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On the mechanical behavior of polypropylene, steel and hybrid fiber reinforced self-consolidating concrete

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HIGHLIGHTS

- Steel fibers are more efficient than PP in improving the crack growth resistance.
- Hybrid composites (PP and steel) are a good alternative for lower fiber volume fractions.
- Steel fibers are more efficient in increasing the strength and result in a lower rate of stiffness degradation.
- The addition of fibers in concrete can delay the strain development in the rebar.

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ABSTRACT

This article presents the results of an experimental investigation on the mechanical behavior of a self-consolidating concrete reinforced with steel, polypropylene and hybrid fibers. Hooked end steel fibers with different lengths and diameters were used as reinforcement in fiber volume fractions of 0.50%, 1.00% and 2.00%. Polypropylene fibers were used as reinforcement in volume fractions of 0.33%, 0.66% and 1.10%. Hybrid composites (HyFRC) were also developed to study the synergy effects of both fibers. The hybrid fiber self-consolidating concrete was produced with the addition of 0.50% of hooked-end steel fibers and 0.66% of polypropylene fibers.

Pre-notched SCC prims where tested under monotonic and cyclic three-point bending. The tests where controlled by the crack mouth opening displacement in order to have a better analysis of the post cracking regime. The addition of polypropylene, hooked-end and hybrid fibers was effective in improving the post-peak strength of the composites, even though the use of steel fibers promoted higher values of flexural residual stress due to its geometrical and material properties. The same behavior was observed for the fracture parameters results with an improvement of the crack growth resistance for the analyzed composites.

Finally, the effect of the fiber reinforcement on the flexural behavior was studied through structural tests on fiber reinforced self-consolidating concrete beams. Both hooked-end steel fiber and hybrid composites enhanced the resistance at yielding and promoted a lower rate of stiffness degradation, while the polypropylene fiber reinforcement presented an improvement in the ductile behavior of the structural composite. The present work gives an important contribution on the structural and cyclic behavior of steel, PP and hybrid fiber reinforced concrete. The paper makes a comparison on the mechanics of the different composite systems aiming its application in structural elements.

1. Introduction

The principle of using fibers with the aim to enhance the mechanical properties of concrete is well known for many years but its practical use in structural engineering applications still depends on the development of technical standards and recommendations. The addition of fibers as reinforcement in concrete may not change its compressive strength [1] and modulus of elasticity [2], but some of the main mechanical properties such as fracture toughness [3], ductility [4] and crack-width control are improved.

FRC has been widely used in many engineering applications, such as precast tunnel lining segmental units [5], when crack propagation control is of primary importance [3], since FRC can considerably enhance the post-cracking behavior with a more efficient crack control than the conventional steel reinforcement

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[6]. However, the use of fiber is not restricted to crack width control, as it can also be used to replace secondary reinforcement in flat slabs [7]. Other applications are related to the use of fibers in a hybrid system which is based on the simultaneous use of steel rebars and fibers. Although, reinforcing bars are efficient for resisting localized stresses in concrete, the distributed stresses are better controlled with the use of fibers. When both localized and distributed stresses are present, hybrid reinforcement can offer an optimal solution [6].

A wide variety of fibers has been used as reinforcement in concrete with the main objective to increase strength of the composites. To meet this purpose, steel fibers is the more conventional reinforcement used due to its high elasticity modulus, which promotes post-peak load carrying capacity of the concrete and strength especially in high volume fractions [8]. The synthetic fibers also showed considerable improvements with respect to strain capacity, toughness and crack control of FRC composites despite its low elasticity modulus [9]. Therefore, the use of polypropylene fibers can be an interesting application when the post cracking residual strength is not the main objective of the fiber reinforcement.

Concrete may also be produced with hybrid fibers by mixing the matrix with distinct types of steel fibers [10] or by reinforcing the plain concrete with steel and polypropylene fibers [11] together. The main objective of the production of hybrid fiber concrete is to combine the mechanical properties of two or more different fibers and take advantage of each individual fiber properties.

Caggiano et al. [11] showed that HyFRC mixtures with more steel fibers presented higher post-cracking flexural strength associated with a re-hardening force-crack response. However, a greater presence of polypropylene fiber showed lower variability in the experimental results when comparing with the other HyFRC composites. The replacement of steel fibers by equal volume of polypropylene fibers causes either no change or slight increase in the fracture properties of HyFRC [12].

Many different standards have already been developed with the aim to evaluate the material's behavior such as the European standard EN 14651 [13] and RILEM TC 162-TDF [14], which evaluate the specimen through notched small beams by a three point bending test. However, new test routines have been developed in the past years such as cyclic flexural fracture tests which is based on cycles of loading and unloading in pre-notched beams [15]. Based on RILEM 89-FMT [16], it is possible to study the cyclic fracture parameter and measure the increase in energy dissipation on the crack face [15]. Boulekbache et al. [17] studied steel fiber reinforced concretes through cyclic tests and reported an increase in the cumulative energy of SFRC with the increase of fiber content, although the aspect ratio showed no significant effect.

On a structural level, Ning et al [18] tested the influence of the steel fibers on the flexural behavior of reinforced self-compacting concrete. The ultimate flexural capacity of SFRSCC beams presented an increase with increasing of fiber content. Moreover, the effect of steel fibers was more pronounced for beams with relatively lower reinforcement ratio. Another important effect of the fiber reinforcement was associated with the steel reinforcement strain during the tests. Although the influence of the steel fibers on the rebar strain is small before cracking, the fibers play a significant role in reducing the steel reinforcement strain fibers after cracking.

The present work aims to compare the effect of steel, PP and Hybrid fibers on the mechanics of SCC. Two types of hooked-end steel fibers and one polypropylene fiber were tested in three fiber volume fractions. Furthermore, one hybrid mixture with polypropylene and steel fibers was tested. All composites were analyzed by bending tests based on the European standard EN 14651 [13]. Moreover, cyclic tests in accordance with the RILEM 89-FMT [16] were carried on with the highest fiber volume fractions of each of the three fibers and the hybrid mixture with aim to compare both monotonic and cyclic tests results of the experiment. The highest fiber volume fraction of both polypropylene and steel composites and the hybrid mixture were tested on self-compacting concrete beams reinforced with conventional steel rebars with the aim to verify the effects of the fibers on a structural level. Pullout tests were carried on both polypropylene and hooked end-steel fibers to investigate the bond mechanism in the concrete SCC matrix. The influence of the different fibers in the structural behavior of R/C elements was evaluated by testing beams with cross section of 150 mm × 150 mm and a 1200 mm length. The work in hand aims to fill in the gap that exists between the effect of fiber reinforcement in materials testing and in the structural scale.

2. Materials and mixing procedure

2.1. Materials

The cementitious materials used in the production of the self-compacting concrete were the Brazilian cement type CPV (ASTM Cement type III), fly ash and silica fume. Two classes of particle size of river sand were mixed together with the rest of the materials: one ranging from 0.15 mm to 4.8 mm (S1) and the other ranging from 0.15 mm to 0.85 mm (S2). Coarse aggregate with maximum diameter of 9.5 mm, silica flour (ground quartz) and superplasticizer (Glenium$^{\infty}$ 51) were also mixed together with the other materials. The water/cement ratio of the mix was 0.5. The average compressive strength after 28 days was 73 MPa and the obtained slump spreading was 750 mm. For more information on the mix procedure and matrix mechanical behavior refer to Pereira [19] and Rambo [20].

2.2. Fiber types

Two steel fibers with hooked ends (SF1 and SF2) and one polypropylene fiber (PPF) were used as reinforcement. The first steel fiber (SF1) presented a length of 30 mm with an aspect ratio of 45 (d = 0.62 mm) while the second one (SF2) presented a length of 60 mm and aspect ratio of 80 (d = 0.75 mm). The PPF presented a length of 40 mm and aspect ratio of 74 (d = 0.54). Other properties of the used fibers, according to their manufacturers, are presented in Table 1.

2.3. Mixing procedure

To evaluate the effects of the fibers on the mechanical properties of the composite, eight different mixtures were produced. The first one associated with the matrix without fibers and three mixtures with steel fiber volume fractions of 0.50% (40 kg/m^3), 1.00% (80 kg/m^3) and 2.00% (160 kg/m^3) named, respectively, as C0.50%SF, C1.00%SF and C2.00%SF. The same fiber volume fractions were used both for SF1 and SF2. Moreover, other three mixtures were tested with polypropylene fiber volume fractions of 0.33% (3 kg/m^3), 0.66% (6 kg/m^3) and 1.10% (10 kg/m^3) named as C0.33%PPF, C0.66%PPF and C1.10%PPF. Finally, one final mixture was produced with the aim to verify the mechanical behavior of a hybrid fiber reinforced SCC with 0.50% (40 kg/m^3) of SF1 and 0.66% (6 kg/m^3) of PPF referred to as C0.50%H. The amount of water, sand, cement and the other supplies for the eight mixtures is presented at Tables 2 and 3. For pullout tests, the matrix composition was produced without the total amount of coarse aggregate.

The mixing procedure was conducted through five main stages. First, all the aggregates (sands S1, S2 and coarse aggregate) were mixed together with 70% of the water for 1 min with the help of a concrete mixer (previously wet). Soon after, all additives (silica