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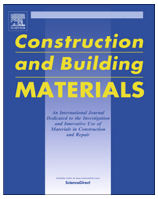

Development of self-compacting strain-hardening cementitious composites by varying fly ash content

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HIGHLIGHTS

- Self-compacting SHCC were designed by adjusting matrix strength and flowability.
- Fly ash was used as strength modifier to fine-tune matrix strength.
- Self-compacting SHCC of different strength were produced.
- Self-compacting SHCC with high compressive strength exceeding 80 MPa was obtained.

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ABSTRACT

This study investigated the role of the matrix in the production of self-compacting strain-hardening cementitious composites (SHCC). High volume fly ash pastes with desirable flowability were first designed, followed by adding micro polyvinyl alcohol (PVA) fibres to produce composite materials. The results showed that the composites were self-compacting in the fresh state, and exhibited stable multiple-cracking and strain-hardening behaviour in the hardened state. Fly ash is used not only to modify the workability of fresh mixtures, but also to adjust matrix strength to the values favourable for producing SHCC materials.

1. Introduction

Strain-hardening cementitious composites (SHCC) exhibit pseudo-strain-hardening behaviour and a multiple-cracking process under direct tension, and have high ductility, crack arresting ability and toughness [1–3]. SHCC materials can find many applications in increasing the serviceability and durability of structures under different loading conditions [4–6]. As the importance of self-compactability in modern concrete technology has recently been clearly demonstrated [7–10], it becomes desirable to develop self-compacting SHCC.

There are only rare reports on producing self-compacting SHCC. Kong et al. [11,12] have developed self-compacting engineered cementitious composites (ECC) by delicate control based on micromechanics, over the particle concentration and the dosages of chemical admixtures. The material design method based on micromechanics offers a comprehensive linkage between the micro-properties of the ingredients and macro-properties of the composites [11–13]. In the present study, a much more straightforward design guideline based on a strength-based theory coupled with simple mini-slump flowability testing was adopted. The flowability and 28-day strength of the mixtures were tuned mainly by varying the content of fly ash along with the corresponding changes in water content and the dosage of superplasticizer. This approach not only results in composites with self-compactability in the fresh state and strain-hardening behaviour in the hardened state, but also enhances the sustainability of the materials by using high volume fly ash in the mixtures.

2. Experimental program

2.1. Materials

The chemical compositions of the Portland cement and the fly ash are shown in Table 1. The chemical composition of the fly

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Table 1
Chemical composition by mass percentage (%) and relevant properties of cement and fly ash.

	Cement	Fly ash
SiO_2	21.1	67.5
Al_2O_3	5.2	23.0
Fe_2O_3	4.3	4.5
CaO	64.2	<1
MgO	1.2	<1
Na_2O	0.05	0.5
K_2O	0.47	1.5
SO_3	2.6	0.1
Loss on ignition (%)	0.8	1.0
Specific gravity	3.13	2.13
Fineness index (m^2/kg)	350	310

ash places it in the range of Class F, according to ASTM standard C618-12a [14].

A PVA fibre (trade name REC), which is similar to the one used in ECC by Li et al. [2], was used in this investigation. To examine the effect of the tensile strength of the fibre on achieving strain-hardening, one composite reinforced with straight steel (SS) fibres was also fabricated. Except for this composite, all the other composites discussed in this investigation were reinforced with REC fibres. The dimensions and properties of the fibres are listed in Table 2.

2.2. Specimen preparation

To determine the strength of the plain matrices, plain matrix mixtures without adding fibres were produced, and cubic samples with side length of 50 mm were cast. The matrices are pastes with fly ash taking up from 0 to 80% by mass of total cementitious materials, that is, a mass ratio of the fly ash to the cement (FA/C) from 0 to 4. The plain matrix mixtures without fibres are referred to as Px where x varies from 0 to 4, where x denotes the FA/C mass ratio. The mix proportions for plain mixtures that contain no fibres are shown in Table 3.

The mix proportions for mixtures containing fibres are shown in Table 4. All mixtures were designed to have spread values larger than 500 mm as stipulated in the standard slump flow test. The fibre volume fraction is kept constant at 2% of the total volume of the mixture. The composites are referred to as Px_REC or Px_SS, where x denotes the FA/C mass ratio and REC or SS, refers to the type of fibre.

The solid components were first placed into the mixer and dry-mixed for about 5 min. Then, water with dissolved superplasticiser was added gradually and mixed for another 10–15 min. The fibres were then added gradually while the mixer was turning and mixed for 5 more minutes. All mixtures obtained were self-compacting, and could be placed in the moulds without applying vibration. Specimens cast were covered with lids and stored at room temperature for 24 h before demoulding. The specimens were cured at 23 °C in a fog room until the age of 28 days. Then the mechanical tests were performed.

2.3. Rheological tests

2.3.1. Mini-slump flow test

Mini-slump flow test is a simple but feasible method to measure the flowability of cement paste. Hence, Mini-slump flow test was used to determine the flowability of plain matrix mixtures. The geometry of the cone and a typical mini-slump spread are shown in Fig. 1, with internal dimensions of the flow cone shown in the inset of Fig. 1(a). The spread value is the average of two measurements of the diameter of the spread.

2.3.2. Standard slump flow test

Standard slump flow test was used to indicate the flowability of the fresh composite mixtures, according to ASTM C1611/C1611M-09b [15].

2.4. Mechanical tests

2.4.1. Compression testing

The compressive strength values of the plain matrices without fibre reinforcement were measured using 50 mm cubic samples according to ASTM C109/C109M-12 [16].

To obtain the compressive stress-strain curve, the compressive test was carried out based on a variation of ASTM C469/M469-10 standard method [17]. To prevent possible explosive failure [18], the movement of the loading platen in the compressive test was controlled by the strain rate, instead of following ASTM C469/M469-10 [17] which suggests the control of the load rate. The compressive test was conducted using Technotest Machine under strain control with the strain rate of (0.1 mm/100 mm)/min. Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were used. At least two specimens were tested for each case. Before testing, the weight of each specimen was recorded. Each density value is the average of at least two specimens.

The elastic modulus in compression was calculated by determining the slope of a straight line between two points on the compressive stress-strain curves. The first point is the point where the stress value is 3.8 MPa. The second point is the point where the stress value is 40% of the strength.

2.4.2. Direct tensile test

The setup of the direct tensile test for the current study is shown in Fig. 2. This setup is a modified version of the one reported in the Ref. [19]. To reduce possible bending, spherical bearings are used at both ends as shown in Fig. 2a. The specimens prepared for direct tensile testing were made with a dog-bone shape as shown in Fig. 3. This design is intended to prevent the specimens from failing outside the deformation measurement range [19].

The direct tensile testing was conducted using SHIMADZU AUTOGRAPH AG-X 100 KN universal testing machine. SHIMADZU non-contact video extensometers with a sensitivity of 1.5 μm were used to measure the deformation by tracking the gauge marks (see Fig. 2). At least two specimens were tested for each case.

The elastic modulus in tension is calculated by determining the slope of a straight line between two points on the linear portion of the tensile stress-strain curves. The first point is the point where the stress value is 0.5 MPa. The second point is the point where the stress value is 40% of the ultimate tensile strength.

3. Results and discussion

3.1. Workability

All the plain paste mixtures were first designed to have mini-slump spread values ranging from 270 to 330 mm, as seen from Table 5. The composite mixtures were made based on the plain matrix proportions shown in Table 3 plus fibres. It has been found that the composite mixtures designed by this approach showed desirable flowability and had spread values larger than 500 mm in the standard slump flow test, as shown in Table 6, which meant that the concrete mixtures were highly flowable and self-compacting.

3.2. The role of compressive strength

The condition for multiple-cracking and strain-hardening under tension is that the load carrying capacity of the fibres is higher than