ductile behavior in the hardened state, are highly desirable. To create self-consolidating ECC, the processing design for self-consolidation focuses on the control of aggregated microstructure in the fresh state. This microstructural control for desirable rheological properties, however, must also be compatible with micromechanics based design, which also determines the microstructure needed to achieve strain-hardening in the solid state. Therefore, we adopt the vertically integrated approach of self-consolidating ECC design to satisfy the microstructures in the different states, as follows. The optimal concentration ranges of the components, given by water/cement (W/C) and sand/cement (S/C), are selected as initial non-negotiable constraints to attain the strain-hardening performance, since the adjustment of processing parameters must not contradict the conditions necessary to achieve ductile mechanical performance. As indicated above, extensive efforts have been devoted to defining the ranges of optimal micromechanical parameters to produce the strain-hardening performance [3,10,16]. Within these limited ranges, the processing parameters are optimized for self-consolidation. These constraints present challenges different from those in the development of self-consolidating concrete [12] or FRCs [17], which allow one to adjust the concentration of cementitious ingredients and their particle sizes within a wide range. For this purpose, we have focused on developing a fresh cement paste with high fluidity by modifying the interactions between cement particles, since this provides the main driving force for a highly deformable fresh mortar matrix mix. The optimized matrix mixes were then used to prepare fresh ECC mixes containing polymer fibers, and fine-tuned to ensure homogeneous flow with the fibers. This approach ensures that the matrix properties are consistent with micromechanical requirements. The systematic control of the fresh properties of the ECC mix is detailed in Section 2.

A strong polyelectrolyte, known as a superplasticizer, and a non-ionic water-soluble polymer are used to modify the interactions between cement particles in the fresh cement paste and thus the fluidity of pastes. The effects of the two polymers on the rheological properties of cement suspension were documented elsewhere [18]. Although many other studies have been utilizing newly synthesized admixtures that provide electrosteric stabilization with a single polymer [19–21], the design of the polymers tend to depend on a trial-and-error approach to adjust the balance between electrostatic and steric stabilization. Therefore, systematic investigation of the individual role of electrostatic and steric stabilization on the fluidity of fresh cementitious mix with a conventional superplasticizer and non-ionic polymer would provide valuable information for designing advanced polymeric admixtures.

In particular, this study examines the stabilizing effects imparted by the two polymers on the fluidity of a fresh mortar mix containing sand and of a fresh ECC mix containing polyethylene (PE) fibers at given W/C and S/C. In addition, the self-consolidating properties of the fresh ECC mix are experimentally demonstrated using various indices, such as the deformability, flow rate, and self-consolidation index [12,22,23]. To verify the strain-hardening performance of the self-consolidating ECC, uniaxial tensile test of ECCs is performed.

2. Rheological control of fresh properties of cementitious suspensions

Self-consolidating performance is achieved by high deformability, good cohesiveness between material ingredients, and excellent consistency of the fluidity over time. It has generally been known that the slump property of a normal fresh cementitious mix is mainly governed by its yield stress. When the yield stress of a fresh cementitious mix is greater than the gravitational stress, the fresh mix is prevented from completely collapsing to the plate surface. As the yield stress becomes less than the gravitation stress, the slump height decreases. In this process, the contribution of the viscosity to the fresh properties is considered to be relatively small. Once the gravitational stress acting on the fresh mix is much greater than the yield stress, the fresh mix completely collapses onto the plate, followed by the spreading of the mix over the plate surface. The role of viscosity is more important during spreading. In addition, segregation, which is mainly caused by inhomogeneous flow between the ingredients of the fresh mix and gravitational sedimentation, also depends on the viscosity of the fresh mix. Consistency, which is quantified by the change of deformability over time, is also related to changes of yield stress and viscosity over time.

In general, the yield stress and viscosity depend on the flocculated microstructure in the concentrated suspensions, including cementitious suspensions [24,25]. Therefore, the flocculation between the cement particles should be limited with appropriate dispersion and stabilization of the cement particles which tend to strongly aggregate. Consequently, the shear viscosity (and yield stress) of fresh cement paste would be reduced, leading to high deformability of a fresh cementitious mix.

In addition, fast growth of flocculated microstructure should be retarded to maintain the initial low-shear viscosity, and thus to obtain high consistency, at least during material processing.

3. Materials and methods

3.1. Materials and mixing of fresh ECC

The ECC material is comprised of cementitious matrix and fibers. In this study, a high modulus PE fiber (Allied Signal Co.) with an aspect ratio of 334 is used as the reinforcing fiber (diameter = 38 μm; length = 12.7 mm; strength = 2.7 GPa; elastic modulus = 120 GPa). Ordinary type I Portland cement (average particle diameter = 11.7 ± 6.8 μm, LaFarge Co.) and silica sand (average particle diameter = 250 μm, US Silica Co.) were used as the major ingredients of the matrix. Both particles were used as received. Two polymeric admixtures, melamine formaldehyde sulfonate (MFS, W.R. Grace Chemical Co.) (a polyelectrolyte) and hydroxypropylmethylcellulose (HPMC, DOW Chemical Co.) (a non-ionic polymer), were used to control the rheological properties of fresh matrix mix.

For the preparation of the fresh ECC mix, all of the dry particles were mixed in a Hobart mixer equipped with a planetary rotating blade. Water was added to form the basic mortar matrix. To ensure the adsorption of HPMC onto the cement particles, the HPMC aqueous solution was first added, followed by the MFS solution. Lastly, PE fibers were manually added to the fresh mortar matrix mix.

3.2. Tests

3.2.1. Rheological measurements of cement pastes

A Bohlin VOR rheometer with strain control was used to measure the rheological properties of the fresh cement paste. In a controlled strain rheometer, the cup rotates at a constant shear rate, and the resulting shear stress is measured, following a rest period for 3–10 min after sample loading and pre-shearing at 140 s^{-1} for 30 s. The viscosity of the tested fresh cement pastes is then automatically calculated based on these measurements.

3.2.2. Deformability test of fresh mortar mix

The small flow cone for the conventional flow table test was used to quantify the deformability of fresh mortar matrix mix, Γ_1 [26]. For fresh mortar mix, flow table tests were performed three times: just after mixing of the fresh mix, after a rest period in the flow cone for 10 min, and just after re-mixing the fresh mix for a minute at a speed of 60 rpm for 30 s. The purpose of the second flow table test is to investigate the consistency of the fresh mix with time, since it takes approximately 10 min from the completion of mixing to fill the formworks, in case of on-site construction. In addition, the purpose of the third flow table test is to investigate the recovery of fluidity of the fresh mix after re-mixing the stiffened mix.

Once the test cones were lifted, the fresh cementitious mix tended to collapse and spread. The maximum diameter of the spread and the diameter perpendicular to it were averaged to d_1. The mortar mix deformability measure Γ_1, which quantifies the change of surface area, was then calculated, as defined in Table 1.

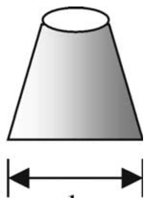
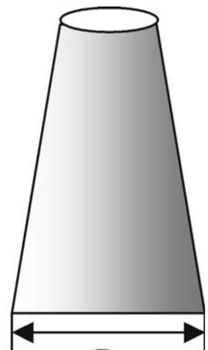
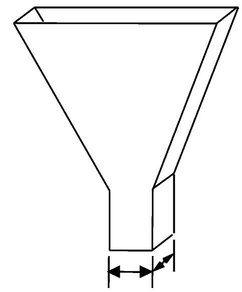
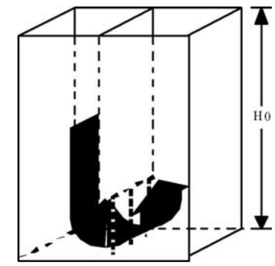
3.2.3. Large scale tests for fresh ECC mix

The conventional slump test was used to quantify the deformability of fresh ECC mix, Γ_2. The test was performed after storage of the fresh mix in a slump cone for 10 min. No external means (e.g. vibration) were applied to consolidate the fresh cementitious mix. The maximum diameter of the spread mix and the diameter perpendicular to it were averaged to D_1. Γ_2 was then calculated, as defined in Table 1.

The flow rate test was conducted by filling the funnel with fresh ECC mix, and then allowing the material to flow through the outlet upon removal of the stopper following a 10 min rest period. The time for the material to vacate the funnel, t, was measured. The index for flow rate, R, was calculated accordingly (Table 1).

A box vessel, as shown in Table 1, was prepared for this test. This box is composed of two chambers divided by a partition in the middle. Three reinforced bars with a net spacing of 3 cm are positioned at the gate at the

Table 1
Geometry of the equipment for the fluid tests of the fresh ECC mix

Test	Deformability test I (flow test)	Deformability test II (slump test)	Flow rate test (funnel test)	Self-consolidating test (box vessel test)
Dimensions of test device				
Definition	$\Gamma_1 = (d_1 - d_0)/d_0$ $d_0 = 10$ cm	$\Gamma_2 = (D_1 - D_0)/D_0$ $D_0 = 20$ cm	$R = 10/t$	$L = H/(H_0/2)$ $H_0 = 30$ cm

bottom of the vessel connecting the two chambers. The test was conducted by filling one of the chambers with fresh ECC mix and subsequently removing the block at the gate. The material then flows to the other chamber through the gate. To flow through the gate, the material must pass through the reinforcing bars successfully without the sand or fibers separating from the matrix at the gate. The height attained by the material in the second chamber, H, was measured. An index for the degree of self-consolidation, L, was calculated by dividing this height by half of the total original height, H_0. The index gives the value of 1 for perfect self-consolidating performance. In this study, the test device was scaled down appropriately for fresh ECC mix from that designed for self-consolidating concrete.

3.2.4. Mechanical test

To verify the strain-hardening behavior of the self-consolidating ECC, direct tensile test was performed with ECC specimens made without any external consolidation, after a rest time of 10 min. The specimens were cured in air for four weeks, following water curing for 2 days. Then, the specimens were loaded with a constant crosshead speed in an MTS testing machine, and the loading force was measured. From the tensile stress–strain curves, the first crack strength, ultimate tensile strength, and ultimate tensile strain were measured.

4. Results and discussion

4.1. Determination of micromechanical constraints

In designing the self-consolidating ECC, it is necessary to use micromechanics to first constrain the microstructural parameters, such as matrix toughness, fiber volume fraction, and interfacial strength, which should be optimized to achieve uniaxial tensile strain-hardening behavior [7–10]. When fibers bridging cracks are pulled-out without rupture, as is the case with PE fibers, the critical fiber volume fraction (V_f^{crit}), the minimum required fiber content to obtain strain-hardening performance, is calculated in terms of the matrix, fiber, and interface parameters (Eq. (1))

$$V_f^{crit} = \frac{12J_c}{g\tau(L_f/d_f)\delta_{max,bridging}} \tag{1}$$

where J_c is the matrix toughness, g is the snubbing factor to relate the fiber orientation to the bridging force across a crack, τ is the frictional bonding force at interface, L_f/d_f is the fiber aspect ratio, and $\delta_{max,bridging}$ is the crack opening at the maximum fiber bridging stress.

As suggested by Eq. (1), the matrix toughness should be low enough to satisfy the steady state crack propagation criteria. This is achieved by minimizing the sand content. This trend is advantageous to achieving the high fluidity of fresh mortar matrix mix, since the increase in the total particle concentration tends to exponentially increase the low-shear viscosity, as predicted by the Krieger–Dougherty equation [27]. However, the S/C ratio should be high enough to prevent severe drying shrinkage of the material. Li et al.'s studies [16] confirmed that a S/C at 0.5 would be appropriate to satisfy these two requirements. A flow table test to measure the deformability of the fresh mix revealed that the inclusion of sand at such concentrations does not deteriorate the fluidity of the cement suspension.

By incorporating the matrix toughness value corresponding to the S/C of 0.5 ($J_c = 0.01$ kJ/m^2), Fig. 1 predicts that a fiber volume fraction, V_f, higher than 0.01 is required to ensure the strain-hardening behavior of

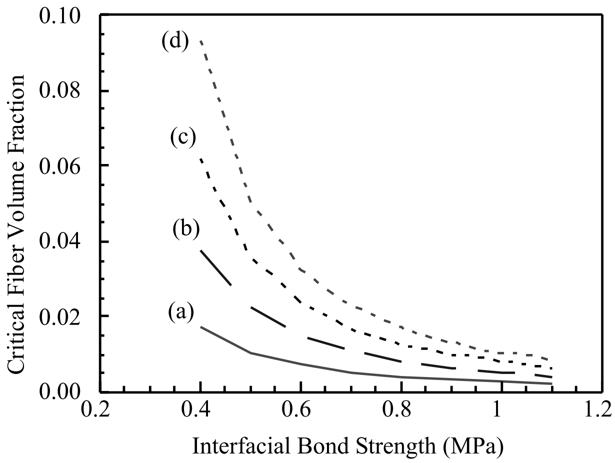


Fig. 1. Effect of matrix toughness and interfacial bond strength on the critical fiber volume fraction ($E_f = 120$ GPa, $L_f = 12.7$ mm, $d_f = 0.038$ mm, $g = 2.0$, $E_m = 25$ GPa): (a) $J_c = 0.005$ kJ/m^2, (b) $J_c = 0.010$ kJ/m^2, (c) $J_c = 0.015$ kJ/m^2 and (d) $J_c = 0.020$ kJ/m^2.

the composite. In general, increasing V_f tends to increase the low-shear viscosity of the suspension [28]. Deformability of fresh matrix mix is reduced, thereby. In addition, the entangled fibers act as obstacles to flow, resulting in segregation between the fibers and fresh matrix mix. A V_f of 0.01, therefore, was selected to satisfy both ductile performance in the hardened state and desirable workability in the fresh state.

For the high modulus hydrophobic PE fiber used in this study, fiber pull-out is expected due to a combination of low interfacial bond strength (τ) and high fiber strength. Fig. 1 predicts that increasing τ from 0.4 to 0.7 MPa greatly reduces V_f^{crit}. In addition, increasing τ is predicted to increase the ultimate tensile and bending strength. τ increases with a decrease in the W/C, although excessively low W/C may induce fiber rupture. Extensive micromechanical predictions and experiments suggested that a W/C of 0.27–0.30 should be appropriate to have a modulus of rupture (MOR) above 15 MPa with 1 vol.% of PE fiber. In this study, a W/C of 0.30 (cement volume fraction: $\phi_{cement} = 0.51$) was selected to maximize W/C within the optimized ranges of the W/C.

4.2. Improvement of fluidity of cement pastes with electrosteric dispersion/stabilization

In the absence of polymeric admixtures, a cement paste prepared at a W/C of 0.30 has a very high yield stress and viscosity. This is attributed to a strongly flocculated microstructure enhanced by strong attractions between the cement particles. To decrease the yield stress and viscosity at a given W/C, the dispersion of strongly interconnected particles is desirable. Thus, we focused on dispersing strongly flocculated particles and preventing re-flocculation between the dispersed particles through the formation of electrosteric adsorption layers on the particle surfaces, while avoiding a substantial increase of medium viscosity. At the low W/C of 0.30, no sedimentation is observed even with a highly dispersed cement suspension. Instead, the slight increase in the medium viscosity significantly increases the viscosity of the cement suspension, reducing the deformability of the fresh cement mix. Therefore, an effort to enhance the viscosity is not necessary at the W/C adopted in this study.

Tables 2 and 3 summarize the effect of HPMC and MFS on the steady shear viscosity of cement suspension, for which the W/C is 0.30 [18]. As shown in Table 2, increasing the MFS concentration decreases the viscosity of the cement suspensions. Prior to the measurements, the cement suspension was allowed to rest for 3 min to promote flocculation between cement particles. The reduction in the viscosity due to the addition of MFS is more significant at low-shear rates than at high shear rates, since the flocculated structure between particles can be readily disrupted with the high shear rate. Incorporation of HPMC of 0.013% (*w*/*w*) combined with MFS of 1.00% produces another reduction in the low-shear viscosity. However, further increase of the HPMC concentration above 0.013% tends to increase the steady shear viscosity of the mix, because of increases in the viscosity of suspending medium [18].

Table 3 shows the effects of the mixing procedure on the steady shear properties of cement suspensions, which

Table 2
Effects of concentrations of MFS and HPMC on viscosity of cement paste

HPMC (% w/w_{cement})	MFS (% w/w_{cement})	Viscosity at 0.06 s^{-1} (Pa s)	Viscosity at 23.2 s^{-1} (Pa s)
0	0.33	1700	2.3
0	0.67	381	1.0
0	1.00	58.1	0.7
0.013	1.00	12.8	0.6
0.050	1.00	33.4	1.1
0.100	1.00	62.3	2.4

$W_{water}/W_{cement} = 0.3$; W: weight.

Table 3
Effects of mixing procedure on viscosity of cement paste

T_{water} (min)	T_{HPMC} (min)	T_{MFS} (min)	Viscosity at 0.06 s^{-1} (Pa s)	Viscosity at 23.2 s^{-1} (Pa s)
2	2	2	12.8	0.6
2	10	2	6.6	0.2
2	2	10	32	0.5

$W_{water}/W_{cement} = 0.3$, $W_{HPMC}/W_{cement} = 0.00013$, $W_{MFS}/W_{sand} = 0.01$; T: mixing time.

T_{water}: mixing time of cementitious ingredients with water before the addition of polymers.

T_{HPMC}: mixing time of cement pastes with HPMC solution prior to the addition of MFS.

T_{MFS}: mixing time of cement pastes after adding MFS.

contain the same concentrations of the polymeric admixtures. In this study, the HPMC concentration was kept constant at 0.013% and the MFS concentration at 1.00%. Increasing the mixing time of MFS from 2 to 10 min results in little change in the viscosity. In contrast, increasing the mixing time of HPMC prior to the addition of MFS leads to a continuous decrease in the shear viscosity.

Hence, the combination of MFS of 1.00% and HPMC of 0.013% coupled with appropriate mixing procedure was adopted to attain high deformability of the fresh cementitious mix by improving its stability. This beneficial effect of optimal concentrations of HPMC and MFS on reducing the viscosity was attributed to the electrosteric stabilization imparted by the two polymers. It was interpreted that MFS electrostatically disperses the flocculated cement particles, and HPMC sterically prevents the re-flocculation enhanced by van der Waals attraction. Increasing mixing time of HPMC prior to the addition of MFS increased the fraction of HPMC adsorbed onto the cement particles, leading to further reduction in the flocculation between particles, and the viscosity of cement paste, in consequence. This was revealed with an adsorption measurement to quantify the amount of HPMC adsorbed onto the cement particles, although it is not shown here. The detailed mechanism of the stabilization was discussed elsewhere with a cement model suspension [18].

4.3. *Effects of rheological properties of cement suspensions (cement pastes) on deformability of fresh mortar matrix mix*

The flow table test was conducted to assess the effectiveness of rheological control of fresh cement pastes on the deformability of fresh mortar matrix mix Γ_1. Table 4 presents the effects of the HPMC concentration on Γ_1 at a constant W/C of 0.30, S/C of 0.50, and MFS concentration of 1.00%. The FM-1 mix does not contain HPMC, while the FM-2 mix incorporates HPMC of 0.013%. On the first flow table test, every fresh matrix mix exhibited Γ_1 large enough to cover the flow table surface (diameter = 26 cm), irrespective of the differences in the HPMC concentration. On the second flow test conducted, Γ_1 of the FM-1 mix was slightly less than that of FM-2 mix, which contains HPMC of 0.013%, although both mixes show a large reductions in Γ_1 as a result of the 10 min rest in the flow cone. With the third flow table test to investigate reversibility of the fresh mix, Γ_1 of FM-2 is more than twice the Γ_1 value of FM-1. This implies that FM-2 has a highly reversible flocculated microstructure, which is mostly disrupted by the mechanical agitation, while FM-1 has a more irreversible flocculated microstructure. This flow table test result is in accordance with the reduction in the steady shear viscosity of cement suspensions containing optimal concentrations of HPMC and MFS, exhibited in Table 2.

Table 5 presents the effect of the mixing procedure on the values of Γ_1 of the fresh matrix mixes. The HPMC and MFS concentrations were kept constant at 0.013% and 1.00%, respectively. In the preparation of the FM-2 mix, the suspension was mixed for 2 min, following the addition of the HPMC solution, then mixed for another 2 min following the addition of the MFS solution. The FM-3 mix was prepared by extending the mixing time of the HPMC solution from 2 to 10 min, and the FM-4 mix was prepared by extending the mixing time of the MFS solution from 2 to 10 min.

All three fresh mixes have the same value of Γ_1 on the first flow table test. After rest for 10 min, the fresh mix FM-3 demonstrated no reduction in Γ_1, thus, covering the entire flow table surface. In contrast, the other fresh mixes FM-2 and FM-4 show a considerable reduction in Γ_1. This is also in accordance with the reduction in the steady shear viscosity of the cement suspension upon extension of the mixing time for the HPMC solution, as shown in Table 3.

Table 4
Effects of concentrations of MFS and HPMC on deformability Γ_1 of fresh mortar mix

	HPMC (% w/w_{cement})	MFS (% w/w_{cement})	Γ_1 on 1st test	Γ_1 on 2nd test	Γ_1 on 3rd test
FM-1	0	1.00	5.8	0.2	1.5
FM-2	0.013	1.00	5.8	0.5	3.8

$W_{\text{water}}/W_{\text{cement}} = 0.3$, $W_{\text{sand}}/W_{\text{cement}} = 0.5$; W: weight.

Table 5
Effects of mixing procedure on deformability Γ_1 of fresh mortar mix

Fresh mix	T_{water} (min)	T_{HPMC} (min)	T_{MFS} (min)	Γ_1 on 1st test	Γ_1 on 2nd test
FM-2	2	2	2	5.8	0.5
FM-3	2	10	2	5.8	5.8
FM-4	2	2	10	5.8	0.4

$W_{\text{water}}/W_{\text{cement}} = 0.3$, $W_{\text{sand}}/W_{\text{cement}} = 0.5$, $W_{\text{HPMC}}/W_{\text{cement}} = 0.00013$, $W_{\text{MFS}}/W_{\text{sand}} = 0.01$; T: mixing time.

These flow tests confirm that the steady shear properties of cement suspensions directly influence the deformability of fresh mortar mix. They also suggest that the addition of non-colloidal sand particles contribute only to increasing the internal frictional force—a factor contributing to increase the viscosity of concentrated suspension—without causing additional effects on the flocculation between cement particles.

4.4. Effect of deformability of fresh mortar mix on the properties of fresh PE-ECC mixes

To investigate the effect of the deformability of fresh mortar mix Γ_1 on the fresh properties of fresh ECC mix containing 1 vol.% of PE fiber, the slump test, funnel test, and self-consolidating test were conducted. Prior to the tests, the fresh ECC mixes were allowed to rest in the measuring device for 10 min. For this experiment, fresh mortar mixes, FM-1, FM-2, and FM-3, which had exhibited comparable value of Γ_1 on the first flow table test, but different values of Γ_1 on the second flow table test, were employed in preparing the fresh ECC mix. The same mixing procedure for the fiber was used in the three mixes, so that the equivalent viscosity of the fresh mortar mix during mixing is expected to produce no significant differences in the uniformity of fiber dispersion. Hence, any differences in the fresh properties of the fresh ECC mix are presumed to result from the differences in the deformability of the fresh mortar mix.

Table 6 indicates that the use of both HPMC and MFS increases Γ_2 from 2.6 to 4.2 and the extension of the mixing time almost doubles Γ_2 from 4.2 to 8. Moreover, Γ_2 of the fresh ECC mix made with FM-3 is equal to Γ_2 obtained with the slump test, which is conducted just after filling the slump cone with the fresh mix. This demonstrates the high consistency of the fresh ECC mix. Hence, this result confirms that the optimal concentrations of HPMC and MFS and the application of the appropriate mixing time for the polymers are beneficial to producing a high Γ_2 of fresh ECC mix.

Table 6 also presents the effect of the fresh mortar mix on the flow rates of the fresh ECC mix. The fresh ECC mix made with FM-1 stiffened in the funnel and did not flow. The less stiffened fresh ECC mix made with FM-2 vacated the funnel slowly, while the fresh ECC mix made with FM-3 exhibited the highest flow rate. This result also confirms the beneficial effects of the optimal doses of polymers and appropriate mixing procedure on achieving desirable flow rates of fresh ECC mix.

Complete self-consolidation is achieved if the height of fresh mix in the left chamber reaches 15 cm, which is half of the initial height of the fresh mix poured into the right chamber. As observed in the previous test, the fresh mix made with FM-1 stiffened in the right chamber, and did not flow into the left chamber. In contrast, the fresh mix made with FM-2 rose up to 10.8 cm in the left chamber ($L = 0.72$) and the fresh mix made with FM-3 rose up to 11.7 cm ($L = 0.78$). Thus, the latter fresh mix exhibits a slightly higher self-consolidation index L.

It is interesting to note that the self-consolidation index values L of the two fresh ECC mixes made of FM-2 and FM-3 are comparable, despite the significant differences in the deformability and flow rate. To accomplish the flow into the left chamber, the fresh mix should first successfully pass through the reinforcement bars, without causing segregation and subsequent clogging. Then, the fresh mix reaching the wall in the left chamber has to be pushed up by the fresh mix supplied from the right chamber. This mechanism implies that the fresh mix can easily rise up, as long as the fresh mix passes through reinforcement bars and is deformable enough to reach the wall. Thus, the vertical height of the fresh mix would depend on the horizontal deformability of the fresh mix more than its vertical deformability. As observed in the slump test, the fresh mix made with the FM-2 had a capacity to flow some distance. Therefore, the small difference in the self-consolidating values between the two fresh mixes is attributed to the short horizontal distance of left chamber. Hence, it is expected that increasing the horizontal distance of the left chamber would magnify the difference in the self-consolidating performance between these two fresh mixes.

A comparison between the fresh properties of the fresh ECC mix made with fresh matrix mix FM-3 and those of self-consolidating concrete [12,22,23] confirms satisfactory fresh performance of self-consolidating PE-ECC mix (Table 6).

Table 6
Effects of deformability Γ_1 of fresh mortar mix on the deformability Γ_2, flow rate R, and self-consolidation index L of fresh ECC mix and comparison with flow indices of self-consolidating concrete

Fresh mix	$D_1/2$ (cm)	Γ_2	T (s)	R	H (cm)	L
FM-1	38	2.6	∞	0	0	0
FM-2	46	4.2	16.7	0.6	10.8	0.7
FM-3	60	8	12.5	0.8	11.7	0.8
Self-consolidating concrete	60–72	8–12		0.8–1.2		1 (0.73[a])

[a] Denotes the criterion proposed by Ozawa co-workers [22,23].

Based on the results discussed above, FM-3 (with mix composition given below Table 5) is regarded as the optimal mixing procedure for self-consolidation.

4.5. Mechanical performance of self-consolidating PE-ECC

Fig. 2 confirms the strain-hardening performance of self-consolidating PE-ECC made with FM-3 under direct tensile load. The tensile strength increased to 3.8–4.6 MPa with the formation of multiple cracks, after the formation of the first crack at 2–3 MPa. The ultimate tensile strain is approximately 1–1.2%.

Fig. 3 shows the multiple crack patterns on the self-consolidating ECC specimen which has experienced maximum tensile load. This picture also confirms the strain-hardening performance of self-consolidating ECC.

The mechanical performance of self-consolidating ECC, however, is not as good as that of high strength PE-ECC prepared at a lower W/C ratio of 0.28, a higher fiber volume fraction of 0.015, and a fiber length of 19 mm. The ultimate tensile strength of high strength PE-ECC is 6.5 MPa and the ultimate tensile strain is 3.4%. The reduced performance is likely due to lower interfacial bonding force and fiber volume fraction in the present self-consolidating ECC. Therefore, further improvement of mechanical performance of self-consolidating ECC material is recommended. However, the test results reported above illustrate the potential of the proposed design approach of self-consolidating ECC materials.

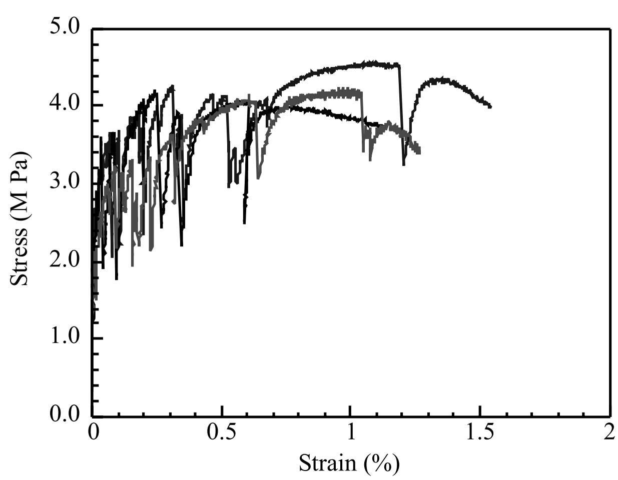


Fig. 2. Measured tensile stress–strain curves of the self-consolidating PE-ECC.

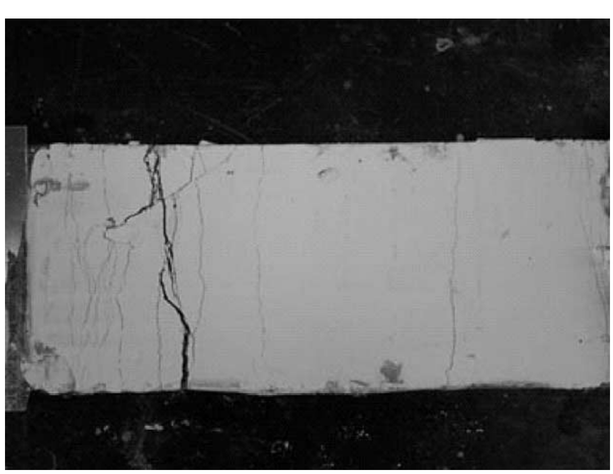


Fig. 3. Formation of multiple cracks in the self-consolidating PE-ECC after experiencing ultimate tensile load.

5. Conclusions

Electrosteric dispersion and stabilization employing optimal concentrations of HPMC and MFS and appropriate mixing procedures have contributed to producing a fresh mortar matrix mix with high deformability and consistency at particle concentrations determined by micromechanics based design. This allowed the development of a self-consolidating PE-ECC mix with 1 vol.% of PE fiber that displays high deformability, high flow rate, and high self-consolidation in the fresh state, and strain-hardening performance in the hardened state. Comparison with the fresh properties of self-consolidating concrete verifies satisfactory self-consolidating properties of the fresh PE-ECC mix. Mechanical test confirms the ductile strain-hardening performance of the hardened self-consolidating ECC. Thus, the compatible control of the material microstructure through parallel micromechanics based design and rheological design has been successfully used to achieve strain-hardening and self-consolidating performance in a single material.

References

[1] Mindess S, Young JF. Concrete. Prentice-Hall; 1981.

[2] Naaman AE, Reinhardt HW. Characterization of high performance fiber reinforced cement composites HPFRCC. In: Proceedings of the 2nd International RILEM Workshop on High Performance Fiber Reinforced Cement Composites, Ann Arbor, MI, vol 2. 1996. p. 1–24.

[3] Li VC. Advances in strain-hardening cement based composites. In: Engineering Foundation Conference on Advances in Cement and Concrete, New Hampshire, July. 1994. p. 24–9.

[4] Li VC. Engineered cementitious composites—tailored composites through micromechanical modeling. In: Banthia N, Bentur A, Mufti A, editors. Fiber reinforced concrete: present and the future. Canadian Society of Civil Engineers; 1998. p. 64–97.

[5] Li VC, Kanda T. Engineered cementitious composites for structural applications. ASCE J Mater Civil Eng 1998;10(2):66–9.

[6] Bouygues, Lafarge, Rhodia Chimie. Concrete comprising organic fibers dispersed in a cement matrix, concrete cement matrix, and premixes. French Patent PCT/FR99/01145, 12 May, 1999.

[7] Li VC. From micromechanics to structural engineering—the design of cementitious composites for civil engineering applications. JSCE J Struct Mech Earthquake Eng 1993;10(2):37–48.
[8] Leung CKY. Design criteria for pseudo-ductile fiber-reinforced composite. J Eng Mech ASCE 1996;22(1):10–4.
[9] Li VC, Leung KY. Steady-state and multiple cracking of short random fiber composites. J Eng Mech ASCE 1992;118(11): 2246–63.
[10] Kanda T, Li VC. Multiple cracking sequence and saturation in fiber reinforced cementitious composites. Conc Res Technol JCI 1998;9(2):19–33.
[11] Kuroiwa S, Matsuoka Y, Hayakawa M, Shindoh T. Application of super-workable concrete to construction of a 20 story building. ACI Mater J 1993:147–61.
[12] Okamura H, Ozawa K. Mix-design for self-compacting concrete. Concr Lib JSCE 1995;25:107–20.
[13] Tanaka K, Sato K, Watanabe S, Arima I, Suenaga K. Development and utilization of high performance concrete employed in the Akashi Kaikyo bridge. In: Proceedings ACI SP-140. 1994. p. 25–51.
[14] Tanaka I, Takeshi T, Suzuki N. Properties of spherical cement. In: Proceedings of the Second Japan International SAMPE, Chiba, Japan, December. 1991. p. 1256–63.
[15] Nawa T, Izumi T, Edamatsu Y. State-of-the-art report on materials and design of self-compacting concrete. In: Proceedings of the International Workshop on Self-Compacting Concrete, JSCE, Kochi, Japan. 1998.
[16] Li VC, Mishra DK, Wu HC. Matrix design for pseudo strain-hardening fiber reinforced cementitious composites. Mater Struct 1995;28:586–95.
[17] Grünewald S, Walraven JC. Rheological study on the workability of fiber-reinforced mortar. In: Proceedings of the Second International Symposium on Self-compacting Concrete, Tokyo, Japan. 2001.
[18] Kong HJ. Electrosteric stabilization of heteroflocculating alumina/silica suspensions and its application on the development of self-compacting engineered cementitious composites. PhD Thesis, 2001.
[19] Yoshioka K, Sakai E, Daimon M, Kitahara A. Role of steric hindrance in the performance of superplasticizers for concrete. J Am Ceram Soc 1997;80(10):2667–71.
[20] Yamada K, Takahashi T, Hanehara S, Matsuisa M. Effects of the chemical structure on the properties of polycarboxylate-type superplasticizer. Cem Concr Res 2000;30:197–207.
[21] Lewis JA, Matsuyama H, Kirby G, Morissette S, Young JF. Polyelectrolyte effects on the rheological properties of concentrated cement suspensions. J Am Ceram Soc 2000;83(98):1905–13.
[22] Ozawa K, Sakata N, Okamura H. Evaluation of self-compactability of fresh concrete using the funnel test. Concr Lib JSCE 1995;25:59–75.
[23] Nagamoto N, Ozawa K. Mixture proportions of self-compacting high-performance concrete. In: High-performance concrete: design, materials, and advances in concrete technology. ACI International SP-172. 1999. p. 623–66.
[24] Schultz MA, Struble LJ. Use of oscillatory shear to study flow behavior of fresh cement. Cem Concr Res 1993;23:272–82.
[25] Larson RG. The structure and rheology of complex fluids. Oxford: Oxford University Press; 1999.
[26] Ouchi MH, Ozawa M, Okamura H. Effect of superplasticizer on self-compactability of fresh concrete. TRB Annual Meeting 1997;574:37–40.
[27] Krieger MI, Dougherty TJ. A mechanism for non-Newtonian flow in suspensions of rigid spheres. Trans Soc Rheol 1959;3:137–52.
[28] Erricson KA, Toll S, Manson J-AE. Sliding plate geometry of planar oriented concentrated fiber suspension. Rheol Acta 1997;36:397–405.