Mechanical properties and crack resistance of sustainable high strength engineered cementitious composites

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Abstract. Engineered cementitious composite (ECC) is a class of high performance fiber reinforced material designed to overcome the brittleness of concrete. The high content of cementitious material restricts the common application of ECC. To develop a new series of sustainable and durable composite, industrial wastes such as fly ash, silica fume and furnace slag were brought in as supplementary cementitious materials (SCMs) in present study. High strength cement matrixes with three types of SCMs were obtained. Tensile performance of PVA-steel fiber reinforced engineered cementitious composite based on above matrixes were evaluated via uniaxial tensile test. Crack resistance of high strength engineered cementitious composite (HSECC) with industrial wastes were experimentally estimated through steel ring test. Results show that suitable addition of industrial wastes somehow improved the mechanical performance and crack resistance of HSECC and further enhanced the durability and sustainability.

1. Introduction
Concrete is a typical brittle material, as first crack occurs, immediate localization of deformation appears followed by sudden decreasing load. Cracks in concrete component often threaten the durability and cause catastrophic damage of building structures. To overcome the brittle nature of concrete, a class of high performance ductile cementitious composite, called Engineered Cementitious Composites (ECC), has been developed recently [1-2]. It has a unique property of strain-hardening accompanied by multiple cracking. Ductility of ECC is resulted from the additional fine cracks formed under tension. Typically, strain localization occurs at a tensile strain of 1-3%, with crack spacing of 3-6mm and crack width around 60μm [3-5]. Such capillary cracks will have little effect on the permeability of water and other deleterious substance. As a consequence, with slight degradation in carrying capacity and transport properties under high deformation, the durability of concrete structure can be maintained [6].

However, in order to obtain this ductile and multiple cracking behaviors, coarse aggregates shall be eliminated and the content of cementitious material increases correspondingly. Generally, admixture of ECC contains over 1000 kilogram in 1 cubic meter. Considering equal-mass carbon dioxide released in the process of cement producing, traditional ECC with cement only as binding material is definitely not sustainable. Researches were carried out in the past decade to develop eco-friendly ductile
materials, and industrial wastes such as fly ash from power station[7-9], silica fume collected in metallurgical industry [10], rice husk from burnt straws[11], ferrous tailings released by iron industry [12-13] and ground granulated blast furnace slag from steel works[14-16], were introduced to the cementitious system of ECC. Since the presence of above powders, flowing ability and mechanical properties of ECC altered significantly due to their supplementary cementitious function. For example, vitreous particles of fly ash enable cement granules to distribute more homogeneously and workability of cementitious materials is improved simultaneously. Industrial by-products provide possibilities for development of green ECC.

On the other hand, constructions indicate that compressive strength of cement matrixes used in green ECC are usually lower than 50 MPa [3, 6]. Even though the ability of crack width controlling maintains adequately, a number of applications, such as permanent formwork for concrete structures, steel-concrete composite bridge decks [17-19], still need the ductile material possesses a relatively higher strength. Apart from strain-hardening characteristic, material properties with high crack resistance ability are required as well. Therefore, high strength ductile cement matrixes incorporating industrial wastes for a new generation of ECC focusing on above applications are in essential need of developing.

In the present paper, high strength engineered cementitious composite (HSECC) is designed using three kinds of industrial waste as supplementary cementitious materials (SCMs). The compressive strength and bending strength of high strength cement matrixes are experimentally evaluated. Tensile performance of HSECC with polyvinyl alcohol and steel fiber is investigated through uniaxial tension tests. In addition, steel ring tests were carried out to obtain the crack resistance ability of HSECC.

2. Experimental program
The purpose of this test program is to investigate the effect of industrial by-products on compressive and bending strengths of high strength cement matrix, tensile performance of HSECC and to obtain the crack resistance behaviour. To achieve this target, three kinds of industrial waste, silica fume (SF), grounded granulated blast furnace slag (SG) and fly ash (FA) were used in the experiments. Silica sands with particle size of 0.075 to 0.150mm, polyvinyl alcohol (PVA) and steel fiber (ST) were used in the tests.

2.1. Materials
The chemical compositions of ordinary Portland cement (OPC) and the three SCMs (SF, SG, FA) used in tests are listed in Table 1. The particle size distribution of above cementitious materials is shown in Figure 1. Fibers used to evaluate the tensile performance of ECC with the developed high strength matrix include Polyvinyl alcohol fiber (PVA) supplied by Kuraray company from Japan and steel fiber supplied by Changhong company in China. The mechanical properties of the fibers are listed in Table 2. In the mix design of ECC, 2% volume fraction of PVA fibers and 1% volume fractions of steel fibers were applied.

| No          | SiO₂ | CaO   | Al₂O₃ | Fe₂O₃ | MgO  | K₂O  | Na₂O  | SO₃ | LOI |
|-------------|------|-------|-------|-------|------|------|-------|-----|-----|
| OPC         | 23.67| 59.98 | 7.21  | 3.07  | 2.07 | 0.62 | 0.17  | 2.14| 1.01|
| Silica fume (SF) | 90.56| 0.81  | 0.41  | 0.52  | 0.95 | 1.59 | 0.63  | -   | 3.72|
| Slag (SG)   | 38.83| 38.70 | 12.92 | 1.46  | 4.63 | 0.37 | 0.28  | 0.60| 0.06|
| Fly ash (FA)| 47.02| 5.08  | 35.06 | 3.88  | 1.36 | 1.30 | 1.18  | 0.89| 1.85|

2.2. Mixture, specimens and curing
Tested mix proportion incorporating with SF, SG and FA are displayed in Table 3. Almost 30 percent of cement is replaced by industrial waste. Rectangular specimens with size of 40 × 40 × 160 mm was
cast to conduct the compressive and bending tests for each mixture at age of 3, 7 and 28 days. For uniaxial tensile test, rectangular coupon specimens with size of $100 \times 200 \times 20$ mm were used. After removing from their molds, specimens were stored in water at $20 \pm 2^\circ$C for curing. The tensile experiments were tested under uniaxial tension with displacement control of 0.0025 mm per second in a 250 kN capacity MTS 810 material testing system. Aluminum plates were epoxy glued onto the ends of the specimens prior to loading at least 6 hours to enhance the ends for gripping. Tensile strain was measured by two extensometers mounted on the lateral surface of the coupon specimen. The measured gage length of extensometer was 50 mm, as shown in Figure 2.

![Figure 1. Particle size distribution of the five fine cementitious materials](image1)

Table 2. Properties of PVA and steel fibers

| Fiber Type | Density (g/cm$^3$) | Tensile Strength (MPa) | E (GPa) | Diameter (mm) | Length (mm) |
|------------|--------------------|------------------------|---------|--------------|-------------|
| PVA        | 1.2                | 1620                   | 42.8    | 0.039        | 12          |
| ST         | 7.8                | 2750                   | 210     | 0.200        | 13          |

![Figure 1. Particle size distribution of the five fine cementitious materials](image2)

Table 3. Mix proportion of tested high strength cement matrixes

| Test Series | Cementitious Materials | Quartz Sand | Water | Superplasticizer (%) |
|-------------|------------------------|-------------|-------|----------------------|
| OPC         | Total(Cement:SF:SG:FA) |             |       |                      |
| SF          | 1(0.90:0.10:0.00:0.00) | 0.833       | 0.192 | 1.79                 |
| SG          | 1(0.80:0.10:0.10:0.00) | 0.833       | 0.195 | 1.95                 |
| FA          | 1(0.70:0.10:0.10:0.10) | 0.833       | 0.181 | 1.32                 |

2.3. Testing procedures

The mixing procedure of the composite material consists of mixing cementitious materials, adding water with superplasticizer and spreading fibers. To evaluate the crack resistance ability of HSECC with industrial waste, ring test was adopted. To obtain the actual composite-steel interfacial compressive stress induced by shrinkage of ECC, four strain gauges along the inner wall of steel ring are placed according to Figure 3(a). A steel ring with the outer diameter of 320 mm and the inner diameters of 290 mm was used in the tests. The thickness of composite was 35 mm and the height 150 mm. The geometry of the ring specimen used in the present study is presented in Fig.3. Each ring specimen was equipped with four strain gauges with a length of 3 mm and width of 2 mm, placed at mid-height on the inner circumference of the steel ring. The fresh composite was cast into the ring mold in two layers and was consolidated by a vibrating table. As is shown in Figure 3(b), drying
direction makes specimen exposed to the air and accelerate the process of cracking. Ring test is proved to be a simple but effective method to estimate the anti-cracking ability of cement-based materials[20].

![Diagram of loading hold and specimen](image1)

**Figure 2.** (a) Tensile test set-up (b) specimen with aluminum plates glued and extensometers mounted

![Diagram of geometry of the ring specimen](image2)

**Figure 3.** Geometry of the ring specimen

3. Results and Discussion

Mechanical properties and crack resistance behavior of sustainable high strength ductile cementitious composites with SF, SG and FA as supplementary cementitious materials were experimentally studied. Results were as follows.

3.1. **Bending and compressive strength**

The overall enhancing efficiency on compressive and bending strength of high strength cement matrix by using silica fume, slag and fly ash is graphically displayed in Figure 4, in which average strength at 3, 7 and 28 days in each test series, including the reference, is presented. Obviously, through the optimizing procedure, compressive and bending strength of the low water to binder ratio matrix can significantly be increased by substituting cement with SF, SG and FA respectively. For example, with a similar fluidity of the fresh mortar, the compressive strength at 3, 7 and 28 days changes from 45.0, 57.8 and 77.9 MPa to 62.0, 80.6 and 108.0 MPa. And the corresponding bending strength at 3, 7 and 28 days may change from 8.1, 12.4 and 14.7 MPa to 10.9, 15.2 and 18.7 MPa. The utilization of industrial wastes not only lower the amount of cement and cut down the contamination, but also enhance the strength of ductile cementitious materials. General range of strength increasing is about 20% to 70% in comparison with the reference. It is rather interesting that such significant strength increasing is based only on the optimization on composition of cementing binder with SF, SG and FA, those actually are industrial by-products and the cost is lower than cement in general, but their filler action and particle packing effect make a great contribution to reduce the porosity of capillary pores in the high strength matrix and minimize the initial crack inside the composite.
3.2. Tensile performance

Tensile performance of PVA-steel fiber reinforced cementitious composites based on the developed high strength matrix is preliminary evaluated by uniaxial tension tests. Figure 5 displays the tensile stress-strain curves of the composites at the age of 7 and 28 days respectively. From the results, we may find that the strain-hardening performance is largely enhanced compared to cement mortar without ductile fibers. The average tensile strength and strain are 7.27MPa, 0.688% and 7.49MPa, 0.815% respectively at 7 and 28 days. Generally, material with tensile strain capacity of 0.5% is ductile for concrete structure. From the tensile curve, fluctuations occur at the level of stress capacity which may indicate the crack propagation process and each crest represents one capillary crack. As a consequence, HSECC with industrial waste maintains the properties of strain-hardening and multiple cracking. In addition, strength is a critical parameter that controls the penetration of chemical agent during service of the structures at the stage without cracking. Strain capacity behaving as the formation of fine cracks is more important for the long term durability and sustainability of the structures at the stage that cracks may occur. The balance optimization between strength, strain and crack resistance of ECCs are definitely needed to meet the requirements of practical applications. Therefore, the crack resistance of PVA-steel hybrid fiber reinforced ECC with developed high strength matrix is experimentally investigated in the following.
3.3. Cracking resistance
To obtain anti-cracking ability of the materials under tensile load, steel-HSECC composite ring tests were conducted. From the ring test, we can obtain the progress of compressive stress in the steel ring, which result from shrinkage of the composite ring. Figure 6 displays the typical curves of hoop strain as a function of curing time obtained by strain gauge attached to the inner circumferential steel ring. Increase of compressive strain can be seen after the initial steady stage, and cracking moment can be deduced by the sudden climb of strain. As for cementitious materials, hoop strain of the interface between steel and composite rings stays around -99 to -120 μm/m. Figure 7 shows the actual circumferential strain of HSECC with SCMs and hybrid fibers. From the curves we may observe that hoop strain increases along with the curing period and reaches -39 μm/m at the age of 28 days which indicates that there is another approximate 51-81 μm/m strain capacity for external load applied to the composite in order to cause cracking. In addition, increasing rate of the strain demonstrates a declining trend and tends to be stable after certain curing time which provides a further proof that crack resistance of ductile cementitious material is somehow enhanced.

4. Conclusions
Mechanical properties and crack resistance of high strength engineered cementitious composite (HSECC) with industrial waste were experimentally evaluated. Effects of silica fume, furnace slag and fly ash on compressive and bending strength of high strength matrix were tested. Tensile properties of HSECC were obtained. Following conclusions can be drawn:
- Combination of silica fume, ground granulated blast furnace slag and fly ash has a positive effect on enhancing compressive and bending strength of high strength cement matrix.
- PVA-steel fiber reinforced HSECC with industrial wastes maintains characteristics of strain-hardening and multiple cracking with strain capacity over 0.8% at the age of 28 days.
- Crack resistance of sustainable HSECC stays in a high level and presents large capacity for coupled load condition according to the steel ring test results.

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