Cement & Concrete Composites 54 (2014) 100–109

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Effect of steel fiber hybridization on the fracture behavior of self-consolidating concretes

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ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 9 February 2014
Accepted 20 February 2014
Available online 12 March 2014

Keywords:
Hybrid reinforcement
Round panel test
Cracking mechanisms
Steel fiber
Self-consolidating concrete
Rheology

ABSTRACT

In the present work the effect of steel fiber hybridization on the mechanical and rheological behavior of self-consolidating concretes was studied. Straight and hooked end steel fibers with different lengths and diameters were used as reinforcement in fiber volume fractions of 1.0% and 1.5%. The viscosity and shear yield stress of the concretes was determined using a parallel plate rheometer. The mechanical behavior was determined by means of compression, tension and bending tests. The movement of the neutral axis under bending load was experimentally determined by strain-gages attached to compression and tensile surfaces. The mechanical response of the material under bi-axial bending was addressed using the round panel test in three different boundary conditions. The obtained results indicated that the fiber hybridization improved the behavior of the composites for low strain and displacement levels increasing the serviceability limit state of the same through the control of the crack width.

1. Introduction

The self-consolidating concrete (SCC) was developed in Japan in the 80s decade in order to improve the durability of concrete [1]. SCC is expected to have low permeability and dense microstructure which helps protect the structures reducing the corrosion rate of the used reinforcement (fibers or steel rebars). The main advantage of SCC compared to the conventional concretes consists on its workability [2], which allows the concrete to fill out the spaces and gaps in a formwork system without the need of vibration [3]. The fresh property improvements were only possible due to developing techniques of cement paste microstructure densification using efficient superplasticizing chemical additives and ultra-fine particles [4]. Furthermore, with the development of new chemical additives such as the viscosity modifiers it was possible to enhance the viscosity of the mixtures leading to a higher resistance to segregation and bleeding [5].

Since the development of the first fiber reinforced concretes (1950s and 60s decades) using steel and glass fibers, continuous developments have occurred resulting in new materials, optimized fiber geometries, new processing, standardization, and in improved products for the construction industry [6,7]. The FRC's (fiber reinforced concretes) or also FRCC's (fiber reinforced cementitious composites), exhibit, in tension, higher strength and ductility compared to the unreinforced concretes. Given the limited amount of coarse aggregate and the higher volume of fines found in the SCC's mixtures, a denser interfacial transition zone (ITZ) can be achieved [3]. This fact contribute to the bond strength between fiber and matrix, leading to an increase in post-cracking toughness of the composites produced with SCC [8,9].

The production of hybrid fiber reinforced self-consolidating concretes aims to combine the mechanical properties of two or more different fibers to the rheological characteristics of self-consolidating matrices. Hybrid reinforcement systems can be used in order to take advantage of each individual fiber properties [10], which depend of several parameters that include fiber dosages, reinforcement ratios, fiber types [6] and the geometrical differences between the sets of fibers [11]. These composite systems can improve not only flexural and tensile strength, but can also lead to a change in the cracking mechanisms [12]. In certain situations, the composites are produced using a multi-scale concept. Rossi et al. [13] developed at the LCPC (Laboratoire Central des Ponts et Chaussés), a cementitious composite where different classes and fiber geometries are used as reinforcement. This composite can present multiple cracking in tension and both strain and deflection hardening behaviors [14].

The manufacturing, the fiber dispersion and the fiber orientation are very important to improve the post-cracking response of the FRC [15]. Thus, the rheological properties of the matrices

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http://dx.doi.org/10.1016/j.cemconcomp.2014.02.004
0958-9465/

should be suitable for the fiber addition [16]. It is worth noticing that most of the research performed on FRC systems found in the literature uses in the mix design matrices that do not contain coarse aggregates, but instead, fine aggregates [17–19].

Kim et al. [19] studied the flexural performance of hybrid ultra-high performance FRC using one micro (L = 13 mm) and four types of macro (L = 30 and 62 mm) high strength steel fibers. The results showed an improvement in deflection and toughness for hybrid systems in comparison to systems reinforced by micro fibers only.

Akcay and Tasdemir [20], produced four different HSFRSCC's (hybrid steel fiber reinforced self-compacting concrete) and reported that it is possible to add a volume fraction of fibers up to 1.5% without affecting its workability. The mechanical behavior showed that the fiber hybridization increased the concrete fracture energy and ductility.

Bending tests are widely used to evaluate the mechanical performance of fiber reinforced concretes. In some situations, this type of test can be troublesome because it does not represent the real structural behavior showing different cracking mechanism and normally higher dispersion on experimental results [15, 21–23]. Structural or quasi-full scale tests as ASTM C-1550 [24], however, have greater representation in relation to the concrete volume, failure mechanisms and toughness. As reported by Bernard [22] the mechanical tests need to reflect the material variations and not variations associated to the test method. Round panel tests were performed in steel fiber reinforced concretes with different dimensions. Results indicate that the main advantage of this test is to allow the detection of a multiple crack pattern which is not observed in tests with small beams. Bernard [25] investigated the influence of support conditions on flexural and shear behavior of steel fiber reinforced concrete slabs. According to the author, bending tests performed on panels supported on three points show a consistent failure mode and allows a more reliable measure of the concrete performance when compared to alternative methods of support. Minelli and Plizzari [21] performed a comparison between round panel and flexural beam tests. Results reported that the geometry and fracture area involved in round panel tests leads to a lower dispersion resulting in a better representation of the real structural behavior.

Hooked end steel fibers represent one of the most common types of fibers used in Brazil. However, few local studies have been generated in order to combine different steel fiber geometries in a single composite (i.e. short and long steel fibers). Thus, the aim of this article is to investigate the effect of hybrid steel fibers in the fracture behavior of self-consolidating concretes. Rheological and mechanical properties of self-consolidating FRC are addressed. Two different hybrid FRC systems were produced, using straight and hooked end steel fibers with different lengths, in fiber volume fractions of 1.0% and 1.5%. The self-consolidating concrete matrix was designed and produced based on the compressible packing model. A parallel plate rheometer was used to determine the influence of fiber hybridization on the plastic viscosity and shear yield stress. Furthermore, empirical rheological tests were performed. Mechanical tests were carried out in the structural and materials scale and the changes in the cracking mechanisms were investigated. Compression, direct tension and four point bending tests were performed in the materials scale while the round panel tests, based on ASTM 1550 [24], were carried out as a structural testing. The round panel tests were performed using three different boundary conditions: with three supports, six supports and fully supported.

2. Materials and processing

The matrix used in this research was previously designed by Marangon [26] following the compressible packing model (CPM) routine [27,28] and then adapted to the case of hybrid reinforcement [29]. The materials used in the SCC composition were a Brazilian slag cement type CPIII 40 with a 28 days compressive strength of 40 MPa, coarse aggregates (D_{max} = 9.5 mm), river sand with two classes of particle size: one ranging from 0.15 mm to 4.8 mm and the other from 0.15 mm to 0.85 mm, fly ash, silica flour (ground quartz), silica fume, and a polycarboxilate superplasticizer with solid contents of 31.2%. Fig. 1 shows the particle size distribution of the used cementitious materials and aggregates. The water/cementitious material ratio, the superplasticizer and VMA dosages were kept constant at 0.32, 45.1 kg/m^3 and 0.36 kg/m^3, respectively.

Two steel fiber types, one straight (SF1) and one with hooked ends (SF2), were used as reinforcement. The straight fiber presented a tensile strength of 1100 MPa, elastic modulus of 200 GPa and a density of 7.85 g/cm^3, and the fiber with hooked ends (SF2) a tensile strength of 1150 MPa, elastic modulus of 200 GPa and a density of 7.85 g/cm^3. The length and aspect ratio of the SF1 fiber were 12 mm and 67 and those presented by SF2 were 35 mm and 65, respectively. The SF1 fiber was produced with a brass coating providing the fiber a relatively smooth surface.

Five concrete mixtures, with the proportions presented in Table 1 were produced. One control mixture without steel fibers, two mixtures with a fiber volume fraction of 1.0% (78 kg/m^3) named as C1.0% (1.0% of SF2) and C1.0%H (0.5% of SF1 + 0.5% of SF2) and two mixtures with a fiber volume fraction of 1.5% (117 kg/m^3) named as C1.5% (1.5% of SF2) and C1.5%H (0.5% of SF1 + 1.0% of SF2).

The concretes were produced in a room with controlled temperature of 21 °C ± 1 °C using a planetary mixer (previously moistured) of 100 l capacity. The cementitious materials were homogenized by dry mixing for 60 s prior to the addition of sand and coarse aggregates. The dry ingredients were mixed for an additional 60 s prior to addition of superplasticizer and water. After 5 min of homogenization, the fibers were manually added to the mix in small amounts, in order to avoid bailing, over about 1 min. The mixture was blended for 8 min.

For the production of all the samples, the concrete mixtures were placed in the steel molds in one layer without any type of consolidation. The round panel formworks with nominal diameter and thickness of, respectively, 750 mm and 75 mm, were produced using a thin steel sheet and a wood base. After pouring the concrete, the round panel surfaces were leveled with a steel plate. The samples did not suffer any kind of vibration. The specimens were covered in their molds for 48 h prior to moist curing for 28 days in a cure chamber with 100% RH and 23 ± 1 °C.

3. Rheological tests

The effect of the hybrid reinforcement on the plastic viscosity and shear yield stress was measured with a parallel plate rheometer developed at the LCPC [30]. Ten rotation speeds ranging from 0.2 rev/s to 0.8 rev/s were used to perform the tests. These speeds correspond to strain rates of 0.25 s^{-1} and 6.0 s^{-1}.

The tests with V funnel were performed in an apparatus with rectangular top and bottom sections of 515 mm × 75 mm and 65 mm × 75 mm (length and width), respectively [31]. Through this test the elapsed time (in seconds) between the opening of the bottom and the time when all the concrete flows through the lower section can be determined in order to measure the concrete flow ability.

The L box test was used to measure the filling and passing ability of the studied concretes [32]. Three different configurations of bars (12 mm of diameter) were used. The space between bars was 94 mm (one bar), 58.66 mm (two bars) and 41 mm (three bars).