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Constitutive rheological control to develop a self-consolidating engineered cementitious composite reinforced with hydrophilic poly(vinyl alcohol) fibers

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Abstract

A self-consolidating engineered cementitious composite (ECC), which exhibits tensile strain-hardening behavior in the hardened state, while maintaining self-consolidating properties in the fresh state, has been developed by employing hydrophilic poly(vinyl alcohol) (PVA) fibers. The constitutive rheological design approach is adopted to separately control the aggregation between cement particles and sedimentation behavior with a combination of a strong polyelectrolyte and non-ionic polymer. This study suggests an effective formulation approach of fresh cementitious mix to maximize its fluidity without segregation, regardless of solids concentration employed. The resulting self-consolidating PVA-ECC exhibits tensile strain up to 5%. Besides, the methodology of constitutive rheological control can be extended to formulating other self-consolidating cementitious materials with various types of polymeric admixtures.

Keywords: Self-consolidating ECC; PVA fibers; Constitutive rheological design; Strong polyelectrolyte; Non-ionic polymer; Electrosteric stabilization

1. Introduction

In our previous study, a self-consolidating engineered cementitious composite (ECC) reinforced by polyethylene (PE) fibers was developed, which exhibits self-consolidating performance in the fresh state and ductile strain-hardening performance in the hardened state [1,2]. Control of the microstructure was considered a key factor to simultaneously satisfy optimal micromechanical design for strain hardening behavior of hardened material and process design for self-consolidating performance of fresh mix in a single material. This was accomplished by determining the optimal concentrations of a strong polyelectrolyte (high range water reducer) and a non-ionic polymer 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) at given particle and fiber loadings. Thus, this contributed to producing a fresh mortar matrix mix with high deformability and high consistency of fluidity, leading to the self-consolidating performance of the fresh PE-ECC mix.

In the PE-ECC, the volume fraction of the PE fiber was limited to 0.01 to retain high deformability of the fresh matrix mix in the presence of the fiber. Thereby, the ultimate material strength and ductility of the self-consolidating PE-ECC were lower than the normal (cast and vibrate) PE-ECC containing higher fiber volume fractions of 0.015–0.020 [1]. To develop a self-consolidating ECC which exhibits mechanical performance equivalent to normal ECC, it was necessary to employ hydrophilic fibers to afford higher fiber loading, since the enhanced fiber wettability in the fresh mortar mix would improve fiber dispersion in the fresh cementitious mix.

Recently, a ECC material reinforced with hydrophilic poly(vinyl alcohol) (PVA) fibers has been developed,

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via extensive micromechanical design and experiments to obtain appropriate PVA fiber bridging response [3–6]. The ultimate tensile strain in PVA-ECC ranging from 4% to 5% was achieved with 2 vol.% of PVA fibers. In addition, PVA-ECC is favored for practical applications, since it is more cost-effective than PE-ECC.

The objective of this work is to develop high performance self-consolidating PVA-ECC with a ductility comparable to normal PVA-ECC. To accomplish this goal, the same approach used in the development of the self-consolidating PE-ECC, the parallel control of micromechanical parameters and processing parameters, was adopted. Thus, we focused on developing fresh cement pastes with optimal fluidity at a given cement particle concentration as determined by the PVA-ECC design and employing these pastes in the fresh mortar matrix mix and fresh ECC mix. Polymeric admixtures were utilized to achieve the desirable fresh properties at a given solids concentration, represented by an optimal viscosity and yield stress, good cohesiveness between ingredients, and satisfactory consistency of initial fluidity over time.

Compared with PE-ECC, higher water/cement (W/C) are required for the ductile performance of PVA-ECC [3]. Therefore, these cementitious suspensions are vulnerable to segregation with the use of the dispersant, known as the superplasticizer, since too low of a viscosity accelerates the sedimentation of the particles [7]. However, it may not be desirable to avoid using the superplasticizer to prevent the segregation, since cement particles will remain aggregated, resulting in very poor workability. To avoid this undesirable phase separation, while maintaining the stability, it will be critical to stabilize the cement particles in the suspending medium, which has a viscosity high enough to prevent the settling of particles.

The beneficial effects of electrosteric stabilization imparted by melamine formaldehyde sulfonate (MFS), a polyelectrolyte, and hydroxypropylmethylcellulose (HPMC), a non-ionic water-soluble polymer, were already demonstrated in the development of the self-consolidating PE-ECC [2,8]. In addition, previous rheological studies illustrated that excess HPMC simply increased medium viscosity of the cement suspension, without causing undesirable flocculation [9].

The most important issue in the incorporation of two polymers is the determination of the optimal polymer concentrations. To satisfy this objective, we introduce constitutive rheological control to separately tailor the interparticle forces between cement particles and the cohesiveness between the cement particles and water with MFS, which acts as electrostatic dispersant, and HPMC, which acts as both steric stabilizer and viscosity-enhancing agent. The effectiveness of the fresh cement pastes optimized by the constitutive rheological control method on attaining desirable fluid properties in the fresh mortar matrix mix and the fresh PVA-ECC is ultimately examined by assessing their deformability (mortar mix and ECC mix) and the self-consolidation ability of the ECC mix [10,11].

2. Materials and methods

2.1. Materials

ECC material is composed of common mortar matrix and polymer fibers. In this study, a micromechanically designed PVA fiber (Kuraray Co. Ltd., Japan) was used as the reinforcing fiber (diameter = 48 μm; length = 12.7 mm; tensile strength = 1.8 GPa; elastic modulus = 35 GPa). Ordinary Type I Portland cement (average particle diameter = 11.7 ± 6.8 μm, LaFarge Co.), silica sand (average particle diameter = 110 ± 6.8 μm, US Silica Co.), and fly ash (FA) (average particle diameter = 2.4 ± 1.6 μm, Boral Material Technologies Inc.) were used as the major ingredients in the matrix. All of the cementitious raw materials were used as received. Polymeric admixtures comprised of melamine formaldehyde sulfonate (MFS, W.R. Grace Chemical Co.) and hydroxypropylmethylcellulose (HPMC, DOW Chemical Co.) were used to control the rheological properties of the fresh mortar 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. Two weight percent of HPMC aqueous solution was added prior to the addition of the MFS solution in order to ensure the adsorption of HPMC onto the cement particles. In the last step, PVA fibers were added manually to the fresh mortar matrix mix.

2.2. Experiments

2.2.1. Rheological measurements for cement pastes

A Bohlin VOR rheometer was used to measure the steady shear properties of fresh cement pastes varied by polymer concentrations. In this controlled strain rheometer, the cup rotates at a constant shear rate, and the resulting shear stress is measured, from which the viscosity of the paste is automatically calculated.

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 concentric cylinder geometry, the paste is deformed at a constant stress within the linear viscoelastic region, and the resulting strain is measured. The storage modulus is then automatically calculated from this measurement.

2.2.2. Deformability test for mortar

The small flow cone for the conventional flow table test was used to quantify the deformability of fresh mortar matrix mix Γ_1. Flow table tests were performed after the fresh mortar mix had rested in the flow cone for 10 min, so that the effect of fluidity consistency over time could be incorporated into the deformability. No external means (e.g. vibration) was applied to consolidate the fresh cementitious mix. Once the test cones were lifted, the fresh cementitious mix tended to collapse and spread. The maximum diameter of the spread d_1 and the diameter perpendicular to it d_2 were measured. Index for deformability Γ_1 was then calculated by $(d_1 + d_2)/2d_0$, where the d_0 is the diameter of flow cone (= 10 cm).

2.2.3. Large-scale tests for ECC mix

A half-cut slump cone, on which half of the top part of the cone was removed to save material, was employed to measure the deformability of fresh ECC trial mixes Γ'_2. In addition, a regular slump cone for the conventional slump test was employed to measure the deformability of the self-consolidating ECC mix Γ_2 [12].

The slump test was performed twice, just after mixing and after storage of fresh ECC mix in the slump cone for 10 min. No external means (e.g. vibration) was applied to consolidate the fresh cementitious mix. The maximum diameter of the spread D_1 and the diameter perpendicular to it D_2 were measured. Deformability Γ'_2 and Γ_2 were calculated by $(D_1 + D_2)/2D_0$, where the D_0 is the diameter of slump cone (= 20 cm).

The box prepared for self-consolidating test was the same as the one used for self-consolidating PE-ECC [2]. An index for the degree of self-consolidation (L) is defined as $2H/H_0$, where H_0 is the initial height of the fresh ECC mix. The index gives the value of 1 for perfect self-consolidating performance.

2.2.4. Mechanical tests

To verify the strain-hardening behavior of the self-consolidating ECC, a direct tensile test was performed with ECC specimens made without any external consolidation process. The ECC specimens were cured in water for four weeks. The specimens were loaded with a constant cross head speed, and the loading force was measured. In addition to the tensile stress–strain curves, the first crack strength, ultimate tensile strength, and ultimate tensile strain were measured. The microcrack width and spacing were also determined.

3. Results and discussion

3.1. Effect of fiber surface properties on the fresh properties of the fresh ECC mix

To investigate the effects of fiber surface properties on fresh properties of the fresh composite mix, we prepared ECC reinforced by hydrophobic PE fibers and hydrophilic PVA fiber reinforced composite (FRC) at the same matrix compositions. Therefore, W/C, sand/cement (S/C), and fiber volume fraction were kept constant at 0.30, 0.50, and 0.01, respectively. (The 1% of PVA-FRC is not expected to achieve the strain-hardening based on the micromechanics calculations. Hence, this composite is a FRC, not an ECC.) The concentrations of polymer admixtures were also kept constant. The matrix composition employed herein is the one optimized to achieve the ductile strain-hardening performance of the PE-ECC [2].

The slump tests show that Γ_2 of the fresh PVA-FRC mix ($\Gamma_2 = 11.5$) is higher than Γ_2 of the fresh PE-ECC mix ($\Gamma_2 = 8.0$) by 43%. The box test also shows perfect self-consolidation of the fresh PVA-FRC mix of 1.0, which is higher than that of the fresh PE-ECC mix ($L = 0.87$) by 15%.

The difference between the aspect ratios of the PE fiber (~334) and the PVA fiber (~264) is negligible in influencing the fluid properties, since a small difference in the fiber aspect ratio is known not to affect the viscosity of the suspension significantly [13]. Therefore, the uniformity of the fiber dispersion, which depends on the fiber wettability in the fresh mortar mix, is regarded as the key factor to cause different fluid properties, since the increase in entangled fiber clumps tends to greatly reduce deformability of the fresh ECC mix. The hydroxyl groups on the PVA fiber surfaces increase the wettability of the fiber in the polar matrix mix, enhancing dispersion of the fibers when coupled with mechanical agitation on mixing. In contrast, the hydrophobic surfaces of the PE fibers do not provide such physicochemical forces to improve fiber dispersion.

The self-consolidating PVA-FRC exhibited an ultimate tensile strain of approximately 0.3%, forming two or three microcracks on the specimen. This ductility is much lower than that of the self-consolidating PE-ECC made with the same matrix. The self-consolidating PE-ECC produces multiple microcracks, leading to an ultimate tensile strain of 1.0%. This brittle performance of PVA-FRC is attributed to not utilizing micromechanical criteria to achieve the strain-hardening performance. This emphasizes the importance of micromechanical design to combine the matrix, fiber, and interfacial properties, necessitating adoption of micromechanical criteria determined for the PVA-ECC in designing the self-consolidating PVA-ECC.

The excellent fresh properties of the PVA-FRC mix, due largely to uniform fiber dispersion, suggest that use of the PVA fiber as the reinforcement of the ECC material can afford the use of a higher fiber content than the PE-ECC without sacrificing the self-consolidating performance. Hence, 2 vol.% of the PVA fibers, as suggested by the micromechanical model for strain-hardening PVA-ECC [6] can be incorporated.

3.2. Determination of micromechanical constraints

Unlike the PE fiber, hydroxyl groups on the PVA fiber surfaces induce hydrogen bonding between the fiber surfaces and the polar cementitious particle surfaces, denoted as a chemical bonding force G_d. In addition, contact between the fiber and mortar matrix provides a frictional bonding force τ_0. The micromechanical computation in Fig. 1 made by Lin et al. [4] describes how to adjust the interfacial bonding forces comprised of G_d and τ_0 to achieve the strain-hardening performance with a low fiber volume fraction of 0.01–0.02. It indicates that G_d should be reduced to decrease the critical fiber volume fraction V_f^{crit}, which is the minimum fiber volume fraction required for strain-hardening behavior. At a given G_d, increasing τ_0 significantly decreases V_f^{crit}, due to improvement in the fiber bridging properties. A further increase in τ_0, however, tends to increase V_f^{crit}, since it increases fiber rupture, deteriorating fiber bridging properties.

The magnitudes of the two interfacial bonding forces can be separately adjusted in composite processing. G_d is controlled by treating the fiber surfaces with an appropriate coating agent to reduce the hydrophilicity of the fiber surfaces. A desirable τ_0 is obtained by optimizing the cementitious particle concentration, represented by the W/C. Generally, increasing the cementitious particle concentration tends to increase the frictional bonding force. Therefore, a very high W/C would induce too low of a fiber bridging force, while a very low W/C would induce fiber rupture, as observed at a high τ_0. Moreover, decreasing the W/C increases the first crack strength, which should be low enough to satisfy the first crack strength criteria [14,15]. Extensive micromechanical predictions and experiments have found that a W/C of 0.45 would be appropriate to achieve a satisfactory first crack strength as well as τ_0. Such adjustments in the interfacial bonding forces would reduce V_f^{crit} to a minimum of 0.01, according to the micromechanical computation. To account for material variability, a PVA fiber content of 0.02 has been used to produce successful normal PVA-ECC with excellent tensile capacity over 4% [5]. To obtain the ductility and ultimate composite strength comparable to this high performance PVA-ECC, the same fiber volume fraction of 0.02 was selected in this study.

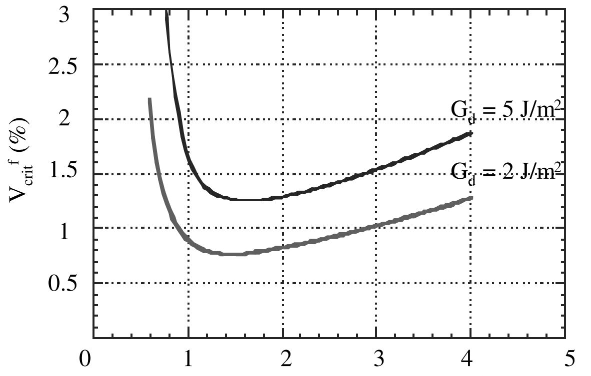


Fig. 1. Adjustment of micromechanical parameters to attain the strain-hardening behavior of PVA-ECC (adapted from Lin et al. [4]).

Another significant criterion for exhibiting the strain-hardening performance is the optimal matrix toughness. It should be low enough in comparison to increase the complementary energy in the fiber bridging performance [5], while retaining high resistance to shrinkage. Thus, very fine sand particles were incorporated into the mortar matrix. Micromechanical experiments showed that a S/C above 0.6 would be desirable, depending on the fiber surface characteristics. However, consideration of self-consolidation ability places a limit on the S/C to minimize the effects of high particle loading on the viscosity [16].

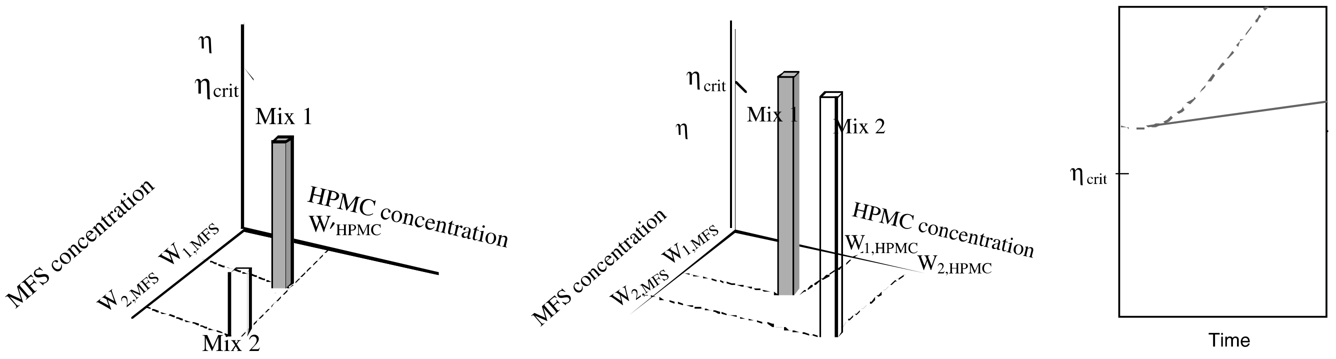
3.3. Constitutive rheological control of cement paste

As illustrated in the development of self-consolidating PE-ECC [2], the fresh properties of fresh cement paste are very important, since these provide the main driving force for the flow of fresh ECC mix and good fiber dispersion. An optimal viscosity, which provides high deformability as well as good cohesiveness, and slow increase of the viscosity over time, is recommended for designing desirable fresh cement pastes.

Fig. 2 illustrates the utilization of constitutive rheological control to determine the optimal concentrations of MFS and HPMC, which would produce the desirable rheological properties. This divides the effect of polymers on the viscosity of fresh cement pastes into the effects on flocculation between particles (Chart I), resistance to segregation (Chart II), and time-dependency of the viscosity (Chart III).

In Chart I, the viscosities of the two cement suspensions are shown as a function of MFS concentration. The same concentration of HPMC at W'_{HPMC} is added to both pastes to build up the steric layers on the particle surfaces, and thus to form electrosteric layers with the adsorbed MFS chains. In this chart, η_{crit} represents the minimum viscosity required to prevent sedimentation of the cement particles.

Extensive studies on the effect of MFS on the rheological properties of cement suspensions revealed that the effectiveness of MFS on reducing viscosity depends on the zeta potential of the cement particles affected by adsorption of MFS [17]. The zeta potential of the cement particles increases upon increasing the MFS concentration. However, a steady state value of zeta potential is reached when the MFS concentration increases above 1.00% (w/w), leading to no further significant reduction in the viscosity of the suspension. This



(a) Chart I (b) Chart II (c) Chart III

Fig. 2. Schematic description of constitutive rheological design to determine the optimal dosages of polymers for desirable fluidity of given cementitious suspension. Chart I: control of viscosity by varying MFS concentration, Chart II: control of viscosity by varying HPMC concentration coupled with MFS, Chart III: viscosity change over time (– – –) Mix 1, (—) Mix 2.

was interpreted as reaching full particle coverage of the cement particles by MFS at 1.00%. Therefore, a MFS dosage at 1.00% (w/w) is regarded as the optimal dosage to maximize the electrostatic dispersion between cement particles. In contrast, a MFS dosage lower than 1.00% (w/w) would still leave flocs formed by electrostatic attractive forces, due to low particle surface coverage. In addition, incomplete surface coverage may enhance bridging flocculation between the particles by adsorbed MFS chains [18,19]. Thus, the difference in the electrostatic interactions between the cement particles depends on the surface coverage, as reflected by the η values of Mix 1 ($W_{1,\mathrm{MFS}} < 1.00\%$) and Mix 2 ($W_{2,\mathrm{MFS}} = 1.00\%$) shown in Chart I. The lower MFS concentration $W_{1,\mathrm{MFS}}$ would produce a higher viscosity due to low particle surface coverage.

At such a high W/C, the polymeric stabilization, however, would reduce the viscosity below η_{crit} for both Mix 1 and Mix 2. This is unavoidable even at lower MFS concentrations than $W_{1,\mathrm{MFS}}$. Thus, more HPMC have to be added to increase the medium viscosity, resulting in the total viscosity above η_{crit} of cement pastes shown in Chart II. For example, in the addition of HPMC of 0.15% (w/w), approximately 40% of the HPMC is adsorbed onto the particles and used to build up the steric layers, and the rest of the HPMC is utilized to increase the medium viscosity [8]. The higher HPMC concentration of $W_{2,\mathrm{HPMC}}$ is required for Mix 2 to recover the viscosity to slightly higher than η_{crit}, since its viscosity in Chart I is much lower than the viscosity of the Mix 1. Thus, both Mix 1 and Mix 2 would have sufficient cohesiveness to prevent phase separation at different HPMC concentrations.

While the viscosity for Mix 1 ($W_{1,\mathrm{MFS}} < 1.00\%$) and Mix 2 ($W_{2,\mathrm{MFS}} = 1.00\%$) are similar in Chart II, the stability of the viscosity of the two mixes over time may be expected to be significantly different. This is illustrated in Chart III which shows that the fluidity loss of Mix 1 over time would be faster than that of Mix 2, because of the fast re-flocculation between bare (not covered with MFS) surface sites on the cement particle surfaces as well as the incomplete dispersion of cement flocs at low surface coverage. Hence, the rheological design depicted in Fig. 2 suggests that Mix 2 with higher concentrations of MFS and HPMC is more desirable than Mix 1.

Fig. 3 compares the steady shear properties of the cement suspensions containing different HPMC and MFS concentrations, which are detailed in Table 1. The W/C was fixed at 0.45. It shows that increasing the MFS concentration from 0.33% to 1.00% (w/w) reduces the low-shear viscosity at a constant HPMC concentration

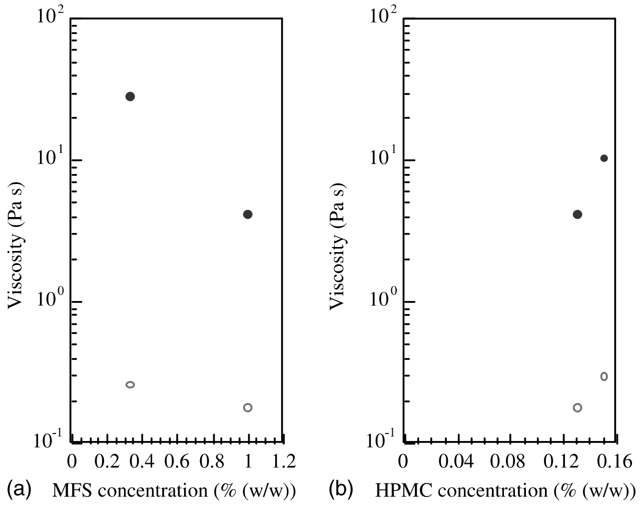


Fig. 3. Effect of polymer compositions on the steady shear viscosity of the fresh cement pastes η following a rest time for 10 min, (●) measured at a shear rate of 0.06 s^{-1}, (○) measured at a shear rate of 23.2 s^{-1}. (a) Effect of MFS concentration $W_{\mathrm{MFS}}/W_{\mathrm{c}}$ at constant $W_{\mathrm{HPMC}}/W_{\mathrm{c}}$ of 0.13%, (b) effect of HPMC concentration $W_{\mathrm{HPMC}}/W_{\mathrm{c}}$ at constant $W_{\mathrm{MFS}}/W_{\mathrm{c}}$ concentration of 1.00% (w/w); W: weight, c: cement.

Table 1
Variation of polymer compositions to adjust the fresh properties of the fresh cementitious mix and their effects on microstructural growth rate

	$W_{\mathrm{HPMC}}/W_{\mathrm{C}}$	$W_{\mathrm{MFS}}/W_{\mathrm{C}}$	G'_0	γ	λ
FM-1	0.05	0.33	56	0.04	
FM-2	0.13	0.33	110	0.03	
FM-3	0.05	0.67			
FM-4	0.13	1.00	7.8		17
FM-5	0.15	1.00	8.4		10

W: weight; C: cement; HPMC: hydroxypropylmethylcellulose; MFS: melamine formaldehyde sulfonate.

of 0.13%. In contrast, increasing the HPMC concentration from 0.13% to 0.15% at a high MFS concentration of 1.00% slightly increases the low-shear viscosity.

Table 1 also compares the growth of the aggregated microstructure over time *t*, quantified by the increase in the storage modulus of the fresh cement paste over time, $G'(t)$. The storage modulus of the suspension containing a low concentration of MFS at 0.33% (w/w) grows exponentially over time, following $G'(t) = G'_0 \exp(\gamma t)$. Variation of the HPMC concentration from 0.05% to 0.13% increases the storage modulus at time zero (measured after resting for 30 s), G'_0, but does not affect the exponential constant, γ. In contrast, the storage modulus of the suspension stabilized with MFS of 1.00% increases linearly with time, following $G'(t) = G'_0 + \lambda t$. This clearly illustrates that the optimal concentrations of HPMC and MFS, (which led to complete MFS coverage of the particle surfaces and appropriate resistance to particle sedimentation), retard growth of the aggregates, leading to a slow increase in the viscosity over time. In addition, the small effect of the variation of HPMC concentrations on the growth of the aggregates (comparing Mix FM-1 and FM-2; Mix FM-4 and FM-5) suggests that the non-adsorbed HPMC chains mainly increase the medium viscosity of the fresh cement pastes, without affecting interactions between cement particles greatly.

3.4. Effects of rheological properties of fresh cement pastes on the fluid properties of the fresh mortar matrix mix

Fig. 4 shows the effect of the polymers on the deformability of fresh mortar mix Γ_1 measured by the flow table test. FA particles were introduced to improve the cohesiveness between the fresh matrix mix and fibers. The effect of the FA will be discussed in another paper. In this experiment, the W/C was kept constant at 0.45, the S/C at 0.60, and the FA/C at 0.15. This figure shows that increasing the MFS concentration from 0.33% to 1.00% (w/w) significantly increases Γ_1. Increasing the HPMC concentration at constant MFS concentration tends to decrease Γ_1. However, the degree of reduction in Γ_1 is much smaller at the higher MFS concentration. It demonstrates that Γ_1 is mainly determined by the particle surface coverage of adsorbing polymers, since a high surface coverage effectively prevents flocculation between the particles. The reduction in Γ_1 induced by increasing the HPMC concentration at a constant MFS concentration is attributed to the increase in the medium viscosity, as explained previously.

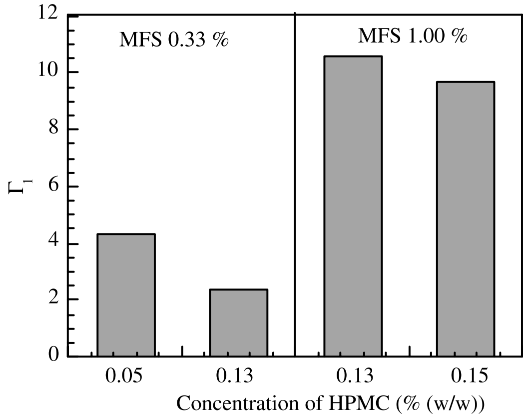


Fig. 4. Effect of polymer concentration on the deformability of the fresh mortar mix Γ_1 on the flow table test (W/C = 0.45, S/C = 0.6, FA/C = 0.15, $V_f = 0.02$).

These results reconfirm the effectiveness of constitutive rheological control to attain a fresh matrix mix with high fluidity, good cohesiveness, and high consistency.

3.5. Effects of fluid properties of the fresh matrix mix on the fluid properties of a fresh PVA-ECC mix

Fig. 5 shows the deformability Γ'_2 of the fresh ECC mix, measured with a half-cut slump cone. Two volume percent of PVA fibers are incorporated into the fresh ECC mix. In general, a larger Γ_1 obtained at higher MFS concentrations corresponds to a larger Γ'_2. The reduction in Γ'_2 over time, denoted as the consistency of fluidity, becomes relatively smaller with increasing MFS

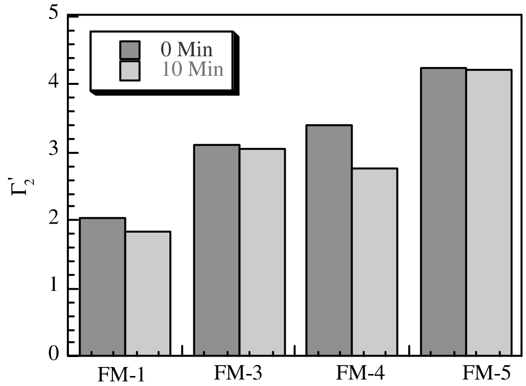


Fig. 5. Effect of polymer concentration on the deformability of the fresh ECC mix Γ'_2 on the half-cut slump test (W/C = 0.45, S/C = 0.6, FA/C = 0.15, $V_f = 0.02$).

concentration. Thus, no slump loss is observed at a MFS concentration of 1.00% (w/w), when the HPMC of 0.15% (Mix FM-5) is added.

In the flow table test, the fresh mortar mix FM-4, stabilized with the combination of HPMC at 0.13% (w/w) and MFS at 1.00%, resulted in a higher Γ_1 of 10.6 than the fresh mortar mix FM-5, stabilized with the combination of HPMC at 0.15% with MFS at 1.00% ($\Gamma_1 = 9.4$). No segregation was observed with these two fresh mortar mixes. The fresh ECC mix made with the FM-4, however, induced segregation at the interfaces between the fresh matrix mix and the fibers. This segregation tends to be more severe over time, leading to a significant reduction of Γ_2' measured after 10 min. This segregation is attributed to too high of a Γ_1, resulting in inhomogeneous flow between the mortar mix and the fibers. Therefore, this necessitates tuning Γ_1 to match the deformability and flow rates of the dispersed fibers, leading to the cohesive flow. Thus, increasing the HPMC concentration to 0.15% enhances Γ_2' measured after 10 min from 2.8 to 4.2, despite the small reduction in Γ_1 from 10.6 to 9.4.

These results emphasize the importance of maintaining balance between the flow of the fresh matrix mix with the flow of fibers, which depends on the uniformity of the fiber dispersion and fiber volume fraction, on obtaining desirable the fresh properties for the self-consolidating performance of the ECC mix.

From the results obtained in the previous sections, constitutive rheological control of the fresh mortar mix to determine the optimal dosages of the polymers and tuning of the deformability between the fresh matrix mix and fiber are employed to design the self-consolidating fresh PVA-ECC mix. To demonstrate the self-consolidating ability of the fresh mix, we performed a deformability test with the conventional slump cone ($D_1 = D_2 = 72.9$ cm; Fig. 6a) and the box ($H = 12.3$ cm; Fig. 6b). The composition of the fresh ECC mix is described in Table 2. Deformability of the fresh PVA-ECC mix, Γ_2, is 12 and self-consolidation index, L, of the fresh ECC mix is 0.82. The fresh PVA-ECC mix exhibits a smooth surface, while the reinforcing bars placed under the partition of the box tend to imprint their shapes on the surface of fresh PVA-ECC mix. This demonstrates the satisfactory self-leveling performance of the fresh PVA-ECC mix.

As compared in Table 3, the deformability of the self-consolidating PVA-ECC mix is greater than that of the self-consolidating PE-ECC, despite a much higher fiber loading. The degree of self-consolidation of the PVA-ECC is also greater than that of the PE-ECC. In addition, the value of the deformability is comparable to the deformability of self-consolidating concrete, ranging from 8 to 12, and the value of the self-consolidation index is also comparable to that of self-consolidating concrete, ranging from 0.73 to 1 [10,11].

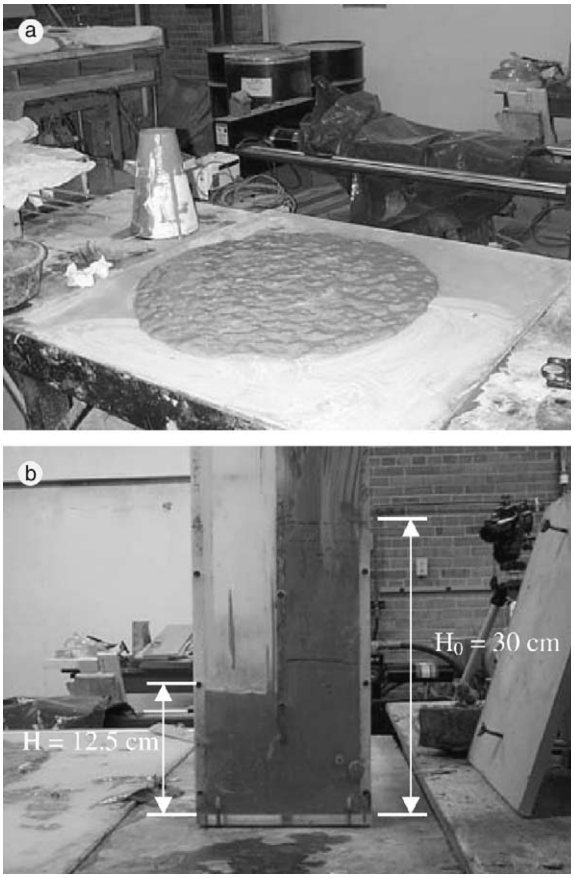


Fig. 6. Demonstration of self-consolidating properties of the fresh PVA-ECC mix. (a) Slump test ($\Gamma_2 = 12$), (b) self-consolidating test ($L = 0.82$).

Table 2
Composition of self-consolidating PVA-ECC reinforced by PVA fiber of 2 vol.%

W_C/W_C	W_S/W_C	W_{FA}/W_C	W_{water}/W_C	W_{HPMC}/W_C	W_{MFS}/W_C
1.0	0.6	0.15	0.45	0.0015	0.01

W: weight; C: cement; S: sand; FA: fly ash; HPMC: hydroxypropylmethylcellulose; MFS: melamine formaldehyde sulfonate.

3.6. Ductile performance of the self-consolidating PVA-ECC

Tensile tests were performed with ECC specimens to confirm the ductile strain-hardening performance of the self-consolidating PVA-ECC. Fig. 7 shows that the ultimate tensile strain of the self-consolidating ECC ranges from 3% to 5% for two different test specimens. During loading, a large number of microcracks with very fine crack spacing (2–5 mm) and small average crack width of 0.08 mm were formed, as observed in Fig. 8. The ductility of the self-consolidating ECC is comparable to that of high performance PVA-ECC cast with external consolidation. Crack closure, though incomplete, was observed on unloading,

Table 3
Comparison of fluidity index of self-consolidating PVA-ECC with PE-ECC and self-consolidating concrete

Material	PVA-ECC	PE-ECC	Self-consolidating concrete
d_1 (cm)	32.7	18	5
Γ_1	9.7	2.24	
D_1 (cm)	72.9	60	60–72
Γ_2	12.3	8	8–12
H (cm)	12.3	11.7	
L	0.82	0.78	0.73–1

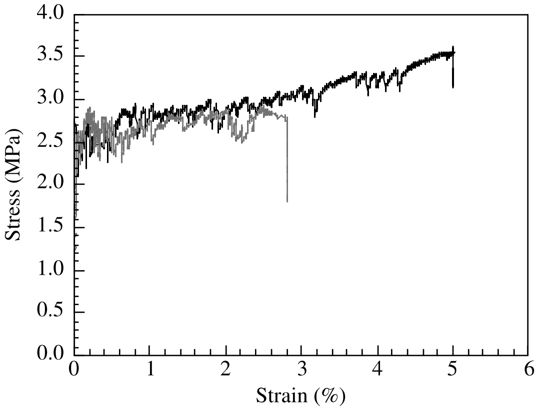


Fig. 7. Demonstration of strain-hardening performance of the self-consolidating PVA-ECC under direct tensile loading.

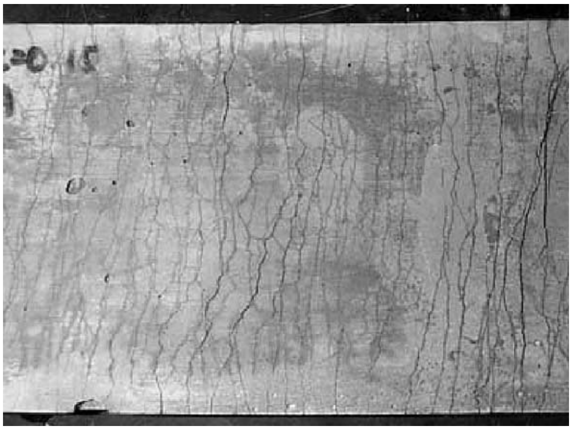


Fig. 8. Fine crack patterns formed on the specimens having experienced ultimate tensile loading.

suggesting that the fibers bridge the cracks, without catastrophic fiber rupture during strain-hardening of the composite.

4. Conclusions

A self-consolidating PVA-ECC (with 2% fibers) which exhibits self-consolidating properties in the fresh state and strain-hardening performance in the hardened state has been successfully developed by employing parallel control of micromechanical parameters and processing parameters. The self-consolidating performance was accomplished by constitutive rheological design to provide repulsive energy between particles and cohesiveness between ingredients. The optimal concentrations of HPMC and MFS to provide the complete surface coverage on the cement particles contributed to electrosterically dispersing and stabilizing the aggregated particles, while avoiding particle segregation. In addition, fine adjustment of the deformability of the fresh mortar mix enhanced the cohesive flow of the fresh mortar mix and the PVA fibers, leading to satisfactory self-consolidating performance which is comparable to that in self-consolidating concrete used in current construction practice. The tensile strain capacity attained from specimens, made without external consolidation, was in excess of 3% under uniaxial tension tests.

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