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Flexural behavior of hybrid steel fiber reinforced self-consolidating concretes

Comportamento mecânico à flexão de concretos autoadensáveis reforçados com fibras híbridas de aço

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Abstract

The simultaneous use of different types of fibers as reinforcement in concrete, mortar or pastes, can avoid the propagation and widening of cracks at different stages of their load-deflection or stress-strain behavior. The purpose of this article is to evaluate the flexural behavior in the material and structural scale of self-compacting concretes reinforced with meso and macro steel fibers. Two tests were used to mechanically characterize the concretes reinforced with volume fractions of 1 and 1.5% hybrid steel fibers: four point bending tests (material scale) and round panel tests (structural scale). The results indicated that hybridization of fiber reinforcement raised the serviceability limit state of concrete, contributing to increased toughness and load bearing capacity for small levels of displacement and crack openings. Such benefits were more evident in the structural tests considering the degree of hyperstaticity and multiple cracking potential of the panels. In the descending branch of the load-displacement curves, where macro-cracks were predominant, macro-fibers were more efficient in increasing the overall capacity for energy absorption of the composites.

Keywords: Self-consolidating concrete, hybrid steel fibers, round panel test, multiple cracking.

Resumo

O uso simultâneo de diferentes tipos de fibras como reforço em concretos, pastas ou argamassas, está diretamente associado ao combate da propagação de fissuras em diferentes estágios do seu comportamento carga-deflexão ou tensão-deformação. O objetivo do presente artigo é avaliar o comportamento à flexão, no nível material e estrutural, de concretos autoadensáveis reforçados com meso e macrofibras de aço. Dois ensaios foram utilizados, visando a caracterizar, mecanicamente, os concretos reforçados com frações volumétricas de 1 e 1,5% de fibras híbridas de aço: resistência à flexão em quatro pontos (nível material) e resistência à flexão em painéis circulares de concreto (nível estrutural). Os resultados obtidos indicaram que a hibridização do reforço fibroso elevou o estado-limite de utilização dos concretos, contribuindo para o aumento da tenacidade e da capacidade de carga para pequenos níveis de deslocamento e aberturas de fissura. Tais benefícios se mostraram mais evidentes nos ensaios estruturais, tendo em vista o grau de hiperestaticidade e o potencial de múltipla fissuração dos painéis. No ramo descendente das curvas carga-deslocamento, quando macrofissuras eram predominantes, as macrofibras mostraram-se mais eficientes, aumentando a capacidade global de absorção de energia dos compósitos.

Palavras-chave: Concreto autoadensável, fibras híbridas de aço, painéis de concreto, múltiplas-fissuras.

1. Introduction

The self-consolidating concrete (SCC) has as its main characteristics a high fluidity and cohesiveness, being able to overcome obstacles within the forms and fill them exclusively through its own weight (Ozawa et al., 1989). The addition of steel fibers to SCC can provide, among other advantages, crack control, increase in post-crack strength, fatigue, impact and abrasion, as well as substantially increase in the material toughness and ductility. Such improvements are dependent, however, on the type, volume fraction, geometric characteristics and spatial arrangement of used fibers (Bentur & Mindess, 2007). The hybridization of fiber reinforcement

can further improve the mechanical behavior of composites by controlling the propagation of cracks at different stages of deformation (Sukontasukkul, et al., 2002, Rambo, 2012).

The production of self-consolidating concretes containing hybrid reinforcement can thus take advantage of the properties of each individual fiber (Sukontasukkul, et al., 2002) improving not only its flexural and tensile strength, as well as the composite fracture mechanisms (Destreé & Mandl, 2008).

One of the most common ways to evaluate the mechanical behavior of fiber reinforced concrete is to perform bending tests under a three or

four point configuration, which are usually performed in small prisms. However, there are questions about the applicability of these results for use in structural design due to the typical result dispersion observed and the differences between the cracking mechanisms in tests on the material and structural levels (Bernard, 2004; Destreé & Mandl, 2008; Di Prisco et al., 2011; Minelli & Plizzari, 2007).

In this context, this work aims to evaluate the flexural behavior at the material and structural scale of self-compacting concretes reinforced with meso and macro steel fibers (HSFRSCC) in volume fractions of 1 and 1.5%.

2. Materials and methods

Mix design

The cementitious materials used in the production of self-compacting concretes were the Brazilian cement type CPIII-40, fly ash and silica fume. In order to avoid bleeding, segregation and maintain the cohesiveness of the concrete produced, it was necessary to use a viscosity modifier (Rheomac UW 410) together with the remaining constituents of the concrete. The used aggregates were crushed stone ($D_{max}=9.5$ mm) and a medium sand ($D_{max}=4.0$ mm). To increase the packaging mix, a ground quartz known as silica fillers 325 was also used.

The tensile strength of the fibers used as reinforcement in concrete, SF1 and SF2 (Figure 1), was, respectively, 1100 MPa and 1150MPa. The production of self-compacting concretes also included the use of a third generation superplasticizer (Glenium® 51).

Five mixtures of self consolidating concrete have been produced, one control mixture without fibers and four mixtures reinforced with steel fibers (Table 1). The characters used in the nomenclature of the produced mixtures indicate the volumetric fiber content (v_f) used in the

mix design and the occurrence, or not, of hybridization of fiber reinforcement. All the mixtures have been produced with 360kg/m^3 of cement and a water/cement ratio of 0.5. When using fiber reinforcement, the dosage was performed with the replacement of coarse aggregate from concrete by the corresponding fiber volume. For each concrete mixture it was produced three prismatic and three circular panels, which were demolded at 48 hours and kept in a cure chamber (relative humidity: 100% and $23 \pm 1^\circ\text{C}$) until 28 days of age.

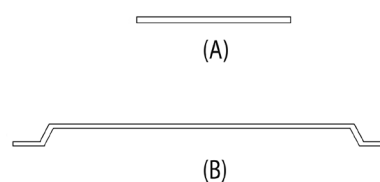


Figure 1

Steel fibers used in the self-compacting concretes production: (A) Straight fiber with 12mm length and 0.18mm diameter (SF1). (B) Hooked end fiber with 35mm length and 0.55mm diameter (SF2).

| Fiber type | C0 | C1.0%H | C1.0% | C1.5%H | C1.5% |
|------------|----|--------|-------|--------|-------|
| SF1 | 0% | 0.5% | 0% | 0.5% | 0% |
| SF2 | 0% | 0.5% | 1.0% | 1.0% | 1.5% |

Table 1

Reinforcement ratio used in self-compacting concretes production.

Both material and structural tests were performed in a Shimadzu servo-controlled testing machine with a capacity of 1000 kN. For each produced mixture six samples were produced and tested: three prisms and three panels. All specimens were tested at 28 days of age.

The flexural tests (material scale) were carried out on prismatic samples with a rectangular section ($100 \times 100 \times 400$ mm), and a span to height ratio equal to three, according to NBR 12 142 (1991) (Figure 2 A). The displacement rate used was set to 0.5 mm/min.

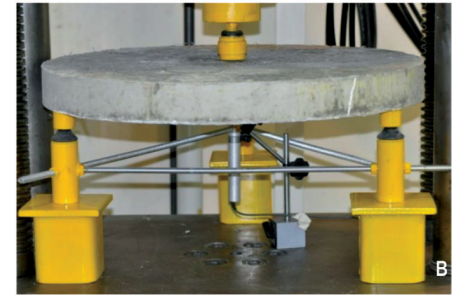
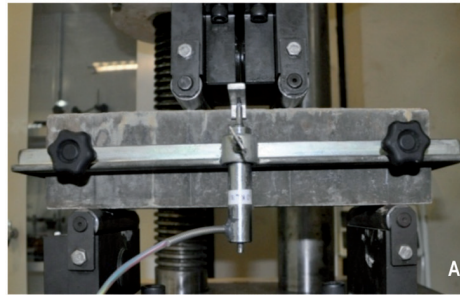
The round panel tests (structural test), adapted from ASTM C1550 was determined using specimens with 750 mm of diameter and 75 mm of thickness (Figure 2 B). The load was applied to the panels using a rigid steel cylinder (50 mm of diameter) in the top surface at a dis-

placement rate of 0.5 mm/min. The panels were supported by three pivots (40mm of diameter), 120 degrees apart radially

and positioned 25mm from the edge of the panel. The panel deflection (40 mm) was measured using a LVDT positioned

in the center of the bottom surface of the specimens.

Figure 2
Set-ups of the flexural tests:
(A) Four point bending tests (material scale)
(B) round panel test (structural scale).



3. Results and discussion

Through the typical curves of four point bending test shown in Figure 3, it can be seen that both hybrid composites (C1.0%H and C1.5H%) at displacement levels close to the first crack displacement, showed higher load bearing capacity and toughness compared to the non-hybrid systems (C1.0% and C1.5%). This is attributed to the mobilization of SF1 fibers (12mm) with shorter diameter and length which help in mitigating the propagation of microcracks in the concrete, thus increasing the load bearing capacity of hybrid composites. For a deflection of 0.049 mm (Figure 3B), for example, it is reported

the collapse of the control mixture, with a rupture load of 25.27 kN (Table 2). The fiber reinforced concretes, however, maintains its load capacity, which is more significant in hybrid composites (C1.0%H and C1.5%H). The increase in load in the fiber reinforced concretes C1.0%H, C1.0%, C1.5%H and C1.5% compared to the control mixture, for the displacement of 0.049mm were respectively 22.51%, 3.52%, 24.65% and 22.67%. The non-hybrid mixtures also exhibited displacement values at the first crack (δ_{cr}) and ultimate displacement (δ_u) smaller than the composites reinforced with only

hooked end steel fibers.

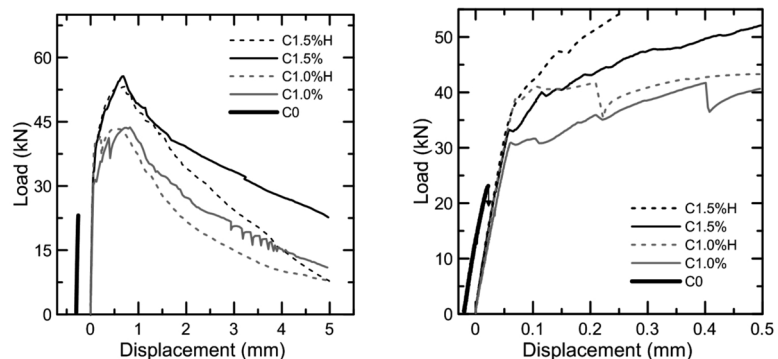
As seen in Figure 3A the post-peak branch of hybrid composites showed a softening phase more pronounced in comparison to non-hybrid reinforced mixtures. This fact is due to the presence of a larger amount of hooked end fibers in the non-hybrid reinforced mixtures which ensure a higher toughness to the material for large deflections where the macro fibers are more efficient.

The round panel test results are shown in Figure 4A and Table 3. In the round panel tests, as evidenced in four point bending test, hybrid composites

Tabela 2
Mechanical results for four point bending tests.

| Mixtures | First crack values | | | Post-cracking values | | |
|----------|--------------------|---------------------|--------------------|----------------------|------------------|-----------------|
| | P_{cr} (kN) | σ_{cr} (MPa) | δ_{cr} (mm) | P_u (kN) | σ_u (MPa) | δ_u (mm) |
| C0 | 25.27 | 7.58 | 0.049 | - | - | - |
| | (2.51) | (0.75) | (0.007) | | | |
| C1.0% | 29.60 | 8.88 | 0.059 | 43.08 | 12.93 | 0.83 |
| | (2.78) | (0.84) | (0.002) | (11.06) | (3.32) | (0.16) |
| C1.0%H | 36.02 | 10.70 | 0.053 | 44.36 | 13.30 | 0.53 |
| | (3.31) | (1.01) | (0.007) | (2.97) | (0.89) | (0.22) |
| C1.5% | 34.95 | 10.48 | 0.056 | 58.89 | 17.66 | 0.72 |
| | (2.82) | (0.84) | (0.007) | (4.49) | (1.34) | (0.07) |
| C1.5%H | 31.42 | 9.42 | 0.049 | 51.46 | 15.43 | 0.67 |
| | (3.29) | (0.98) | (0.007) | (13.35) | (4.00) | (0.05) |

Figure 3
Influence of fiber reinforcement on the bending behavior of concrete prisms:
(A) overall flexural response.
(B) zoom in load vs. displacement curves.



(C1.0%H and C1.5%H) showed higher load bearing capacity in comparison to non-hybrid composites (C1.0% and C1.5%) for small displacements levels (Figure 4B). The increase in toughness and in load was extended, however, for higher levels of displacement, even after the peak load due to the hyperstaticity of the system.

The load corresponding to the first crack observed for the hybrid composites (C1.0%H and C1.5%H) was higher than that observed for the non-hybrid composites with the same reinforcement ratio (C1.0% and C1.5%) and for the control

mix (C0). The addition of fibers provided to the composites first crack displacements 30% to 102% higher than that of the control mixture.

Figure 5 shows the energy absorption capacity of the produced composites subjected to the flexural tests performed in this study. While addressing the same concrete, the curves of Figures 5 (A) and (B) show a significant difference, since represent tests with different configurations. As seen in Figure 6, multiple cracking is enhanced in the round panel test. This behavior shows in a more clear way the superiority of the toughness of hybrid fiber

reinforced concrete in the structural test (Figure 5B). For the concrete C1.5%H, the increase in toughness were so expressive that, for the entire displacement, toughness values were greater than those obtained for the non-hybrid concrete C1.5%. The concrete C1.0%H maintained toughness values higher than the non-hybrid system C1.0% up to 22mm.

Differently from the structural tests in which several cracks were observed (Figure 6B) the tests with prismatic samples showed the formation of a macro-crack with ramifications of micro-cracks on its periphery (Figure 6A).

| Mixtures | First crack values | | Post-cracking values | |
|----------|--------------------|--------------------|----------------------|-----------------|
| | P_{cr} (kN) | δ_{cr} (mm) | P_u (kN) | δ_u (mm) |
| C0 | 30.71 | 0.72 | - | - |
| | (3.72) | (0.05) | | |
| C1.0% | 29.76 | 0.95 | 39.66 | 3.42 |
| | (2.66) | (0.08) | | |
| C1.0%H | 41.16 | 1.46 | 45.50 | 3.26 |
| | (0.61) | (0.25) | | |
| C1.5% | 40.25 | 1.23 | 53.82 | 5.30 |
| | (0.58) | (0.16) | | |
| C1.5%H | 46.36 | 1.16 | 63.38 | 5.23 |
| | (2.62) | (0.51) | | |

Table 3
Mechanical results for round panel tests.

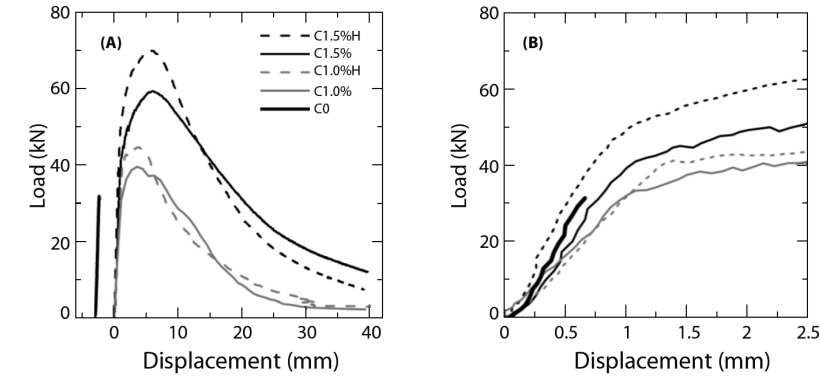


Figure 4
Influence of fiber reinforcement on the round panel test results: (A) overall response and (B) zoom in load vs. displacement curves.

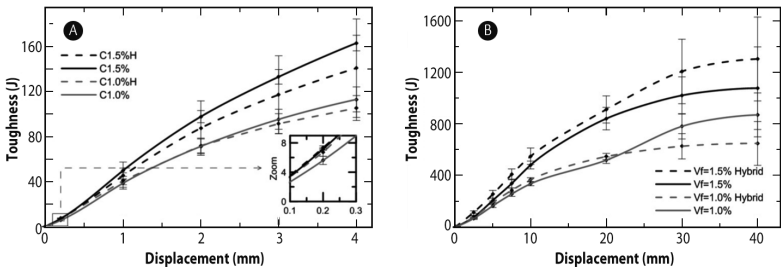


Figure 5
Effect of the reinforcement ratio on the toughness values for: (A) prisms and (B) round panels.

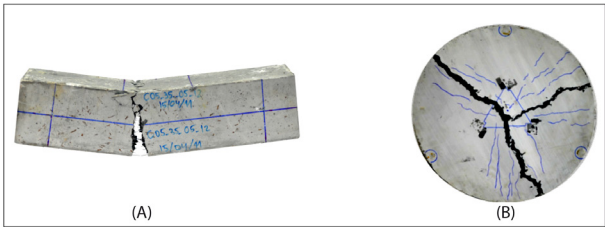


Figure 6
Typical cracking patterns for (A) prisms and (B) round panels after being loaded under flexural loading.

4. Conclusions

The present paper presented an experimental investigation on the use of hybrid steel fibers for the reinforcement of concrete. Flexural tests in the materials and structural levels were performed and the following conclusions can be drawn:

- The addition of steel fibers to the self-consolidating concretes produced significant increases in flexural strength and toughness of the material, and this increase was more pronounced for the highest reinforcement ratio used (1.5%).
- The combined use of the meso and macro reinforcement for the same reinforcement ratios in the mixture

increased the serviceability limit state of the studied concretes, raising the toughness and increasing the load bearing capacity of the composites at small levels of displacement. These benefits were noticed in both flexural tests and reinforcement ratios (1% and 1.5%).

- All fiber reinforced concretes showed a deflection hardening in four point bending tests for both the reinforcement ratios. The hybridization of fiber reinforcement was more effective in increasing the toughness of the prisms at central displacements up to 0.5 mm. The fracture mode of prisms occurred through the formation of

a macro-crack with ramifications of micro-cracks in their periphery.

- The improvements provided by the hybridization were more significant in tests performed on round panels, due to the hyperasticity of the structural test. The test results exhibited a cracking pattern characterized by the formation of three major yield lines and several microcracks. The hybridization of the fiber reinforcement has been able to limit the initiation and propagation of micro cracks, increasing the load of the first crack and the peak load of the concrete in the two reinforcement ratios.

5. Acknowledgements

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