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Influence of silica fume on stress–strain behavior of FRP-confined HSC

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HIGHLIGHTS

- Influence of silica fume on compressive behavior of FRP-confined HSC was investigated.
- Sufficiently confined HSC with and without silica fume exhibits highly ductile behavior.
- For a given concrete strength, silica fume does not alter strength enhancement effects of confinement.
- For a given concrete strength, silica fume increases ultimate axial strains of confined HSC.
- Silica fume influences the behavior of confined HSC along transition regions of stress–strain curves.

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ABSTRACT

Confinement of high-strength concrete (HSC) columns with fiber reinforced polymer (FRP) composites has been receiving increasing research attention due to the advantageous engineering properties offered by the composite system. The use of silica fume as a concrete additive is a widely accepted practice in producing HSC. However, the influence of the presence and amount of silica fume on the efficiency of FRP confinement is not clearly understood. This paper presents the results of an experimental study on the influence of silica fume on the compressive behavior of FRP-confined HSC. 30 FRP-confined and 30 unconfined concrete cylinders containing different amounts of silica fume were tested under axial compression in two phases. In the first phase of the study, specimens with a constant water–cementitious binder ratio were tested. The results of this phase indicate that for a given water–cementitious binder ratio, the compressive strength of unconfined concrete increases with an increase in the amount of silica fume. It is found that this increase in strength leads to an increased concrete brittleness, which adversely affects the effectiveness of FRP confinement. In the second phase, water–cementitious binder ratios of the specimens were adjusted to attain a constant unconfined concrete strength for specimens containing different amounts of silica fume. The results of these tests indicate that for a given unconfined concrete strength, strength enhancement ratios of FRP-confined HSC specimens are not influenced by the silica fume content of the concrete mix. On the other hand, it is found that the silica fume content influences the axial strain enhancement ratios of these specimens. In addition, the transition zones of the stress–strain curves of FRP-confined HSC are observed to be sensitive to the amount of silica fume used in the mix.

1. Introduction

The popularity of higher strength concretes in the construction industry has been on a steady incline during the last two decades due to the superior performance and economy offered by high-strength concrete (HSC) over normal-strength concrete (NSC) in a large number of structural engineering applications. The use of FRP for confinement of HSC leads to high-performance columns that exhibit very ductile behavior as was demonstrated in Ozbakkaloglu and Saatcioglu [1,2] and Idris and Ozbakkaloglu [3]. It has been reported in a number of studies that the efficiency of FRP confinement reduces with an increase in concrete strength [4,5]. However, the main contributors to this adverse effect of higher concrete strength have not been fully identified. Silica fume is one of the most popular pozzolans used to increase concrete strength [6–9], and it is known to have a significant effect on the compressive behavior of confined concrete [10–12]. Although several studies have reported that silica fume alters the brittleness of confined concrete [10,12,13], its influence on the behavior of confined concrete has been difficult to quantify due to the limited

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results and controversial experimental observations found from existing triaxial compression tests of HSC [10,12,14–18].

In FRP-confined HSC, the influence of silica fume is even less understood. Silica fume has been used in the existing experimental studies [4,5,19–27] to produce desirable concrete strengths. However, none of these studies attempted to establish the influence of silica fume on the behavior of confined concrete. This paper presents the results of the first-ever experimental study undertaken to address this gap, where the changes in the axial stress–strain behavior and ultimate conditions of FRP-confined HSC with silica fume were investigated.

2. Experimental program

2.1. Test specimens and materials

30 FRP-confined and 30 unconfined control concrete cylinders were manufactured and tested under monotonic axial compression. All of the specimens were 152.5 mm in diameter and 305 mm in height. The influence of silica fume on the mechanical properties of the confined and unconfined specimens was investigated using 10 separate batches of concrete mixes containing different percentage replacements of cement with silica fume and water–cementitious binder (*w*/*c*) ratios. The cementitious binder materials used were ordinary Portland cement and silica fume. Their chemical compositions and physical properties are given in Table 1. Detail of the mix proportions of each batch of concrete is given in Table 2. Crushed bluestone gravel of 7 mm maximum size and graded sand were used as the aggregates. Carboxylic ether polymer based superplasticiser was used in all batches. The superplasticiser contained 80% water by weight. The test results of the unconfined specimens are given in Table 3.

The experimental program consisted of two phases. The first phase consisted of specimens fabricated from four different concrete batches containing different amounts of silica fume at designated *w*/*c* ratios. In Batches 1, 2A, and 3 that contain a fixed *w*/*c* ratio of 0.27, the percentages of silica fume that replaced cement were 0%, 8%, and 16% by weight. The *w*/*c* ratio was reduced to 0.24 in Batch 2B that contain 8% silica fume. As shown from Table 3, the unconfined concrete strengths (f'_{co}) of specimens in this phase varied with the silica fume content and *w*/*c* ratios.

The aim of Phase II of the experimental program was to attain a same unconfined strength among each specimen group having 0%, 8%, and 16% silica fume. The specimen groups in this phase were manufactured using two different concrete grades (i.e. a higher grade HSC with an average strength of 84.7 MPa in Batches 4–6 and a lower grade HSC with an average strength of 54.6 MPa in Batches 7–9). To establish the final *w*/*c* ratios used in Batches 4–9, a large number of trial batches were manufactured and tested.

A total of 30 confined specimens was fabricated and tested in the two-phase experimental program. In Phase I, 12 specimens wrapped with Aramid FRP (AFRP) were prepared using a manual wet lay-up process by wrapping epoxy resin impregnated unidirectional fiber sheets around precast concrete cylinders in the hoop direction. The 18 specimens in Phase II were manufactured as tube-encased specimens using S-glass FRP (GFRP) tubes. The GFRP tubes were also prepared using the manual wet lay-up process, with the resin impregnated fiber sheets wrapped around precision-cut high-density Styrafoam templates, which were removed prior to concrete casting. The specimens tested in Phase I and the higher grade HSC specimens in Phase II had six layers of FRP, whereas the lower grade HSC specimens in Phase II had four layers of FRP. The specimens with four layers of FRP were wrapped with one continuous sheet with a single 150-mm long overlap zone, whereas the specimens with six layers were wrapped with two sheets creating two overlap zones of 150 mm terminating at the same location.

The FRP epoxy adhesive used consisted of two parts: epoxy resin binder (MBrace Saturant) and thixotropic epoxy adhesive (MBrace Laminate Adhesive), which were mixed in the ratio of 3:1. The material properties of the unidirectional fiber sheets used to manufacture the FRP tubes and jackets are provided in Table 4. The table reports both the manufacturer-supplied fiber properties and the tensile tested FRP composite properties. The tensile properties of the FRP made from these fiber sheets and epoxy resin were determined from flat coupon tests undertaken in accordance with ASTM D3039 [28].

Three flat coupon specimens were made using the wet layout technique in a high-precision mold with 1 mm thickness and 25 mm width for each type of fiber. The coupons had a 138 mm clear span with each end bonded with two 0.5 mm by 85 mm aluminum tabs for stress transfer during tensile tests. Each coupon was instrumented with two 20 mm strain gauges at mid-height, with one on each side, for the measurement of the longitudinal strains. The coupons were allowed to cure in the laboratory environment for at least 7 days prior to testing. The tensile test specimens were tested using a screw-driven tensile test machine that had a peak capacity of 200 kN. The load was applied at a constant cross-head movement rate of 0.03 mm per second. The test results from the flat coupon specimens, calculated using nominal fiber thicknesses and actual coupon widths, are reported in Table 4. As evident from Table 4, the average rupture strains obtained from the tensile coupon tests were slightly lower than those reported by the manufacturer.

Three nominally identical specimens were tested for each unique specimen configuration. The FRP-confined specimens were tested on the same day with their companion unconfined specimens, through which the test day unconfined concrete strengths (f'_{co}) reported in Table 3 were established.

2.2. Specimen designation

The specimens in Tables 3 and 5 were labeled as follows: letters B, SF, WC, A or G, and W or T were used to represent the test parameters, namely the concrete batch, silica fume percentage, *w*/*c* ratio, type of FRP (i.e. AFRP or GFRP), followed by the number of layers and the confinement technique (i.e. wrapped or tube-encased), respectively. Each letter was followed by a number that was used to represent the value of that particular parameter for a given specimen. Finally, the last number in the specimen designation (i.e., 1, 2 or 3) was used to make the distinction between three nominally identical specimens.

2.3. Instrumentation and testing

The specimens were tested under axial compression using a 5000-kN capacity universal testing machine. During the initial elastic stage of the behavior, the loading was applied with the load control set at 5 kN per second, whereas displacement control operated at 0.004 mm per second beyond the initiation of transition region until specimen failure. Prior to testing, all specimens were ground at both ends to ensure uniform distribution of the applied pressure, and load was applied directly to the concrete core using precision-cut high-strength steel plates.

The hoop strains of the specimens were measured using a minimum of three unidirectional strain gauges placed at the mid-height around the circumference of specimens outside the overlap region. As illustrated in Fig. 1, the axial strains of the confined specimens were measured using three different methods: (i) four linear variable displacement transformers (LVDTs) mounted at each corner of the steel loading platens with a gauge length of 305 mm; (ii) four LVDTs placed at the mid-height at a gauge length of 175 mm at 90° spacing along the circumference of specimens; (iii) three axial strain gauges with a gauge length of 20 mm placed at the mid-height at 120° spacing along the circumference of specimens.

3. Test results and discussion

3.1. Failure mode

The typical failure modes the unconfined HSC specimens tested in Phase I are illustrated in Fig. 2. As can be seen in Fig. 2(a), the formation of microcracks and the surface spalling of concrete were observed in the unconfined specimens containing 0% silica fume at failure. On the other hand, Fig. 2(b)–(d) shows that the unconfined specimens containing 8% and 16% silica fume failed due to concrete crushing after the formation of major macrocracks. The observed variations in the failure mode pattern suggest that the brittleness of the concrete increases with its strength in the presence of and with an increase in the amount of silica fume.

Table 1
Chemical composition and physical properties of cementitious materials.

Item	Cementitious materials (%)	
	Ordinary Portland cement	Silica fume
SiO_2	21.46	92.5
$ZrO_2 + HfO_2$	–	5.5
Al_2O_3	5.55	0.35
Fe_2O_3	3.46	0.4
P_2O_5	–	0.3
CaO	63.95	0.02
MgO	1.86	–
SO_3	1.42	0.9
K_2O	0.54	0.02
Na_2O	0.26	0.02
	Compounds	
C_3S	50.96	–
C_2S	23.10	–
C_3A	8.85	–
C_4AF	10.53	–
	Fineness	
Surface area (m^2/kg)	330	18,000