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Experimental analysis of load capacity in beams with steel fiber reinforcement on the compression face

Análise experimental da capacidade portante em vigas com reforço de fibras de aço na face tracionada



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Abstract

The use of steel fibers in the concrete is mainly aimed at increasing the post-peak toughness, due to the adhesion of the fibers to the cementitious matrix. However, there are several typologies of steel fibers, and the main differences are in the form (relation between length and diameter), fiber geometry, and the characterization between macrofibers and microfibers, which generally serve to reduce macrocracking and microcracking, respectively. In this context, this work evaluated the use of microfibers (20 kg/m³ or volume equal to 0.26% (V_f) of concrete volume), macrofibers (20 kg/m³ or V_f = 0.26%) and hybridization (10 kg/m³) + macrofibers (10 kg/m³) inserted in a high strength concrete (f_c = 80 MPa). Two types of steel fibers were used: macrofibers with a diameter of 0.75 mm and a length of 60 mm (a form factor of 80); and microfibers with a diameter of 200 µm and a length of 13 mm (a form factor of 65). The fibers were used in concrete to act as a reinforcement on the compression face of reinforced beams (12×20×160cm), and the mechanical characteristics of the concretes were analyzed: (i) flexural strength in prismatic specimens (10×10×35 cm), (ii) compressive strength in cylindrical specimens (20×Ø10 cm) and (iii) modulus of elasticity in cylindrical specimens (20×Ø10 cm). Analysis of the results showed that compressive strength increased by approximately 8% for all the compositions with fibers compared with concrete without fibers. Similar behavior was verified for the modulus of elasticity. In the prismatic specimens (10×10×35 cm) an increase in toughness was observed, with the macrofibers performing better. In beams measuring 12×20×160 cm, an increase in bearing capacity was verified regarding cracking time and plastic rotation, with the best result also obtained using macrofibers. Overall, it can be concluded that the application of reinforcement with steel fibers in the compression face of beams was efficient, even though it did not present a significant increase in compressive strength, a fact that could be correlated with the reduced volume of fibers used.

Keywords: reinforcement, high-performance concrete, steel fibers, microfibers, macrofibers.

Resumo

A utilização de fibras de aço no concreto visa aumentar principalmente a tenacidade, em função da aderência das fibras à matriz cimentícia. Entretanto como existem diversas tipologias de fibras de aço, as principais diferenças estão no fator de forma (relação entre comprimento e diâmetro), na geometria das fibras, e, na caracterização entre macrofibras e microfibras, que de modo geral servem para reduzir a macrofissuração e microfissuração, respectivamente. Dentro deste contexto, este trabalho avaliou a utilização de microfibras (20 kg/m³ ou volume igual a 0,26% (V_f) do volume de concreto), macrofibras (20 kg/m³ ou V_f = 0,26%) e a hibridização entre os dois tipos (microfibras (10 kg/m³) + macrofibras (10 kg/m³)) inseridas em um concreto de alta resistência (f_c = 80 MPa). Foram utilizados dois tipos de fibras de aço: as macrofibras com diâmetro de 0,75 mm e comprimento de 60 mm (fator de forma igual a 80, com gancho na extremidade); e microfibras com diâmetro de 200 µm e comprimento de 13 mm (fator de forma igual a 65). As fibras foram utilizadas no concreto para atuar como reforço na face tracionada de vigas armadas (12×20×160cm), e foram analisadas as características mecânicas dos concretos: (i) resistência à flexão em corpos de prova prismáticos (10×10×35 cm), (ii) resistência à compressão em corpos de prova cilíndricos (20×Ø10 cm) e (iii) módulo de elasticidade em corpos de prova cilíndricos (20×Ø10 cm). Análise dos resultados mostraram que na resistência à compressão houve um acréscimo de aproximadamente 8% para todas as composições com fibras em relação ao concreto sem fibras. Quanto ao módulo de elasticidade foi verificado comportamento semelhante. Nos corpos de prova prismáticos (10×10×35 cm) ocorreu aumento na tenacidade, sendo que as macrofibras tiveram melhor desempenho. Nas vigas de 12×20×160cm, ocorreu aumento da capacidade portante, quanto ao momento de fissuração e rotação plástica, sendo que o melhor resultado também foi obtido com as macrofibras. De modo geral, pode-se concluir que a aplicação do reforço com fibras de aço na face tracionada das vigas foi eficiente, embora não apresentou aumento significativo na resistência à compressão, fato que pode estar correlacionado ao reduzido volume de fibras utilizado.

Palavras-chave: reforço, concreto de alto desempenho, fibras de aço, microfibra, macrofibras.

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1. Introduction

When they are well designed and executed, reinforced concrete structures show great durability, yet they require preventive and corrective maintenance to ensure their functionality. In the construction industry, reinforcements are solutions used to avoid problems and to increase the carrying capacity of structural elements, which for numerous reasons no longer meet the requirements for which they were designed [1].

One of the ways to reinforce and improve the performance of concrete structures is the addition of fibers, which generally promote a gain in toughness, an increase in static tensile strength, dynamic fatigue and impact, traction, a reduction in demand deformations, and control of the number and speed of propagation of cracks. Together these effects contribute to the increased durability of the structure, since the presence of the fibers assists in reducing crack apertures, while also controlling and delaying their propagation, allowing for the stabilized occurrence of cracks.

Over time and through technological advances, different types of fibers have been investigated and developed, imbued with characteristics that made them more suitable for incorporation into concrete, which has allowed the development of a generation of composites with increasingly better properties, and with greatly-improved performance compared with traditional concrete, in certain respects. In the most recent literature, for example, we find references to such terms as macrofibers and microfibers, used to differentiate larger and more resistant fibers, which act initially in post-cracking of the matrix, from smaller, more disseminated fibers, which act primarily in cracking delay [2]. An example of the contribution of the fibers in the flexural dimensioning of a reinforced concrete beam [3] showed a reduction in the area of steel area of 11, 17 and 21%, using fiber consumption of 20, 30 and 45 kg/m^3, when using Dramix RC 80/60 steel fibers.

This topic isboth relevant and current, since many structures have been built with increased demand for strength and durability, or subject to the most varied demands arising from exceptional support or loading conditions. This study proposed evaluating the performance of steel microfibers, together with macrofibers, used in reinforced concrete as structural reinforcement.

2. Fundamental aspects of fiber reinforced cement matrix composites

The purpose of reestablishing a reinforced concrete structure is to return it to its original strength or increase its load capacity. Reinforcement is the act of correcting a structural or functional deficiency that often focuses solely on reducing the rate of deterioration. Finally, it is expected that a renovated and/or reinforced structure should perform better than it did before the intervention [4].

Steel fibers were chosen, as in work developed by Quinino [5], because they are the most widely used cement matrix reinforcement, due to the numerous benefits and economic importance of this material. Fibers act as a mechanism of tension transfer across cracks, allowing the concrete to present greater deformations under peak load and greater post-cracking load capacity, i.e. the ductility and residual resistance to traction of the material is increased [6]. According to Figueiredo [7], the random distribution of fibers in the material reinforces the structural element overall, in contrast to that which occurs with conventional reinforcements in reinforced concrete. It is important to emphasize that the use of the fibers as reinforcement is generally not considered to be sufficiently efficient to replace conventional reinforcement. In addition, it is imperative that aspects like matrix-fiber compatibility and adhesion are considered, to obtain the desired result.

For Martineau and Agopyan [8], fiber placement modifies the cracking process, acting as a transfer mechanism of forces across cracks, and ensuring minimal change in the load resistance capacity when these occur. Mehta and Monteiro [9] observed that even when fiber-reinforced concretes sustain deformations far superior to conventional concrete fracture deformation, they continue to withstand considerable loads, and the ultimate strength of the first crack depends heavily on matrix parameters and is influenced by the characteristics of the fiber. Doubts remain concerning the efficacy of fiber addition for improving ultimate strength; however, the consensus is that fibers improve the ductility of cementitious composites.

3. Experimental methodology

To begin, four groups were defined: i) reference concrete, without fibers (A); ii) concrete with macrofibers (B); iii) concrete with microfibers (C); and iv) concrete with micro and macrofibers (D). The following test specimens were produced for each group: two 12×20×160 cm reinforced concrete beams for 4-point bending tests; two cylindrical specimens (20×Ø10 cm) for resistance to axial compression and modulus of elasticity; and two 10×10×35 cm prismatic specimens to determine the flexural strength of the concrete.

Flexural reinforcement was dimensioned according to the criteria of NBR 6118 [10], considering a compressive strength for concrete of 80 MPa and CA-50 steel, adopting two 12.5 mm diameter bars for main reinforcement to resist flexural deformation. Stirrup spacing was 10.0 cm and 12.5 cm and the diameter was 5.0 mm. In addition , 2.5 cm spacers were used to ensure reinforcement cover.

Macrofibers measuring 600×0.75 mm (form factor of 80, trade name RC 80/60 BN, manufacturer ArcelorMittal/Dramix®) were used in groups B and D, and microfibers measuring 13 mm×200 μm (form factor of 65, trade name OL 13/.20, manufacturer ArcelorMittal/Dramix®) were used in groups C and D.

Concreting was done in two phases. In the first phase, only some of the beams (12×20×160 cm) from groups B, C, and D were concreted. The beams of group A (reference) were concreted in their entirety because they had no fiber reinforcement. The prismatic (10×10×35 cm) and the cylindrical specimens (20 × Ø10 cm) without fibers also were concreted together with this first phase. The concrete mix proportions were 1:2.3:2.7 cement:sand:gravel, with a water/cement (w/c) ratio of 0.4. The cement used was type CP-IV. The concrete was mixed in a 400 L concrete mixer. The consistency of the concrete was verified by the abatement test and was 11 cm. All the beams were concreted simultaneously with concrete made in the laboratory and densified with immersion vibrators and a vibrating table. The beams were concreted up to a height of 13.75 cm. This limit was controlled during the first concreting phase, by an internal mark inside the form, such that reinforcement used to resist flexural deformation in groups B, C and D was exposed. The reinforcement dimensions in groups B, C and D were determined to be twice that of the reinforcement cover plus the diameter of the reinforcement bar (2.5+2.5+1.25=6.25 cm). This dimension was maintained during the second phase of concreting (groups B, C, and D), and only the type of fiber addition varied.

The second phase of concreting of the beams (12×20×160 cm) was done 24 h after the end of the first phase. The reconstitution of the tensioned face of the beams of groups B, C and D included the presence of fibers in 6.25 cm thickness defined above. The surface was not previously prepared since the stirrups served as the point of bonding for the new concrete. In the groups that received fiber reinforcement, the amount added was 20 kg/m^3 or V_f = 0.26% in relation to the concrete volume. The prismatic (10×10×35 cm) and cylindrical specimens (20×Ø10 cm) with fiber additions were concreted together with this second phase.

Twenty-four hours after concreting, the cylindrical specimens were demolded and placed in submerged curing until 28 days of age, to test axial compressive strength [11] and modulus of elasticity [12]. The prismatic specimens and reinforced concrete beams were demolded 14 days after the final phase of concreting. They were painted to improve crack analysis. The age of rupture for all beams was 28 days after the second phase of concreting. The beams (12×20×160 cm) were identified as follows: group A, beams A1 and A2; group B, beams B1 and B2; group C, beams C1 and C2; and group D, beams D1 and D2. Beams A1, B1, C1 and D1 refer to beams instrumented with strain gauges connected to the steel and concrete, while beams A2, B2, C2 and D2 had no sensors. The prismatic specimens (10×10×35 cm) were identified as Ap, Bp, Cp, and Dp, according to each group.

All the beams were submitted to the 4-point bending test. The loads were applied from top to bottom over a metal profile (Profile I - 10×25.5 cm) which transferred the load to the beams at two point loads precisely dividing the theoretical span of the beam into thirds. The beams were positioned under a metal reaction portal and the load was applied by an electrical hydraulic cylinder, with 500 kN capacity. The load values were recorded by a load cell arranged between the hydraulic cylinder and the distribution beam (Profile I - 10×25.5 cm). The vertical displacements at 3 points (LVDT 1, LVDT 2 (center), LVDT 3) along the length of the beam were evaluated using linear variable differential transformers (LVDT). Deformations were monitored using strain gauges bonded to materials at strategic deformation points: concrete and flexural reinforcement (Figure 1). The equipment was connected to a QuantumX® data acquisition system interface with HBM® catman®Easy software.

Verifications were made to analyze the behavior of each group at different time-points during load application: when the maximum displacement allowed (L/250) was reached, according to the norms, and at rupture. First, the load required to reach the maximum displacement allowed (L/250) was verified, considering L=150 cm as the theoretical span of the beams, which resulted in a displacement of 6.0 mm. Lastly, the load and displacement that led the beam rupturing were verified. The experimental elastic line of the beam was determined using the bending test results - load curves *vs* vertical displacements - obtained with the LVDTs positioned along the beam length. Deformation values provide a better understanding of the limits of the deformation stages regarding bending moment of cracking and bending moment of plastification. A model was developed that characterized the phenomenon of change in deformation stages of a fiber-reinforced beam by observing the relationship between the bending moment and the curvature formed in the cross-section of the beam. Finally, the development of cracks and the form of rupture were mapped.

4. Results and discussion

4.1 Reinforced concrete beams (12 × 20 × 160cm)

4.1.1 Loading and displacement at rupture

The loads and the displacements verified at the rupture of the

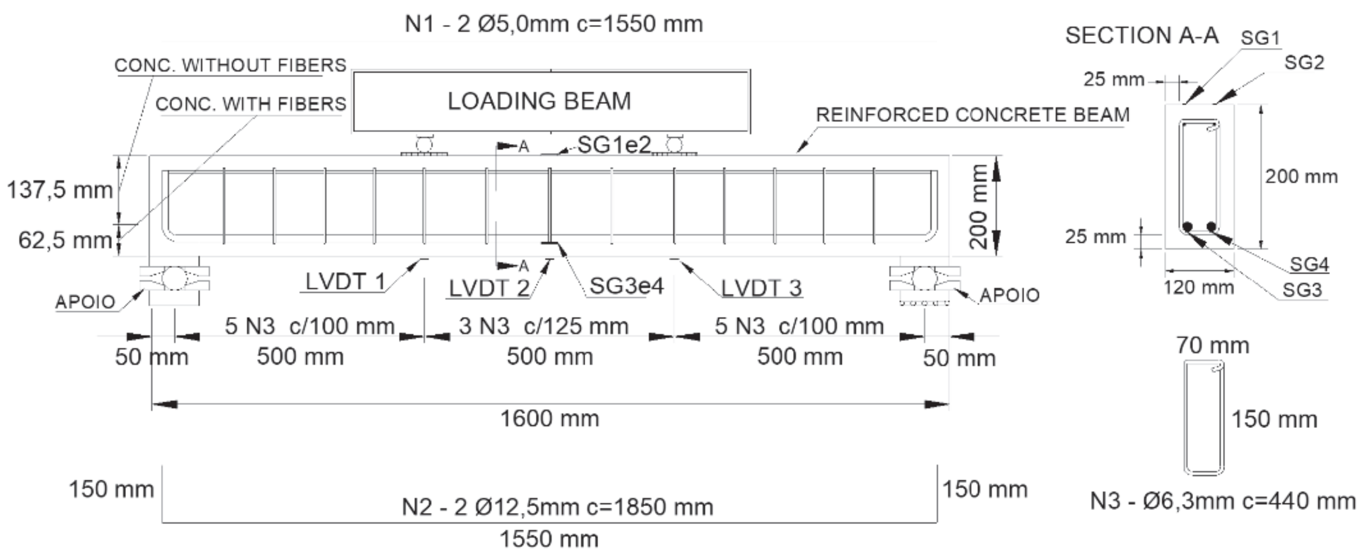

Figure 1
Positions of the LVDTs and SGs along the beam

Table 1
Results of loading and displacement of the beams at rupture (12 × 20 × 160 cm)

Beams	Load (kN)	Displacement left (mm)	Displacement middle (mm)	Displacement right (mm)	Ductility factors
GROUP A – No fibers					
A1	84.22	13.77	16.91	15.48	1.98
A2	85.60	13.62	15.77	12.61	1.92
Mean (D.P)	84.91 (0.98)	13.69 (0.11)	16.34 (0.81)	14.05 (2.03)	1.95 (0.04)
GROUP B – Macrofibers					
B1	89.09	14.33	18.30	16.07	2.00
B2	86.67	9.62	12.72	10.68	1.55
Mean (D.P)	87.88 (1.71)	11.98 (3.34)	15.51 (3.95)	13.38 (3.81)	1.78 (0.32)
GROUP C – Microfibers					
C1	88.88	11.20	14.39	11.67	1.77
C2	87.70	14.64	12.24	12.07	1.65
Mean (D.P)	88.29 (0.83)	12.92 (2.43)	13.31 (1.52)	11.87 (0.28)	1.71 (0.08)
GROUP D – Macrofibers + Microfibers					
D1	86.99	13.90	18.71	13.91	2.11
D2	85.16	11.37	14.21	11.74	1.85
Mean (D.P)	86.07 (1.29)	12.63 (1.79)	16.46 (3.18)	12.83 (1.54)	1.98 (0.18)

beams and the ductility factors are shown in Table 1. The behavior of the percentages that justify the increase in bearing capacity between the groups was different in displacement up to rupture. To achieve rupture in the beams from group B, the load required was 3.5% higher than for group A, while group C required 4.0% higher loads, and group D required 1.4% higher loads. Regarding displacements, these were very similar between all the groups. When analyzing the average values of loads at rupture (Figure 2), an increase was observed for beams B and C with macrofiber and microfiber additions, respectively. Despite the lower form factor, microfibers showed a tendency to increase, which could be associated with larger amounts of fiber, and their efficiency at reinforcing concrete during microcracking provoked before rupture. When using macrofibers + microfibers (group D), a reduction in rupture load of the beam was observed, but it remained better than the reference beams (group A). Comparison between this result and beams with either macro

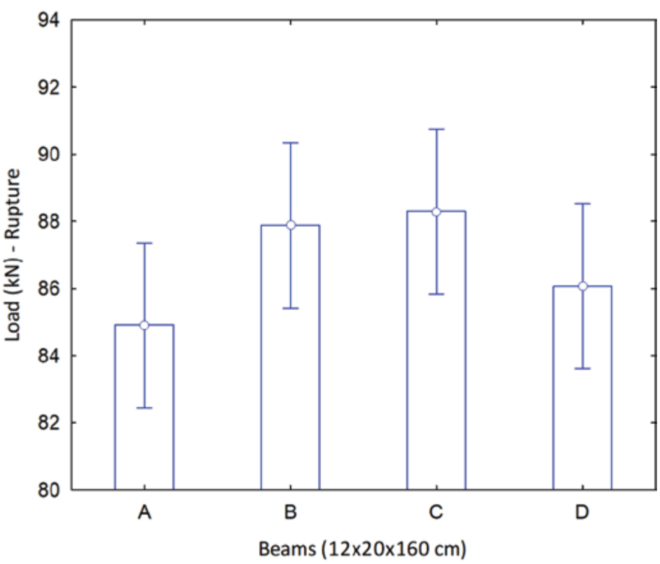

Figure 2
Analysis of load results at rupture – beams (12 × 20 × 160 cm)

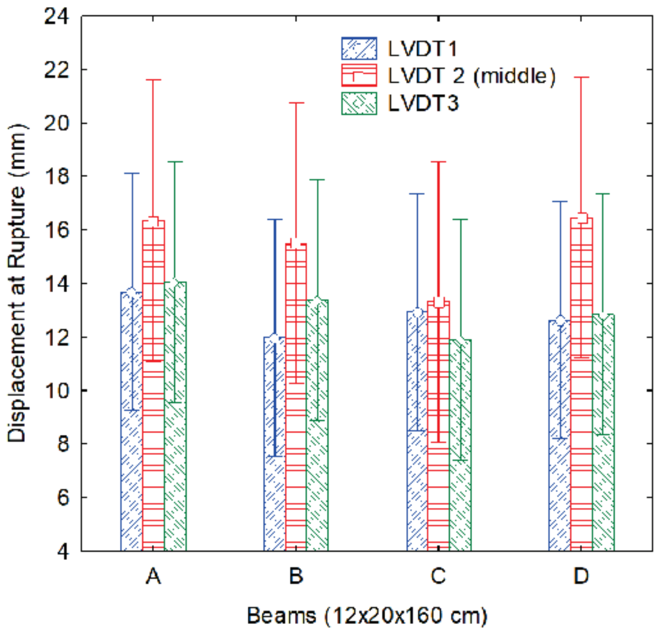

Figure 3
Analysis of the results of displacement at rupture in beams (12 × 20 × 160 cm)

or microfibers suggests the most plausible explanation is a loss of strength due to the lower compactness of the composite cementitious matrix with both fibers. Regarding displacement in the beams at rupture, group C showed that microfibers did not contribute to an increase in the final displacement before rupture. The ductility factor, obtained between the ratio of displacement at rupture and displacement at the moment of plastification, determined that group D showed better behavior than reference group A.

4.1.2 Load behavior *versus* displacement

Figure 4 presents the load versus displacement of all beams (12×20×160 cm). The behaviors between the groups were similar for the ultimate loads and the service loads (L/250). The beams of all groups exceeded the maximum displacement allowed according to current norms (L/250 = 6.0 mm) before coallapsing. All the beams broke by crushing concrete on the compressed face.

The sequence of images in Figure 5 illustrates the particularities of the form of rupture and cracks in the four groups of beams (12×20×160 cm). The reference group A (no fibers in the traction face) presented the largest number of visible cracks, which surpassed the middle third region. Groups B, C, and D were similar regarding the appearance of cracks concentrated in the middle third of the theoretical span of the beam, and the appearance of some shear cracks.

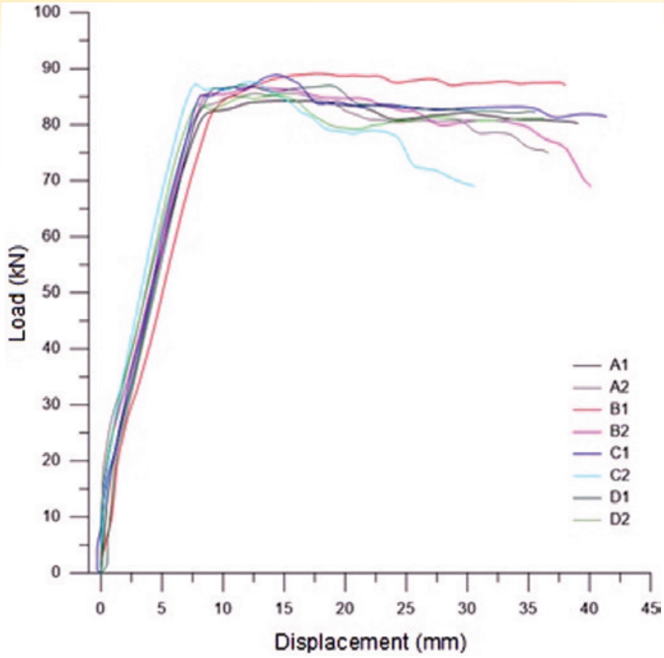

Figure 4
Load *versus* displacement behavior in beams (12 × 20 × 160 cm)

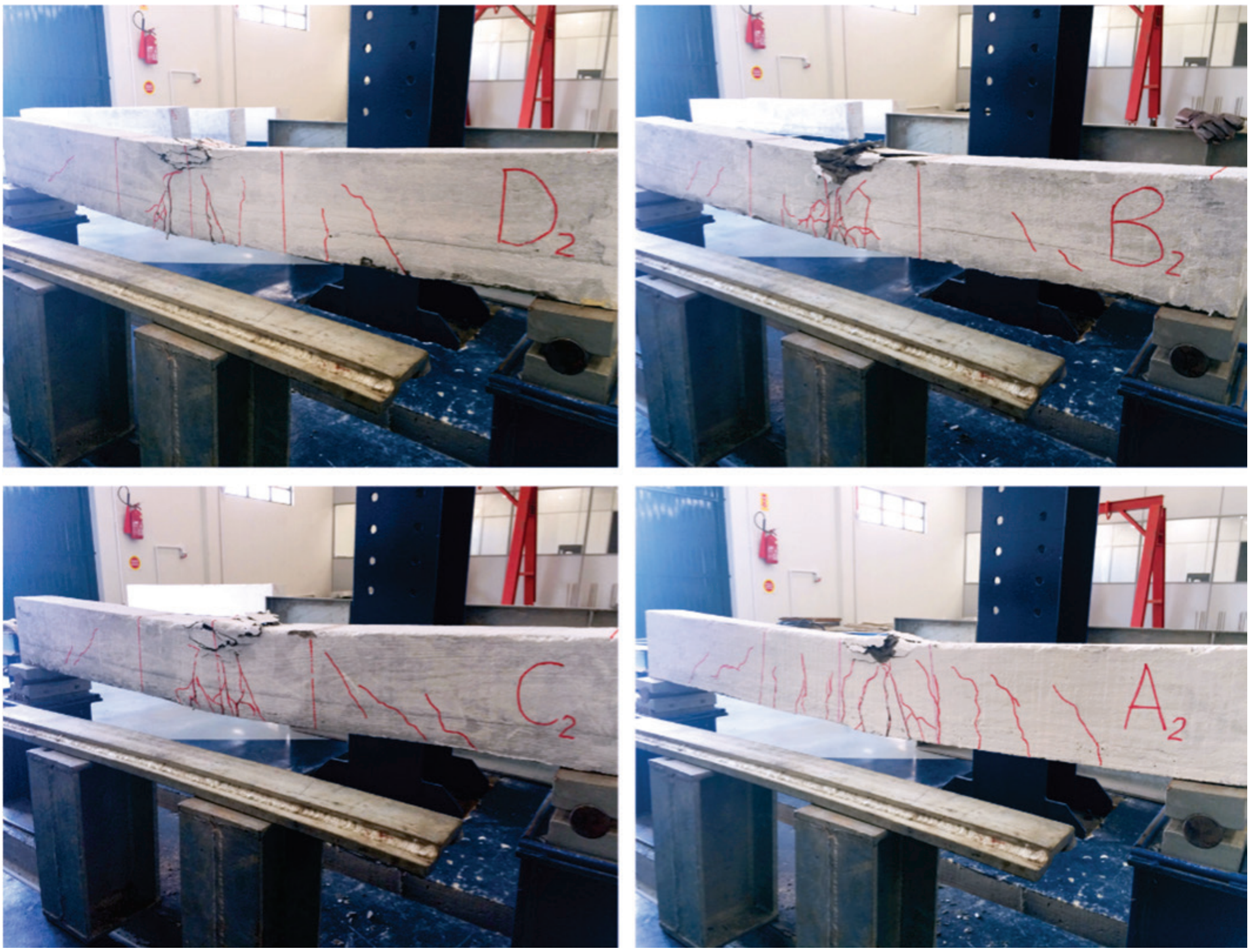

Figure 5
Form of rupture and cracks in beams (12 × 20 × 160 cm)

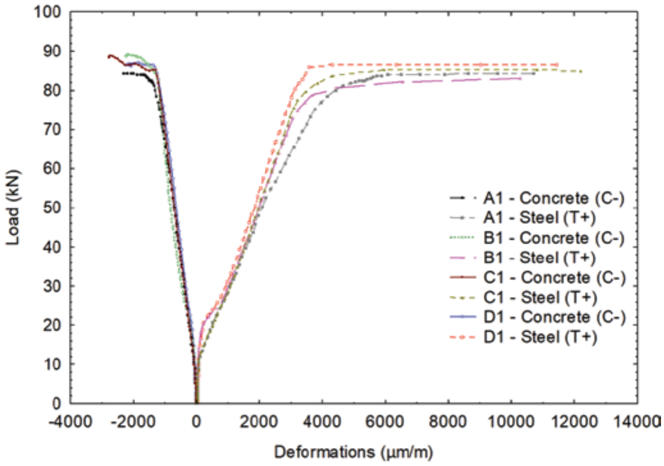

Figure 6
Specific deformations of steel and concrete in beams (12 × 20 × 160 cm)

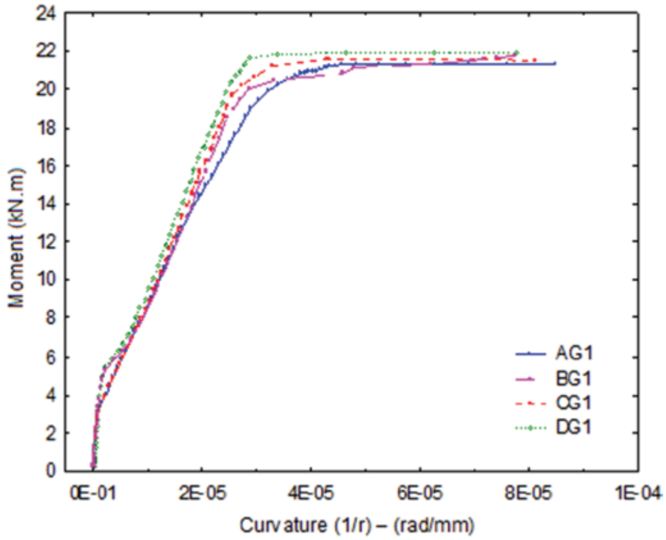

Figure 7
Bending moment-curvature diagram for beams (12 × 20 × 160 cm)

4.1.3 Analysis of specific deformations

Figure 6 shows specific deformations in the concrete in the uppermost compressed face and that of the steel in the lower, most tensioned face (steel bar, Ø12.5 mm), both located in the central cross section (Figure 1). Note that the final deformations in concrete and steel were similar between the groups, approximately 2200 µm/m for concretes and 11000 µm/m for steels. However, groups B and D presented a smaller steel deformation between loads of 10 kN and 20 kN, which contributed to increasing the period of cracking. When a loading value was set between 10 and 20 kN, the smallest deformation (steel) occurred in the beams with the micro and macrofibers, followed by beams only with microfibers, only with macrofibers and finally, the reference concrete. These results show the potential of using microfibers in conjunction with macrofibers to improve the structural behavior of the reinforcement, before and after the occurrence of cracks. Recent research has shown the beneficial effect of using hybrid fibers - macro and microfibers – to improve the resistance to deformation in multiple cracking states [13].

4.1.4 Analysis of the bending moment-curvature diagram

Table 2 presents the results of moments and curvatures and the differences in percentages regarding the reference beam, while Figure 7 shows the bending moment-curvature diagrams for beams A1, B1, C1 and D1. Group B (+ macrofibers) presented 6.5 times greater cracking time than group A (reference), followed by groups D and C. Regarding rotation, the results for cracking time-points (Mr) in group B were 19.6 times higher than group A (reference), followed by groups D and C. This behavior shows that fibers increased the time of cracking and plastic rotation, but the isolated addition of microfibers contributed the least. The geometry

Table 2
Results of the bending moments and curvatures of the beams (12 × 20 × 160 cm)

Moments						
Beams	Moment of cracking M_r (kN.m)	Difference	Moment of plastification M_y (kN.m)	Difference	Moment of rupture M_u (kN.m)	Difference
A	0.7	Ref.	20.6	Ref.	21.3	Ref.
B	5.4	+655.7%	20.5	-0.7%	22.6	+5.7%
C	2.8	+291.8%	19.1	-7.1%	22.5	+5.5%
D	4.5	+529.6%	21.7	+5.3%	22.0	+3.2%

Curvature in moments						
Beams	1/r (M_r)	Difference	1/r (M_y)	Difference	1/r (M_u)	Difference
A	1.15E-07	Ref.	3.57E-05	Ref.	7.65E-05	Ref.
B	2.37E-06	+1960.9%	3.32E-05	-7.1%	8.16E-05	+6.6%
C	7.95E-07	+592.2%	2.47E-05	-30.8%	8.85E-05	+15.7%
D	1.45E-06	+1161.2%	2.90E-05	-18.8%	7.95E-05	+3.9%

Table 3
Results of compressive strength and modulus of elasticity (20 × Ø10 cm)

Samples	f_c (MPa)	Difference	E_c (GPa)	Difference	Compositions
A1	81.8	–	54.2	Ref.	Concrete
A2	80.6	–	–	–	Concrete
Mean (D.P.)	81.2 (0.85)	Ref.	–	–	Concrete
Samples	**f_c (MPa)**	**Difference**	**E_c (GPa)**	**Difference**	**Compositions**
B1	86.3	–	57.3	+5.7%	Concrete + Macrofibers
B2	89.3	–	–	–	Concrete + Macrofibers
Mean (D.P.)	87.8 (2.12)	+8.1%	–	–	Concrete + Macrofibers
Samples	**f_c (MPa)**	**Difference**	**E_c (GPa)**	**Difference**	**Compositions**
C1	86.8	–	57.2	+5.5%	Concrete + Microfibers
C2	89.6	–	–	–	Concrete + Microfibers
Mean (D.P.)	88.2 (1.98)	+8.6%	–	–	Concrete + Microfibers
Samples	**f_c (MPa)**	**Difference**	**E_c (GPa)**	**Difference**	**Compositions**
D1	88.4	–	55.4	+2.2%	Concrete + Macrofibers + Microfibers
D2	88.3	–	–	–	Concrete + Macrofibers + Microfibers
Mean (D.P.)	88.4 (0.07)	+8.8%	–	–	Concrete + Macrofibers + Microfibers

of macrofibers, with their hooks and non-smooth surfaces, unlike microfibers, contribute to this property [13].

4.2 Mechanical properties of the concretes

4.2.1 Compressive strength (f_c) and modulus of elasticity (E_c)

To mechanically characterize the concrete, tests to determine compressive strength and modulus of elasticity were performed. For compressive strength, the maximum difference between the groups was 8.8%, and the concretes with fiber addition showed very similar results to each other, and were approximately 8% better than the reference concrete, without fibers (Table 3). According to Mehta and Monteiro [9], increasing the amount of steel fibers in concrete using contents less than 2% of volume exerts minimal influence on the compressive strength. However, for high strength concretes, an increase in compressive strength was verified for a concentration of 0.5% microfibers [14]. A study by Su et al. [14] used a maximum of 2.5% of two types of steel microfibers, with form factors of 50 (6×0.12 mm) and 125 (15×0.12 mm), and achieved compressive strengths of 114 MPa and 145 MPa, respectively. In this work, the form factor of the microfibers was 65 (13×0.2 mm), and a lower concentration of fibers was used. The increase resistance obtained was satisfactory, and was associated with greater resistance to the propagation of microcracks during loading.
Concerning the modulus of elasticity, the maximum difference between the groups was smaller, approximately 6% (Table 3), between the concrete with macrofibers and microfibers (groups B and C), than for the concrete without fibers. This difference may have been caused by the higher density of the concrete with fibers.

4.2.2 Flexural test – prismatic test bodies (10 × 10 × 35 cm)

Regarding load and displacement at rupture (Figures 8 and 9, respectively), groups C and D achieved higher loads for displacement at rupture; load was 13% higher in group C than in group A, with mean displacement of 0.27 mm, while group D showed a load increase of 8%, with mean displacement of 0.30 mm. Group B showed no increase in resistance in relation to group A. Again, a tendency for increased resistance to cracking, when using microfibers or microfibers plus macrofibers, was verified compared with the reference concrete. When using prismatic specimens, rather than reinforced concrete beams, this improvement was more evidently promoted by microfibers. Although the differences were small, fiber volume was also low (Vf = 0.26%). This low amount was used because the

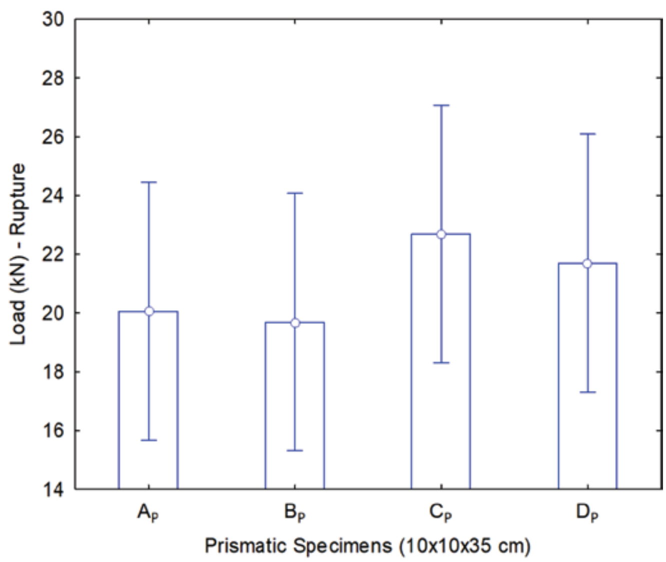

Figure 8
Analysis of the load results on the rupture in prismatic specimens (10 × 10 × 35 cm)

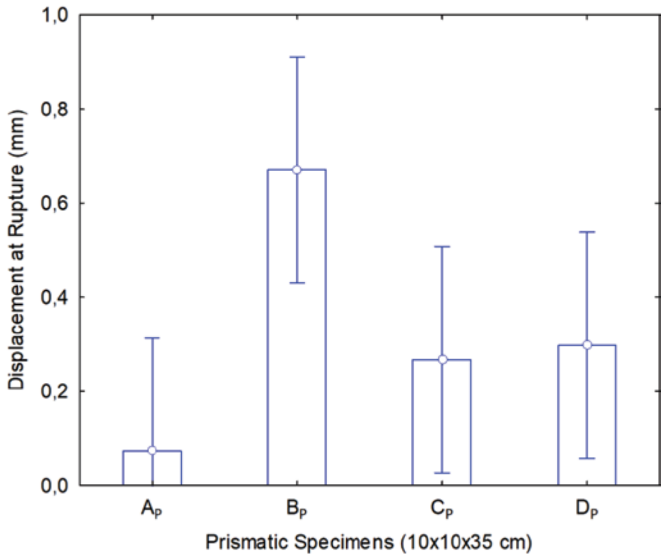

Figure 9
Analysis of the results of displacement at rupture in prismatic specimens (10 × 10 × 35 cm)

concrete being tested had reinforcement, thus maintaining the ease of application. Similar behavior was observed in displacement up to rupture among prismatic specimens with fibers, wherein specimens with microfibers presented the best results.

The results for toughness are presented in Figures 10 and 11 and show a higher index for group B (+ macrofibers). Groups C and D presented lower values than group B and higher than the group A. The higher toughness caused by macrofibers can be explained by its higher form factor and the consequently larger fiber-matrix contact area. In addition , macrofibers have hooks which improve the post-cracking resistance of the concrete when compared with smooth fibers [13].

5. Final considerations

Regarding the results obtained, the following conclusions can be drawn:

- Regarding the loading and displacement results (according to the L/250 norm and at rupture) obtained for reinforced concrete beams (12×20×160 cm) and concrete beams (10×10×35 cm), the results improved for all the groups containing steel fibers on the tensioned face;
- In the bending moment-curvature diagram, both fibers increased cracking time and plastic rotation;
- Cracks in the 10×10×35 cm beams indicate that group A presented fragile behavior, leading to abrupt rupture;
- Compressive strength results were higher (8%) for concretes with fiber additions;
- Macrofibers presented the best results compared with the remaining groups, for 12×20×160 cm and 10×10×35 cm beams;
- Comparing microfiber addition with macrofiber addition, microfibers improved the flexural strength and displacements of reinforced beams and improved compressive strength despite the low volume used. Macrofibers were better for increasing toughness or behavior after rupture;
- Use of a hybrid fiber addition - macrofibers + microfibers - did not present significantly differentiated behavior than when the fibers were used alone, but this combination did contribute to improvements in the region of microcracking and post-cracking, though to a less significant extent.

Finally, the method of applying reinforcement with steel fibers on the tensioned face of the beams proved to be effective, though it did not present increments of high resistance. The fibers contributed numerous results and were particularly efficient at combating cracking.

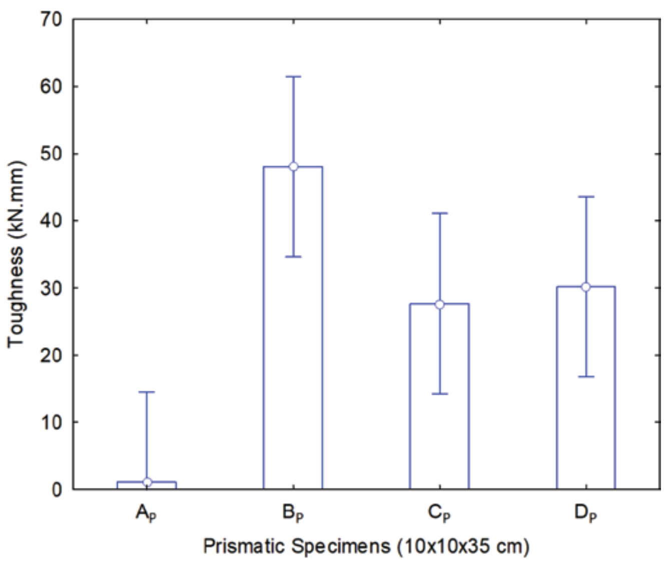

Figure 10
Analysis of toughness results in prismatic specimens (10 × 10 × 35 cm)

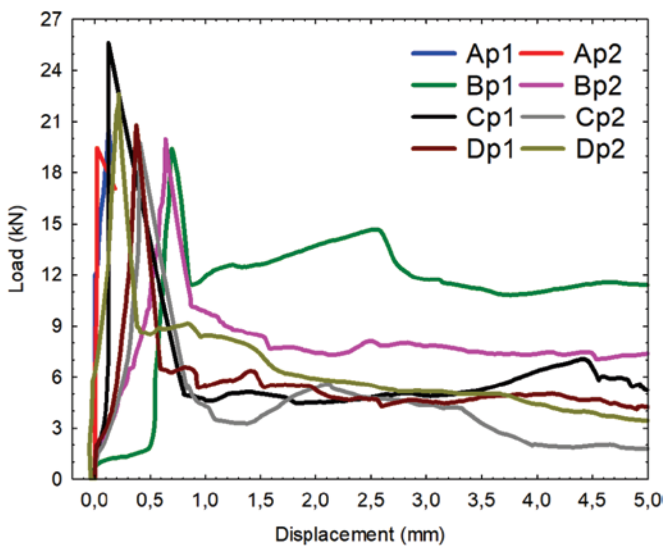

Figure 11
Load *versus* displacement behavior in prismatic specimens (10 × 10 × 35 cm)

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