Uniaxial Tensile Properties of High Ductility Cementitious Composites with Sulphoaluminate Cement

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Abstract. This study evaluates the effect of sulphoaluminate cement content on the performance of high ductility cementitious composite (HDCC) as repair material. To prepare the HDCC, Portland cement was partially replaced with 10%, 15%, or 20% rapid hardening sulphoaluminate cement. The compressive and flexural strength developments and tensile properties of the sulphoaluminate cement containing HDCC were investigated. The microscopic mechanism by which sulphoaluminate cement affects the macroscopic performance of HDCC was examined by scanning electron microscopy. Before 14 d, the mechanical properties were directly proportional to the sulphoaluminate cement content, but at 28 d, the sulphoaluminate cement content exerted no obvious effect. The sulphoaluminate cement content largely influenced the ultimate tensile strain but little affected the tensile strength. The mechanical properties were optimized in HDCC containing 10% and 15% sulphoaluminate cement. The reduced tensile ductility in sulphoaluminate cement containing HDCC is attributed to the large amount of ettringite formed on the surfaces of the reinforcing PVA (polyvinyl alcohol) fibers.

1. Introduction

High ductility cementitious composite (HDCC) is a high performance, fiber reinforced material characterized by strain hardening and multiple cracking behavior under tension and bending [1]. HDCC is used for the repair and rehabilitation of concrete structures such as bridge decks and rigid concrete pavements [2-5].

Repair construction often requires rapid strength development. The hardening time of HDCC is usually increased by including flash setting admixtures in the sprayed HDCC [6]. However, if the setting time is too short, the sprayed HDCC’s rough surface cannot be easily handled and dust pollution becomes a serious problem. To improve the construction conditions, control the setting time and achieve the desired strength development rate, sulphoaluminate cement is applied as the cementitious materials in HDCC. However, the effect of sulphoaluminate cement content on the properties of HDCC has been little investigated.
In this paper, Portland cement was partially replaced with sulfoaluminate cement. The sulfoaluminate cement contents were varied as 10%, 15%, and 20% by mass, and the strength developments and tensile properties of the prepared HDCC as repairing materials were investigated.

2. Experimental

2.1. Materials

The materials used in this test were Portland cement (P II 42.5R), rapid hardening sulfoaluminate cement (R·SAC 42.5), grade I fly ash, river sand (maximum size 2.5 mm), ordinary tap water, viscosity modifying agents (VMA) and a polycarboxylate type high performance water reducing admixture. The reinforcing fiber was polyvinyl alcohol (PVA) fiber. The material properties are given elsewhere [7,8].

2.2. Mix proportions

Table 1 shows the mix proportions of HDCC with rapid hardening sulfoaluminate cement. The mix number (column 1) describes the mass percent of sulfoaluminate cement in the HDCC; for example, SAC-10 denotes that 10% of the HDCC has been replaced by sulfoaluminate cement.

In all mixtures, the water to binder ratio, sand to binder ratio and fly ash replacement percentage were 0.30, 0.30, and 60% (by mass), respectively. The dosage of water reducing admixture and VMA were 0.7% and 0.5%, respectively. The volume fraction of PVA fiber was 2%.

Table 1. Mix proportions of rapid hardening HDCC

| Mix number | P II cement (kg/m³) | Sulphoaluminate cement (kg/m³) | Fly ash (kg/m³) | Sand (kg/m³) | Water (kg/m³) | Water reducing admixture (%) | VMA (%) | PVAF (kg/m³) |
|------------|--------------------|-------------------------------|----------------|--------------|--------------|-----------------------------|---------|--------------|
| SAC-0      | 496                | 0                             | 744            | 372          | 372          | 0.7                         | 0.5     | 26           |
| SAC-10     | 446.4              | 49.6                          | 744            | 372          | 372          | 0.7                         | 0.5     | 26           |
| SAC-15     | 421.6              | 74.4                          | 744            | 372          | 372          | 0.7                         | 0.5     | 26           |
| SAC-20     | 396.8              | 99.2                          | 744            | 372          | 372          | 0.7                         | 0.5     | 26           |

2.3. Test methods

The mechanical properties (flexural and compressive strengths) were tested on 40 mm × 40 mm × 160 mm prism specimens as described in “Method of testing cements- Determination of strength (ISO)” (GB/T 17671–1999).

The uniaxial properties of HDCC were determined in uniaxial tensile tests. These tests accorded with the Japan Society of Civil Engineers code, titled “Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC)”. Before acquiring the tensile stress–strain curve, the specimens were cured for 28 days at (20 ±2)°C and ≥ 95% relative humidity.

3. Result and Discussion

3.1. Compressive strength and flexural strength

The compressive strength and flexural strength of the HDCCs with sulfoaluminate cement contents of 0, 10%, 15% and 20% are presented in Figs. 1 and 2, respectively.
In the 7 d and 14 d old samples, the compressive strength linearly increased with increasing sulfoaluminate cement content. The linear relationships were statistically significant, being described by $y = 0.4869x + 20.723$ (correlation coefficient $R^2 = 0.9783$) in the 7 d sample, and $y = 0.5309x + 27.302$ ($R^2 = 0.9655$) in the 14 d sample. In the 28 d old samples, the compressive strengths of the HDCC were independent of sulfoaluminate cement content.

The flexural strengths of the 7 d and 14 d old samples behaved similarly to the compressive strengths. The flexural strength was linearly related to sulfoaluminate cement content, and was described by $y = 0.12x + 8.8$ ($R^2 = 0.9026$) in the 7 d sample and $y = 0.1177x + 10.226$ ($R^2 = 0.9873$) in the 14 d sample. After 28 d, the flexural strength decreased slightly with increasing sulfoaluminate cement content, but the range was no more than 1.1 MPa.
Overall, the mechanical properties were directly proportional to the sulfoaluminate cement content during the first 14 days, but were not obviously affected by sulfoaluminate cement at 28 days.

3.2. Results of uniaxial tensile tests
The uniaxial tensile properties of sulfoaluminate cement containing HDCC at day 28 (tensile stress vs. tensile strain curves) are shown in Figures 3–6. The tensile strengths and ultimate tensile strains of the HDCC are listed in Table 2.

![Figure 3. Uniaxial properties of HDCC without sulfoaluminate cement.](image)

![Figure 4. Uniaxial properties of HDCC with 10% sulfoaluminate cement.](image)
The tensile strengths and ultimate tensile strains are the means of three specimens, excluding specimens showing the maximum and minimum ultimate tensile strains. After initial cracking, the tensile load gradually increased as multiple micro cracks developed. The micro crack development was followed by a rapid decrease in tensile stress, and some of the cracks increased in width. Beyond a certain width of the main crack in the mid span, the specimen completely lost its bearing capacity.

As evident in Table 2, the tensile strengths and ultimate tensile strains of the HDCC decreased with increasing sulfoaluminate cement content. The tensile strengths of the HDCC containing 10%, 15% and 20% sulfoaluminate cement were 11%, 10% and 18% lower than that of HDCC containing no sulfoaluminate cement, respectively. In the HDCC containing 10% and 15% sulfoaluminate cement, the ultimate tensile strain was almost unchanged from that of SAC-0. However, in the specimen containing 20% sulfoaluminate cement, the ultimate tensile strain decreased significantly (by 70% from that of SAC-0). In general, the sulfoaluminate cement content greatly influenced the ultimate tensile strain but exerted minor effect on the tensile strength. Considering the compressive
and flexural strengths of the prismatic specimens, we infer that the mechanical and uniaxial tensile properties of HDCC are improved by adding sulphoaluminate cement at mass percentages of 10% and 15%. That is, 10% and 15% are the optimal sulphoaluminate cement dosages in HDCC.

Table 2. Tensile strengths and tensile strains of sulphoaluminate cement containing HDCC

| Mix number | Tensile strength (MPa) | Ultimate tensile strain (%) |
|------------|------------------------|----------------------------|
| SAC-0      | 4.66                   | 2.10                       |
| SAC-10     | 4.13                   | 2.18                       |
| SAC-15     | 4.19                   | 2.07                       |
| SAC-20     | 3.80                   | 0.62                       |

Figure 7. sulphoaluminate cement hydration product-HDCC with 10% sulphoaluminate cement.

Figure 8. sulphoaluminate cement hydration product- HDCC with 20% sulphoaluminate cement.

3.3. Microscopic mechanism of sulphoaluminate cement influence on HDCC performance

Figures 7–8 are scanning electron micrographs of the hydration product (namely, ettringite (AFt)) on the PVA fiber surfaces. The main mineral phase of sulphoaluminate cement is C4A3S. The hydration proceeded as follows [9]:

1. with sufficient gypsum: \( \text{C}_4\text{A}_3\text{S}+2\text{CSH}_2+34\text{H} \rightarrow \text{AFt}+2\text{AH}_3\text{(gel)} \)  
2. with insufficient gypsum: \( \text{C}_4\text{A}_3\text{S}+18\text{H} \rightarrow \text{AFm}+2\text{AH}_3\text{(gel)} \)  
3. with CH: \( \text{C}_4\text{A}_3\text{S}+8\text{CSH}_2+6\text{CH}+74\text{H} \rightarrow 3\text{Aft} \)

sulphoaluminate cement hydration produces ettringite, which significantly increases the early strength. However, a large amount of ettringite on the PVA fiber surfaces increases the friction force during the tensile process. As fiber is pulled off through friction processes, the tensile strain of the HDCC decreases. The larger the sulphoaluminate cement content, the more ettringite is formed on the fiber surface, and the greater is the decline in the ultimate tensile strain.

4. Conclusions

Before 14 d, the mechanical properties were directly proportional to the sulphoaluminate cement content, but at 28 d, the sulphoaluminate cement content exerted no obvious effect on the mechanical properties.

The sulphoaluminate cement content largely influenced the ultimate tensile strain but little affected the tensile strength.
The optimal sulphoaluminate cement dosages for HDCC were determined as 10% and 15%. The large amount of ettringite formed on the PVA fiber surfaces increased the friction force during the tensile process. Consequently, the PVA fiber was easily pulled off, decreasing the tensile strain of the HDCC.

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