Construction and Building Materials 49 (2013) 128–133

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Flexural behavior of hybrid concrete beams reinforced with ultra-high performance concrete bars

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HIGHLIGHTS

- The concept of UHPC bars as tension reinforcement is introduced.
- Flexure behavior and strength of UHPC-reinforced concrete beams are examined.
- Tests support the concept of new hybrid construction using UHPC bars
- Wider UHPC bars perform better than thicker bars having same cross-sectional area.

ARTICLE INFO

Article history:
Received 28 April 2013
Received in revised form 28 July 2013
Accepted 8 August 2013
Available online 4 September 2013

Keywords:
Ultra-high performance concrete
Flexural stress
UHPC bars
Hybrid beam
Tensile strength
Transformed section

ABSTRACT

As steel-fiber reinforced ultra-high performance concrete (UHPC) has flexural tensile strength exceeding 30 MPa, a novel idea of utilizing UHPC bars as tension reinforcement to provide flexural strength has been explored in this work. Normal concrete beam specimens, reinforced with precast deformed UHPC tension bars, were tested in four-point bend test to determine the flexural strength and observe behavior. Test results show that UHPC bars function adequately, developing flexural tensile strength of about 30 MPa at the peak load without any bond slip. The beams show post-peak load ductility with softening in which deflection increases with progressive reduction in residual strength.

1. Introduction

A considerable amount of work has been devoted to the study of various material and durability properties of UHPC for which references [1–19] can be cited as representation samples of such works. These studies have firmly established the superior material properties of UHPC. In recent studies undertaken by the authors, the effect of cyclic exposure on the tensile properties of UHPC and the effect of thermal cycles on the fracture properties have been investigated [18,19].

As UHPC can offer solutions for specific concrete construction which heretofore were not possible, attempts are being made to utilize UHPC for innovative applications. Perry and Zakariasen [20] have reported the first use of UHPC as train station canopy, Graybeal [21] has highlighted the use of UHPC in highway bridge girders in the USA and application of UHPC in footbridges have also been reported [22,23].

The flexural tensile strength of over 30 MPa offered by steel fiber reinforced UHPC provides for the first time an opportunity to seek hybrid construction of flexural members in which UHPC can provide the required tensile strength. Such construction, if structurally satisfactory, can offer significant advantage for application in corrosive environment, where corrosion of steel is a major concern for durability. Two possible forms of one-way floor slab construction, cast-in-place or precast, have been explored by the authors [24]. In one, the floor slab consists of a bottom tension layer of UHPC, topped with a layer of normal concrete [25,26]. In the second form, the elements are reinforced with precast UHPC bars [27] much in the same fashion as the conventional reinforced concrete elements, floating the conceptual idea of using UHPC bars as possible tension reinforcement.

The primary objective of this paper is to present the findings of an exploratory study on the behavior of hybrid concrete beam type specimens reinforced with precast UHPC deformed bars and to highlight structural behavior and future possibilities of such

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http://dx.doi.org/10.1016/j.conbuildmat.2013.08.005

construction. The experimental findings lend support to this new concept of using UHPC bars as possible tension reinforcement.

2. Experimental program

The experimental work involved testing prepared test specimens to observe flexure strength and behavior of hybrid beam-type specimens cast with UHPC bars with the aim of seeking an alternative form of construction that may obviate the need of traditional steel reinforcement.

2.1. Mix design

A suitable UHPC mixture using locally available materials such as fine sand, cement, micro-silica and superplasticizer (Glenium® 51) was developed using several trials. Only steel fibers were imported. As the compressive strength and durability of UHPC are known to be highly satisfactory, the primary focus of the mix design was to attain flexural tensile strength of at least 30 MPa.

The selected UHPC mix had the composition per cubic meter as follows: ASTM Type I Portland cement 900 kg; micro-silica 220 kg, fine sand 1005 kg, steel fiber 157 kg (about 6.3% by weight of UHPC), superplasticizer 40.3 kg (Glenium® 51) and water 162.4 kg (representing water–binder ratio of 0.145). The steel fibers were of 0.15 mm in diameter and 12.7 mm in length with ultimate strength of 2500 MPa. The mix design yielded cube compressive strength over 160 MPa and flexural tensile strength exceeding 30 MPa. Fig. 1 shows the UHPC mix after mixing in the mixer. The mix proportion of normal concrete used consisted of cement 400 kg/m^3, coarse aggregates 1092 kg/m^3, fine aggregate 729 kg/m^3 and water 184.4 kg/m^3 (corresponding to water–cement ratio of 0.42) to produce an average cylinder compressive strength of about 40 MPa.

2.2. Test specimens

2.2.1. Specimens details

It was planned to use simply supported beam-type specimens that would fail in flexure but not in shear, as the beams were not be provided with shear reinforcement, analogous to one-way simply supported slabs that do not normally require shear reinforcement. Also, the size of the test specimens was kept within acceptable dimensions, neither too large to create handling problems nor too small to have any size effects. Two beam sizes were chosen: (i) 150 × 150 × 760 mm and (ii) 150 × 200 × 900 mm (200 mm depth). The UHPC bars used were square or rectangular cross-section in four sizes: (i) 2–25 × 25 × 750 mm, (ii) 2–25 × 50 × 750 mm, (iii) 2–50 × 50 × 750 mm and (iv) 2–25 × 25 × 890 mm. Table 1 lists the details of all test specimens, including the numbers of samples used.

2.2.2. Casting of specimens

All UHPC bars were cast using same UHPC mix and casting procedure. In other words, mix design and casting procedure were invariant. For casting of UHPC bars, the weighed amounts of cement, sand, microsilica were placed in a horizontally revolving planetary mixer (Fig. 1) and mixed thoroughly following which the mixture of water and plasticizer was added. Thereafter, steel fibers were added in small amounts for uniform dispersion of fibers within the plasticized mix. The mixing procedure prescribed in ref [24] was followed. The mixing time was about 14 min. The prepared mix was placed in molds for casting. The top surface of the bars was left unfinished to provide good bond with concrete. To improve further the bond between UHPC bars and concrete, the two vertical edges of bars were cast with grooves as shown in Fig. 2. After casting, the bars were heat-cured at a temperature of 90 °C for 48 h to accelerate curing and strength development.

Table 1
Test specimens and the number of specimens.

Beam size (mm)	UHPC bar size (mm)	Beam ID	No. of test samples
150 × 150 × 760	2–25 × 25 × 750	HB-1	3
	3–25 × 25 × 750	HB-2	3
	2–25 × 50 × 750	HB-3	3
	2–50 × 50 × 750	HB-4	3
150 × 200 × 900	2–25 × 25 × 890	HB-5	3

The precast UHPC bars, after two days of heat-curing, were transferred to a mold (Fig. 2) and then normal concrete was poured and vibrated for compaction. It should be noted that as the bars were placed directly in the mold, there was no bottom cover to UHPC bars (Fig. 3). The top surface was trowel finished. Fig. 3 shows the view of beams with UHPC bars inside. All specimens were moist-cured for 28 days prior to testing.

2.3. Testing of specimens

All beam specimens were tested in a four-point bend test under a test frame using monotonically increasing load till failure (Fig. 4). For beam sizes of 150 × 150 × 760 mm in size, the span L was 630 mm with a = 240 mm. For 150 × 200 × 900 mm beams, L = 750 mm and a = 300 mm. All beams were tested with a shear span to depth ratio of about 1.5. The maximum load in kN sustained by a beam is denoted by P_u.

The mid-span deflection was measured by a LVDT. The declining post-cracking load path was recorded following the attainment of peak load to observe ductility. Two beams were strain-gauged at top and bottom surfaces and at two locations on the vertical faces to record normal strains for comparison with the theoretical values. In addition, crack growth was also noted along with the mode of failure for each test specimen. Fig. 5 shows the crack advancement during a test.

3. Results and discussion

3.1. Material properties of UHPC bars

The UHPC bars had the following material properties: compressive strength about 160 MPa, flexural tensile strength about 32 MPa and direct tensile strength of about 11–12 MPa. The flexural tensile strength was found to be approximately 2.5–3 times larger than the direct tensile strength, a commonly observed behavioral trait of fibre-reinforced UHPC bars [4,19] similar to that of normal concrete for which the flexural tensile strength, referred to as modulus of rupture, is also much higher than the direct tensile strength. The flexural tensile strength was determined using bars in a four-point bend test using simple bevelled support ends that provided end rotation It should be noted that as the test results are size-dependent, the values should be determined for

Fig. 1. UHPC after mixing.

Fig. 2. UHPC bars in a mold prior to concrete placement.