

Structural behavior of ultra high performance concrete beams subjected to bending

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ABSTRACT

Ultra high performance concrete (UHPC) exhibits improved performance compared to conventional concrete. Various experimental tests on structural behavior are of importance in order to establish reasonable design specifications for UHPC. Therefore, this study provides a detailed presentation of experimental test results for the flexural behavior of ultra high performance concrete beams. The experimental parameters included the amount of rebar and the placing method for the UHPC. The flexural behavioral characteristics were examined with respect to test results on UHPC beams with rebar ratios less than 0.02 and steel fibers with a volumetric ratio of 2%. Steel fiber-reinforced UHPC proves to be effective at controlling cracks and exhibits ductile behavior with a ductility index ranging between 1.60 and 3.75. In addition, the method of placing UHPC affects the flexural behavior with regard to the orientation of the steel fibers. The results of this study provide valuable data that can be used in future studies on the development of computational models of the deflection and flexural behavior of UHPC.

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1. Introduction

1.1. Research background

Concrete is currently the most widely used building material. Although many structures are built of concrete, there are still some limitations related to the use of conventional concrete, such as low tensile strength and almost no ductility. High performance concrete reinforced with steel fibers may be able to overcome these limitations. The study of steel fiber-reinforced concrete has been an area where significant effort is focused. Aitcin [1] proposed reactive powder concrete containing steel fibers. Richard [2] and Behloul [3] studied the applicability of reactive powder concrete. The addition of steel fibers increased the ductile behavior of beams in a study by Oh [4,5] and in a study by Ashour et al. [6], the bearing capacity in a study by Campione [7], shear strength in a study by Lim et al. [8]. Chunxiang et al. [9] and Ashour [10] investigated the effects of steel fiber-reinforced high strength concrete on the flexural behavior of beams. Bayard et al. [11] and Naaman et al. [12] studied high performance fiber-reinforced concrete, and their results showed the advantages of fiber-reinforced concrete. Kooiman [13] proposed a

method for modeling the post-cracking behavior of high performance fiber-reinforced concrete. In addition, RILEM [14,15] specified a bending test method for steel fiber-reinforced concrete.

Ultra high performance concrete (UHPC) reinforced with steel fibers has been developed in recent decades [16]. This material is promising because of its compressive and tensile strength as well as its durability. Yuguang et al. [17] carried out a feasibility study of applying UHPC to bridge decks. In addition, Van Mier [18], Marković et al. [19] and Marković [20] studied the applicability of hybrid fiber-reinforced concrete. It is known that the high ductility of UHPC results from a bridging effect of the fibers across cracks and that the use of UHPC can limit the amount of rebar used compared to conventionally reinforced concrete.

Most studies on UHPC have focused on special concrete materials with characteristics that differ from those of conventional concrete at the material level. For example, Habel et al. [21] presented a study of the evolution of indexes related to hydration and their correlation to the development of mechanical properties of ultra high performance fiber-reinforced concrete. Granger et al. [22] performed mechanical tests on UHPC and acoustic emission analysis of its cracking mechanism. De Larrard et al. [23] presented models to predict the packing density of particle mixes for UHPC.

However, few experimental test results are available on the flexural capacity and deflection of UHPC beams at the structural level. Manfred et al. [24] and Si-Larbl et al. [25] studied the bending design and behavior of UHPC. Accordingly, there are few

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rational methods that can predict the flexural behavior of steel fiber-reinforced UHPC. For example, recommendations for UHPC were proposed by AFGC [26], JSCE [27], and DAFStB [28]. More information is required in order to develop and upgrade the methods for predicting the flexural behavior of steel fiber-reinforced UHPC.

Since UHPC does not include coarse aggregates and exhibits high fluidity, the orientation and dispersion of steel fibers may depend on the flow direction due to the placing sequence of the UHPC or the shape of the structure. Only a few studies [29–31] have dealt with the influence of fiber on the tensile behavior, but they were performed on the specimen scale. The results of these studies imply that the fiber dispersion and orientation might be influenced by the method of placing UHPC. Further investigation is required in order to understand the effect of the method of placing UHPC on structural behavior at the structural member scale.

1.2. Research objectives and scopes

The purpose of this paper is to examine the basic behavioral properties of UHPC beams with steel rebar. The experimental parameters included the use of steel rebar and the method of placing UHPC. The UHPC beams used in this study had a water ratio under 0.02. In addition, the UHPC did not use coarse aggregate and had steel fibers with a volumetric ratio of 2%. The experimental test results from static loading of the steel fiber-reinforced UHPC beams revealed the characteristics of flexural behavior of the steel fiber-reinforced UHPC. Flexural behavior included cracking, failure pattern, deflection, ductility, and flexural capacity measurements. The test results from this study provide more information to help establish a prediction model for the flexural capacity and deflection of UHPC beams under bending conditions.

2. Experimental program

2.1. Mixing proportions and sequence of UHPC

The UHPC developed in this study is a kind of reactive powder concrete [1,2]. The constituent material proportions were determined, in part, based on an optimization of the granular mixture. This method allowed for a finely graded and highly homogeneous concrete matrix. Compared to conventional concrete, UHPC should show significantly improved mechanical properties such as high compressive strength and high tensile strength. Addition of fibers to a conventional concrete mixture may result in reduced workability. The best possible way to improve workability is to produce self-compacting concrete. This concrete has high flow characteristics and flows under its own weight. To achieve the conditions mentioned above, the following mixing principles for UHPC were considered.

- Low values of the water–binder ratio.
- Elimination of coarse aggregate, namely, the application of only fine aggregate.
- A limited amount of fine aggregate.
- Packing density in which each grain fills the voids between the larger grains.

The major parameters for the concrete mixture were the water–binder ratio, the silica fume–cement ratio, the fine aggregate–cement ratio and the fiber content by volume. Optimization of the concrete mixture was carried out by varying the major parameters and using the compressive strength test, the splitting tensile strength test and the slump flow test. Extensive tests were performed. The development of the mixing proportions presented above is shown in Fig. 1. Finally, material proportions reflecting all the test results were determined as shown in Table 1.

Fine aggregates were sands with diameters less than 0.5 mm. They represented dimensionally the largest granular material.

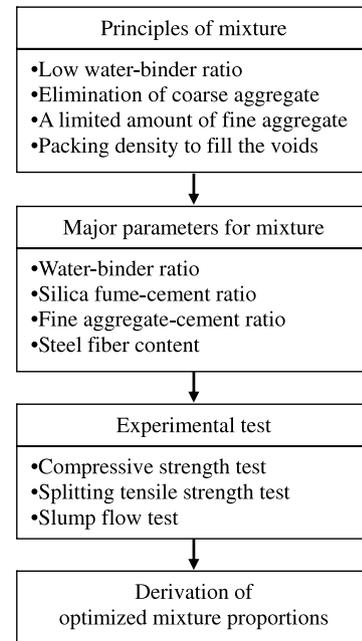


Fig. 1. Flow chart for the mixture design of UHPC.

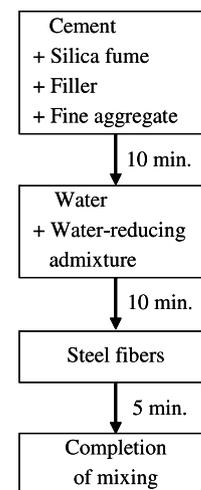


Fig. 2. Mixing sequence of UHPC.

Coarse aggregates were not included. The next largest particle was that of ordinary Portland cement. The filler material used for UHPC was the crushed quartz with an average diameter of 10 μm and a density of 2600 kg/m^3 . The silica fume, which was the smallest particle in the UHPC components, had a diameter small enough to fill the interstitial voids between the cement and crushed quartz particles. The workability provided by the low water-to-cement ratio is secured by the addition of a high performance water-reducing agent; The water-reducing agent in this case was polycarboxylate superplasticizer with a density of 1060 kg/m^3 . The steel fibers used for this study were straight steel fibers with a diameter of 0.2 mm and a length of 13 mm. The fibers have a density of 7500 kg/m^3 and a yield strength of 2500 MPa. The volume percentage of steel fibers was fixed at 2.0%. The proportions of the components in this UHPC mixture are given by their weight ratios in Table 1.

The mixing sequence for UHPC shown in Fig. 2 was as follows. First, cement, silica fume, filler and fine aggregate were premixed for about 10 min. Then, water and water-reducing admixture were added and mixed for about 10 min. When the mixture became flowable, the steel fibers were added and mixed for an additional 5 min.

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