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Characterization of hardened state behavior of self compacting fiber-reinforced cementitious composites (SC-FRCC's) with different beam sizes and fiber types

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ABSTRACT

This paper presents the second part of a comprehensive study to evaluate the hardened state performances of SC-FRCCs, which was carried out to understand the effects of various parameters on the mechanical performance of these materials.

Main objective of this study was to identify the different behaviors of SC-FRCCs in terms of hardened state performance by considering parameters such as specimen thickness/fiber length ratio (t/f_L), fiber type (straight or hooked), and fiber aspect ratio. Specimens were cast using same self-compacting mix designs, only fiber length, fiber type and specimen depth were varied. Four different fiber lengths (6, 13, 35 and 50 mm), two different fiber types (straight and hooked-end) and ten different specimen thickness (from 18 to 100 mm) values were set. As a result, 12 different groups of specimen were obtained.

Experimental studies include fiber orientation density, flexural strength, strain localization and crack propagations measurements for hardened state using both traditional methods and a full field image-based method called Particle Image Velocimetry (PIV), which measures surface displacements and strains using digital image analysis. Hardened state tests were carried out with un-notched specimens under four-point bending. Results obtained from both traditional measurement methods and PIV analyses, were combined and used in order to have a detailed understanding on how changing material parameters may affect the material behavior.

1. Introduction

SC-FRCC materials combine the self-compacting, highly flowable and non-segregating performance in the fresh state with the deflection-hardening and multiple cracking behavior of high performance fiber-reinforced cementitious composites [1]. [2] Therefore, the use of SC-FRCC will continue to increase all around the world due to its many advantages compared to traditional concrete.

Steel fibers, being randomly distributed in the concrete, bridge cracks as they form in the initial stages and as a result reduce the tendency of these micro-cracks to form into larger cracks. After cracking, the fibers transmit tensile forces accross the crack into the surrounding concrete. Therefore, fibers bridging accross the cracks usually lead to increased flexural toughness, ductility, strain capacity and reduced crack widths. Parameters such as fiber type, fiber geometry, fiber dimensions and fiber dispersion features enormously affect the material performance.

However, more research is needed to quantify the effects of different parameters on the material performance. Further research is required for a comprehensive understanding and a more widespread use of SC-FRCC materials.

There are numerous experimental methods available for crack monitoring under different types of loads [3]. Measuring related displacements/crack widths is especially important. Some of the

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conventional measurement equipments are electrical resistance strain gauges, extensometers and linear variable differential transformers (LVDTs). All of these equipments are effective and trustworthy if they are accordingly used with a proper loading set-up and system. However, there are typical drawbacks faced with the use of these conventional measurement devices [4] and these drawbacks have led researchers to develop non-contact full field deformation measurement techniques.

One of the methods that has been used for non-contact deformation measurement as well as crack monitoring is particle image velocimetry (PIV). This technique is used to determine instantaneous fields of the vector velocity by measuring the displacements of numerous fine particles that accurately follow the motion of the fluid [5]. Nowadays, PIV has been used in the field of concrete/composites also, in order to measure displacement and strain fields [6–9] and monitoring fracture process zones (FPZs) and cracks [10,11]. However, the number of studies on the application of this technique for crack monitoring of cement-based materials is still limited.

Therefore, one of the objectives of this study is to further investigate the ability of PIV for measuring concrete performance especially in hardened states, for crack opening measurements.

In this study, the differences in terms of mechanical performance of SC-FRCC beams were identified by considering the parameters such as specimen dimensions, fiber length/specimen thickness ratio (t/f_L), fiber type (straight/hooked) and fiber aspect ratio. The influence of the t/f_L ratio, fiber orientation and resulting crack propagation behavior were studied together with the mechanical performance of SC-FRCC beams, for evaluating and characterizing the flexural behavior of the beams.

2. Materials

2.1. Materials and mix design

The self-compacting mix used was adapted from the previous studies by the authors, where an SCC mortar mix was optimized to obtain high flowability, high segregation resistance and high performance for thin section precast elements [4,12,13]. Cement, slag, sand, water, superplasticizer and fibers were used. No coarse aggregate was used in the mixture. Mixture had excellent flow ability with good static and dynamic segregation resistance as previously discussed in Refs. [13,14].

The mix proportions of the SCC used for control mixes without fibers were as follows. Cement: Sand: Slag: Water: Plasticizer: 498: 1150: 418: 220: 18 kg/m^3. The mix proportions of the SCC used for both straight and hooked end steel fiber-reinforced mixes were as follows. Cement: Sand: Slag: Water: Plasticizer: Fiber: 497: 1114: 418: 220: 18: 94.8 kg/m^3. Therefore, the amount of sand was gradually decreased to obtain similar workability when fibers were used. Desired fiber-reinforced cement-based mixture was also obtained after several trials. The mortar mixes were manufactured using a water-cement ratio of 0.44 (w/c = 0.44) by weight, water-binder ratio of 0.24 (w/b = 0.24) and dosage of superplasticizer was kept 1.7% for all the mixes.

Cement used for mortar specimens was CEM I 42.5 R, with a density of 3.14 g/cm^3. Densities of the sand (diameter $\leq$ 1 mm) and slag used for mortar mixtures were 2.65 g/cm^3 and 2.92 g/cm^3, respectively. A polycarboxylate-based superplasticizer having 1.075 g/cm^3 density, was used (1.2–1.3%) in the mortar mixtures. Two different types of steel fibers were used (straight and hooked-end steel fibers). Density of steel fibers used for mixtures was 7.17 g/cm^3 and tensile strength of the fibers was ranging between 1100 and 1400 MPa.

2.2. Formwork dimensions, specimen numbering and curing

Different sizes of molds were selected, to have same length (400 mm) and width (100 mm), but various thicknesses changing from 18 mm to 100 mm, as can be seen in Table 1.

Same mixes were cast, with 2 different fiber types (straight and hooked), 3 different fiber aspect ratios and 4 different fiber lengths (6 mm and 13 mm for straight fibers; 35 mm and 50 mm for hooked-end fibers). Details can be found in Table 2.

The specimens were named according to their thickness, width and fiber lengths. (i.e: S 24/100/13, S representing "Specimen", the number on the left hand side implying the specimen thickness, the number in the middle implying the width and the number on the right hand side showing the fiber length).

The specimens were left in molds for 24 h at a temperature of 20 °C ± 2 °C. They were then de-molded, moved to a water tank and stored there at a temperature of 20 °C ± 2 °C and a relative humidity $\geq$95% for 90-days. The reason for curing for 90 days was to see the effect of high amount of slag used in the mixture.

3. Methods used for experiments and analyses

Fresh state performance of the material was evaluated by using mini slump flow and mold flow tests. The flowability and fiber aligning ability as well as dynamic segregation resistance of the material were evaluated by using the data obtained during measurements, details were given in the former study by Sanal et al., 2015 [4].

3.1. Particle image velocimetry (PIV)

PIV technique was originally implemented using double-flash photography of a seeded flow and the resulting photographs were divided into a grid of test patches. For PIV analysis, displacement vector of each patch during the interval between the flashes is found by locating the peak of the auto correlation function of each patch in PIV method. A modified approach was used to implement PIV in geotechnical testing by White et al. [15]. According to their investigations, the modified PIV technique offers an order-of-magnitude increase in accuracy, precision, and measurement array size compared with previous image-based methods of displacement measurement [15]. The PIV analysis procedure can be summarized as follows [11,15,16]: i) Subdivide the first image into subsets (patches) and select a test patch; ii) Evaluate the cross-correlation of the selected test patch, and search the patch using the fast-Fourier transform (FFT); iii) Normalize by cross-correlation of the search patch with the mask function (the most likely displacement is the peak of the function); iv) Find the subpixel location of the correlation peak using bicubic interpolation; v) Repeat the procedure for other test patches of the first image; vi) Repeat for all images in the series, and calculate the displacement vectors; and vii) Calculate the strain tensor using the obtained displacement field.

As detailed discussion on PIV technique is beyond the scope of the current study, further details on the PIV technique can be found in the studies by White and Take [17], and White et al. [15]; besides, necessary discussions on the technique are provided in the following sections. It should be noted that application of the PIV technique in structural tests has been comprehensively discussed in Refs. [6–11].

3.2. Fiber orientation density

3.2.1. Indirect measurement by using PIV

Visual observations during mixing and casting of test specimens