Materials and Design 54 (2014) 32–42

Contents lists available at ScienceDirect

Materials and Design

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

Mechanical behavior of hybrid steel-fiber self-consolidating concrete: Materials and structural aspects

Dimas Alan Strauss Rambo, Flávio de Andrade Silva *, Romildo Dias Toledo Filho

Civil Engineering Department, COPPE, Universidade Federal do Rio de Janeiro, P.O. Box 68506, CEP 21941-972, Rio de Janeiro, RJ, Brazil

A R T I C L E   I N F O

Article history:
Received 24 April 2013
Accepted 5 August 2013
Available online 14 August 2013

Keywords:
Hybrid reinforcement
Round panel test
Crack formation
Steel fiber
Self-consolidating concrete

A B S T R A C T

This work presents the preliminary results of an experimental investigation on the mechanical behavior of self-consolidating concrete reinforced with hybrid steel fibers in the material and structural scale. 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%. In the fresh state the concrete was characterized using the slump flow, L-box and V-funnel tests. To determine the effect of the hybrid reinforcement on the plastic viscosity and shear yield stress a parallel plate rheometer was used. Following, the mechanical response was measured under tension and bending tests. In the flexural test, the movement of the neutral axis was experimentally determined by strain-gages attached to compression and tensile surfaces. Furthermore, the mechanical response of the material under bi-axial bending was addressed using the round panel test. During the test the crack opening was measured using three linear variable differential transformers (LVDT's). The cracking mechanisms were discussed and compared to that obtained under four point bending and direct tension. 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. For large displacement levels the use of the longer fibers led to a higher toughness but with an expressive crack opening. Due to its structural redundancy the round panel test allowed the formation of a multiple cracking pattern which was not observed in the four point beam tests. Finally, the obtained material's properties were used in a nonlinear finite element model to simulate the round panel test. The simulation reasonably agreed with the experimental test data.

1. Introduction

The first works on fiber reinforced concrete (FRC) were realized in the 1950s and 60s decades of the last century with the aim of understanding the mechanical behavior of steel fiber reinforced concrete [1,2]. Since that period, other fibers have been evaluated as reinforcement in concrete elements, but steel is still the most used fiber. Its popularity is associated with the fact that steel presents a good affinity with concrete, the ease of use, the high toughness and resistance to static and dynamic loads [3]. Several categories of fiber reinforced concrete have been developed over the past three decades presenting different mechanical properties. Conventional FRC presents an increase in the ductility when compared with the plain matrix showing a strain softening behavior after the appearance of the first crack. On the other hand the high performance fiber reinforced cementitious composites (HPFRCC) exhibit a deflection hardening behavior and can also present a strain-hardening type of response accompanied by multiple cracking in tension which leads to an improvement in strength and toughness compared to the non-reinforced matrix [4–6].

In the last few decades significant improvements in the development of cement based materials have been achieved resulting in high performance concrete that can present uniaxial compressive strength ranging from 150 to 400 MPa [5,7,8]. These improvements were only possible due to developing techniques of cement paste microstructure densification using efficient superplasticizing chemical additives and ultra-fine particles. 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 [9], which depend on the shape, type, size and the volume fraction of the used fibers [1]. These composite systems can improve not only flexural and tensile strength, but can also lead to a change in the cracking mechanisms. The manufacturing, the fiber dispersion and the fiber orientation are very important to improve the post-cracking

* Corresponding author. Tel.: +55 (21) 2562 8493x48; fax: +55 (21) 2562 8484.
E-mail address: fsilva@coc.ufrj.br (Flávio de Andrade Silva).

0261-3069/$ - see front matter
http://dx.doi.org/10.1016/j.matdes.2013.08.014

response of the fiber reinforced concrete [10]. Thus, the rheological properties of the matrices should be suitable for the fiber addition [11]. 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 [12–14].

Kim et al. [14] 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 [15], 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.

A multi-scale reinforced cement composite was developed by Rossi et al. at the Laboratoire Central des Ponts et Chaussés (LCPC) [16]. Two types of materials were developed by using the multi-scale concept. A cement based compositewhich was reinforced by 7% of two metal fibers of different geometries, and the CEMTEC$_{multiscale}$® that was reinforced by 11% of three classes of steel fibers [17,18]. Both materials present a tension hardening behavior but the MSCC can achieve up to 15 MPa under direct tension while the CEMTEC up to 20 MPa.

The mechanical behavior of fiber reinforced concrete is usually evaluated using bending tests, mostly performed in small prisms. This type of test does not represent the real structural behavior because it results in a different cracking mechanism and normally leads to a higher dispersion on experimental results [10,19–21]. Structural or quasi-full scale tests as ASTM: C-1550, however, have greater representation in relation to the concrete volume, failure mechanisms and toughness. As reported by Bernard [20] 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 [22] 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 [19] 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.

The effects of the steel fiber hybridization on the rheological and mechanical properties of self-consolidating FRC are addressed in the present work. 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. Direct tension and four point bending tests were performed in the materials scale while the round panel tests for the structural testing. A non-linear finite element model was used to simulate the mechanical behavior of the studied FRC system in the structural scale.

2. The compressible packing model

The compressible packing model (CPM) was developed by de Larrard and his collaborators and used in this research to design the matrix of the self-consolidating fiber reinforced concrete [23,24]. Composite materials like concrete are made up of grains embedded in a matrix. The aim of the design is to use the least possible amount of binder by combining these grains in order to minimize the concrete porosity [23]. The equation representing the virtual packing density of a granular mix containing n classes of grains, ordered in such a way that its diameters are $d_1 \geq d_2 \geq \ldots d_i \geq d_{i+1} \geq \ldots \geq d_n$, when the class i is dominant, is expressed by the following equation:

$$\gamma^{(i)} = \frac{\beta_i}{1 - \sum_{j=1}^{i-1} y_j\left(1 - \beta_i + b_{i,j}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right) - \sum_{j=i+1}^{n} y_j\left(1 - a_{i,j}\frac{\beta_i}{\beta_j}\right)} \quad (1)$$

where $\gamma^{(i)}$ is the virtual packing density when the ith class is dominant; y_i is the volumetric fraction of the ith class; β_i is the virtual packing density of the ith class; it represents the volume of grains contained in an unitary volume, compacted with an ideal compaction energy that would correspond to a maximum virtual packing; $a_{i,j}$ and $b_{i,j}$ represent the loosening effect and the wall effect exerted by the grains, respectively; they can be determined either experimentally or by the following formulas:

$$a_{i,j} = \sqrt{1 - (1 - d_j/d_i)^{1.02}}$$
$$b_{i,j} = 1 - (1 - d_i/d_j)^{1.50} \quad (2)$$

The virtual compactness of the mix can be found by using the formula:

$$\gamma = inf(\gamma^{(i)}) \quad (3)$$

where inf indicates the least value.

The actual compactness depends on three main parameters: the size of the grains, the shape of the grains, and the method of processing the packing. The compressible packing model allows making the transition from virtual compactness, which cannot be obtained in practice, to the actual compactness of the mix, which depends on the energy being applied at the time of placing. A scalar K called compaction index enables connecting the virtual compactness (γ) with the actual compactness (ϕ). This scalar is strictly dependent on the protocol implemented for the particular mix. As K tends to infinity, the compactness ϕ tends to the virtual compactness γ.

The general shape of the compaction index equation, for n classes of grains, is as follows:

$$K = \sum_{i=1}^{n} \frac{y_i/\beta_i}{1/\phi - 1/\gamma^{(i)}} \quad (4)$$

where ϕ is the actual compactness of the granular mix.

The values of index K are calculated from the binary mixes for each placing processes. K assumes a value of 4.5 when the compaction process is the simple pouring, 6.7 for water demand and 9 when the placing process is vibration plus 10 kPa compression [23].

If the actual compactness for a single granular class i (ϕ_i) is experimentally determined, by means of a compaction process having compaction index K, it is possible to use Eq. (5), derived from Eq. (4), to determine the virtual compactness of the granular class i.

$$\beta_i = \frac{\phi_i}{K}(1 + K) \quad (5)$$