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Influence of flowability, casting time and formwork geometry on fiber orientation and mechanical properties of UHPFRC

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In this study, fiber orientation in ultra-high-performance fiber-reinforced-concrete (UHPFRC) with different formwork geometry was evaluated using visualization model concrete and via analysis involving 3D visualization based on X-ray computed tomography (CT). Differences in fiber orientation in the height direction were first reviewed. Furthermore, the influence of flowability and casting time on the fiber orientation and mechanical properties of UHPFRC were examined. The results indicated that flowability dictates eventual fiber orientation in parts close to the surfaces of formwork. The use of UHPFRC with superior flowability results in more fibers being oriented parallel to the longitudinal direction of slabs in comparison to UHPFRC with inferior flowability. It was also found that flowability and casting time can have strong influences on the mechanical properties of UHPFRC. Residual flexural strength after initial cracking exhibited perfect linear dependence on the effective number of fibers at fracture planes.

1. Introduction

The long history of research on fiber-reinforced concrete (FRC) includes the recent development and practical application of strain-hardening cement composites (SHCC) and ultra-high-performance fiber-reinforced concrete (UHPFRC), which have been actively studied. UHPFRC is a self-compacting concrete (SCC) with a compressive strength generally ranging from 180 to 200 MPa and a flexural strength of around 30 MPa due to its high-strength steel fiber content [1].

One of the major properties of UHPFRC is its superior post-cracking flexural strength, which is owed to the stress transfer provided by fiber bridging at crack surfaces. However, recent research has shown that this property is strongly influenced by fiber orientation and distribution [2–5]. Large numbers of fibers with favorable orientation at the crack surface (mostly perpendicular to it) create higher flexural strength, while fewer fibers with inferior orientation at the crack surface (mostly parallel to it) result in loss of bridging capability in these areas [6].

Fiber orientation and distribution are known to significantly affect the mechanical properties of UHPFRC. Their influence must be considered for structural applications where variations in fiber orientation and distribution in large sections may result in considerable variability in mechanical properties within the section [7]. The ability to analyze and predict fiber orientation and distribution within concrete will enable enhanced structural performance based on the anisotropy of UHPFRC and considerably reduce structural instability that may arise if fiber orientation is not controlled [8]. However, fiber orientation is a highly complex phenomenon, being influenced by wall effects that depend on the geometry of the element to be cast and on shear-induced orientation, which in turn depends on the rheological behavior of the material, the geometry of the element to be cast and the casting process [9]. Most related research to date has focused on 2D fiber orientation/distribution within concrete, there has been no discussion of the height-direction dependence of these variables, which may be significant even in thin elements.

Furthermore, unlike ordinary FRC, UHPFRC is a SCC that flows and fills the formwork without the need for vibration. Ferrara et al. [10] evaluated the influence of rheology on fiber dispersion with vibrated FRC and self-compacting FRC, and several authors have discussed the influence of casting methods on the orientation of UHPFRC [11,12]. However, in the construction field, UHPFRC flowability varies widely and is easily influenced by the amount of super-plasticizer used. The casting time also varies with the flowability of fresh concrete.

In this study, two beams, three slabs and three walls were cast, fiber orientation in the height direction was first reviewed with focus on UHPFRC with different formwork geometry characteristics. Furthermore, the slabs and walls were cast using UHPFRC with different degrees of flowability depending on super-plasticizer content and different casting times, the influence of flowability and casting time on the fiber orientation/distribution and mechanical properties of UHPFRC were evaluated. After the curing stage, prismatic specimens were cut out from the slabs and walls. Analysis involving 3D visualization of

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Table 1
UHPFRC mix proportions.

	Unit weight (kg/m^3)				
	Water	Premixed	Fine sand	Superplasticizer	Fiber
Mixture 1	165	1278	934	15	157
Mixture 2	160.5	1278	934	19.5	157

fiber orientation based on X-ray computed tomography (CT) (a technique widely used with carbon fiber reinforced polymer/plastic (CFRP) and by Global Remuneration Professionals (GRPs)) was employed to evaluate fiber orientation/distribution throughout structural elements [13]. The mechanical properties of prismatic specimens cut out from UHPFRC structural elements were also assessed in three-point bending tests. The number of fibers and their orientations across crack surfaces were determined from 3D orientation analysis based on X-ray CT, and the relationship between fiber orientation/distribution and post-cracking flexural strength was examined.

2. Experiment

2.1. Materials and concrete mixture

The constituent materials and mix proportions of the commercially available premixed UHPFRC used in the study are shown in Table 1. These were as specified by the manufacturer, involving the use of premixed cement, fine aggregate, superplasticizer and 2 vol% steel fiber with a yield strength of 2700 MPa. The fibers were 15 mm in length and 0.2 mm in diameter. The total unit weight of the water and superplasticizer was 180 kg/m^3 for mixtures 1 and 2 alike, while mixture 2 was made with more superplasticizer content for superior flowability. The UHPFRC was mixed in a forced-action biaxial mixer with a capacity of 120 L. Standard flow cone tests based on Japan Concrete Institute (JCI) recommendations were adopted to evaluate the properties of the two mixtures in a fresh state [14]. The flow test results for mixture 1 and mixture 2 showed values of around 210 and 270 mm without jigging, respectively. After placement, the specimens were air-cured at 20 °C for 24 h with the top surface covered in plastic wrap. This was followed by steam curing at 90 °C for 48 h in line with JCI recommendations [14]. Compressive strength and Young's modulus were determined using cylinders of 100 mm in diameter and 200 mm in height after steam curing. The averages of these values were 184 MPa and 51 GPa, respectively.

2.2. Specimens

To clarify how specimen length affected fiber orientation, as shown in Fig. 1, beam A (referred to here as BA) measuring 100 × 100 × 400 mm (b × h × l) and beam B (BB) measuring 100 × 100 × 1000 mm (b × h × l) were cast using mixture 2 with a velocity of 4 L/min (see Table 2). Three slabs measuring 100 × 400 × 1000 mm (h × b × l) and three walls measuring 400 × 100 × 1000 mm (h × b × l) were cast using UHPFRC with different degrees of flowability and casting times (see Table 2). Slab A (referred to here as SA) and wall A (WA) were cast using mixture 1 with a velocity of 1.6 L/min, which had a longer casting time due to its low flowability. Slab B (SB) and wall B (WB) were cast using mixture 2 with superior flowability and the same casting time as that used for SA and WA. Slab C (SC) and Wall C (WC) were cast using mixture 2 with superior flowability and a shorter casting time than that used for SB and WB at a velocity of 4 L/min. Fresh concrete was poured continuously at one end of the mold using a U-shaped channel for all specimens.

After curing, UHPFRC beam specimens were cut to observe the state of fibers on the cut planes. As shown in Fig. 1(a), a block measuring 100 × 100 × 50 mm (h × b × l) was cut from around the middle span of specimen BA. Three blocks were cut from specimen BB for evaluation of fiber orientation with different flow distances. One was cut from the middle span of the specimen, and the others were extracted from near each end (see Fig. 1(b)). The state of fibers on the parallel surfaces (shown in red) of the beam blocks were observed. Prismatic specimens measuring 50 × 50 × 200 mm (h × b × l) were cut out from the slabs and walls and numbered based on their characteristics of symmetry (see Fig. 2). Analysis involving 3D visualization of fiber orientation based on X-ray CT was employed for the specimens cut out from the middle of the slabs and walls in order to evaluate fiber orientation/distribution throughout the structural elements. All specimens extracted from the slabs and walls were subjected to three-point bending tests to determine their flexural properties. The number of fibers and their orientation across crack surfaces were determined using 3D orientation analysis based on X-ray CT, and the relationship between fiber orientation/distribution and post-cracking flexural strength was examined.

2.3. Analysis involving 3D visualization of fiber orientation based on X-ray CT

Fiber orientation and distribution in FRC can be clarified using X-ray CT [3,12,15,16], electrical resistivity [12], magnetic induction [17], AC-

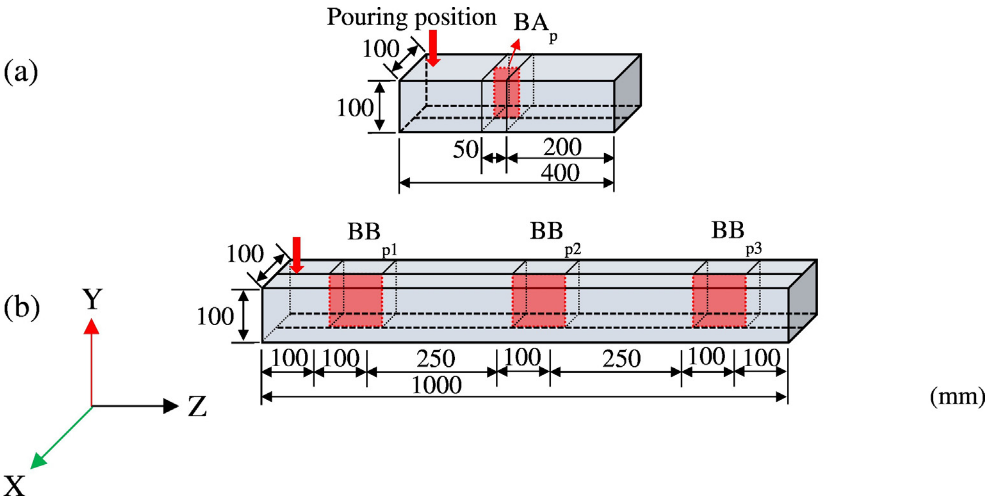

Fig. 1. UHPFRC beam specimens and cutting locations; (a) beam A (BA) (b) beam B (BB).