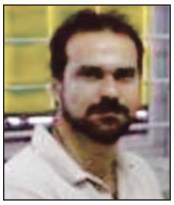
Volume 4, Number 1 (March, 2011) p. 049 - 078 • ISSN 1983-4195

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS
IBRACON STRUCTURES AND MATERIALS JOURNAL

Steel fibers reinforced self-compacting concrete – behavior to bending

Concreto autoadensável reforçado com fibras de aço – comportamento à flexão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Abstract

This study was carried out to investigate the behavior of self-compacting concrete beams reinforced with steel fibers subjected to the bending. For such, steel fibers with a ratio l/d of 50, in a volume fraction of 1% were used. Reinforced concrete beams with dimensions of 12,5 x 23,5 x 132 cm were in four-point bending, at 28 days of age. During the test were taken strain measurements in the stirrups and the longitudinal reinforcement bars, besides measurements of the strain in the compressed region of concrete and of deflections at mid-span. The data collected showed that the addition of steel fibers in self-compacting concrete (SCC) promotes a notable increase in the beam's resistant capacity, resulting in lower deflections at mid-span, lower deformations of the reinforcement bars, both transversal as longitudinal, and improved cracking control, compared to control beams produced with conventional concrete, with or without steel fibers.

Keywords: Self-compacting concrete; Steel fibers; Reinforced concrete beams; Four-point bending test.

Resumo

Este estudo foi desenvolvido para avaliar o comportamento de vigas de concreto autoadensável (CAA) reforçado com fibras de aço submetidas à flexão. Para tal, foram utilizadas fibras de aço com fator l/d = 50, em uma fração volumétrica de 1%. Foram confeccionadas vigas armadas de dimensões (12,5 x 23,5 x 132) cm, as quais foram ensaiadas por flexão a quatro pontos, aos 28 dias de idade, sendo feitas medições das deformações apresentadas nos estribos e armadura longitudinal, além de medições das deformações do concreto na região comprimida e das flechas no meio do vão. Os resultados dos ensaios mostraram que a adição das fibras de aço ao CAA promoveu sensível ganho na capacidade resistente da viga, com menores flechas, menores deformações das armaduras, longitudinal e transversal, e melhorado controle da fissuração, em comparação às demais vigas produzidas com concretos convencionais, com e sem fibras de aço.

Palavras-chave: Concreto autoadensável; Fibras de aço; Vigas de concreto armado; Ensaio de flexão a quatro pontos.

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Received: 24 Oct 2009 • Accepted: 19 May 2010 • Available Online: 04 Mar 2011

1. Introduction

Self-compacting concrete (SCC) is characterized by high fluidity and moderate viscosity. It is able to move in the formworks and fill them uniformly under its own weight. Moreover, the use of SCC is cost-effective because this concrete does not give rise to any mechanical vibrations, it requires fewer construction workers during the casting stage, and the noise level due to mechanical vibration equipment is lower at the construction site, thereby diminishing sound effects on the environment and improving working conditions. The SCC has been widely employed to produce beams of complex shapes and/or with high density of reinforcement structures.

Besides ensuring the expulsion of air bubbles from the fresh mix with no need for mechanical vibration, the SCC must have segregation ability and bleeding strength. In concrete mixes such characteristics are obtained by addition of third generation superplasticizers and a high volume of fine materials, and/or by introduction of viscosity modifying agents (Gomes [1]).

From a mechanical viewpoint, both the conventional and self-compacting concretes perform less satisfactorily when they are subjected to tensile effects. This has motivated constant research into new materials that can meet the demands of structural performance. In order to achieve the best possible material; that is, a concrete with fewer constitutive deficiencies and/or a larger number of positive features, several researchers have been devoted to the optimization of the properties of concrete beams, and new components and admixtures have been investigated.

One way to improve the physical and mechanical properties of a concrete is the production of a composite material either via addition of steel bars commonly used as reinforcement in current civil engineering practices or by random introduction of steel fibers into the concrete mixture. A combination of both approaches is also possible, although the latter has found more restricted and less widespread use.

As outlined by Kim and Mai [2], both the cement matrix and the fibers keep their original chemical and physical identities in the composite material. However, due to the presence of an interface between these two constituents, a combination of mechanical properties that cannot be obtained with the constituents alone is achieved in the hybrid concrete.

Bearing in mind the technical and economic benefits of SCC, the addition of steel fibers to this type of concrete should significantly enhance its properties in the hardened state, mainly when it is submitted to tensile stress, as in the case of concrete beams under flexural effects. Therefore, if the use of SCC is advantageous, the addition of steel fibers should provide it with new positive features and further possibilities of application, since a more efficient material would be obtained both at the fresh and hardened states.

In this context, this work aims to study the load bearing capacity behavior of reinforced self-compacting concrete beams, with and without addition of steel fibers, under normal and tangential forces, and compare the results with the load bearing capacity behavior of ordinary reinforced concrete beams.

1.1 Justification

The reinforcement ratio in structural elements is related to the mechanical properties of the concrete, such as compression and tensile strength. As cited by Borges [3], the tensile strength of concrete has a direct influence on the development of cracks. Furthermore, according to CEB-FIP [4], the tensile strength is also related to the contribution of the material to shear efforts, among other aspects.

The addition of steel fibers to concrete gives rise to two important effects. First of all, it contributes to reinforcement of the composite under loads that induce tensile stress. Secondly, the presence of the fiber improves the ductility and toughness of the material (Gava et al. [5]).

Concerning SCC, its well-known advantages are related to the lower electrical energy necessary during placement and compacting of this type of concrete. However, the large amount of finer particles present in this material generally culminates in a denser structure whose characteristics and mechanical behavior can be enhanced. Nevertheless, these factors are often overlooked because the main action of SCC in its fresh state is filling all the empty voids in the formworks with no vibration efforts. If the denser structure of SCC diminishes the presence of air voids so that better bonding between the concrete and steel is achieved, (Almeida Filho [6]; Hossain and Lachemi [7]), this could be beneficial and lead to better results in terms of the mechanical behavior of the constituents compared with that of conventional concrete. In addition, if steel fibers are introduced into SCC with a view to arresting the propagation of cracks and improving the tensile strength, the resulting material may have a longer lifetime and/or present better behavior compared with structural elements made with ordinary cement concrete.

2. Materials

Four different concrete mixes were designed in this study, in order to enable future comparisons among them. The Portland cement and the water-to-cement ratio were kept constant. The concrete mixes studied herein were designated self-compacting concrete (SCC); steel fiber-reinforced self-compacting concrete (SFRSCC); reference concrete (RC); and steel fiber-reinforced reference concrete (SFRRC).

The SCC mix proportion was selected from previous studies developed in the Federal University of Alagoas (Lisbôa [8]; Cavalcanti [9]), and a limestone powder obtained from marble and granite beneficiation waste (MGBW) was employed as a mineral filler.

The RC mix was produced with the same aggregates (fine and coarse), cement content and type, and water-to-cement ratio as that utilized in the case of the SCC mix, and the proportioning method developed by ABCP (Brazilian Association of Portland's Cement) was employed. RC beams with and without steel fibers were obtained, so as to allow for a comparison between the properties of SCC at the hardened state with those of cements compacted by vibration.

In order that the RC mix contained the components most often encountered in normal concrete, the MGBW filler was not incorporated into the RC mix. A plasticizer was used instead, to promote adequate workability, so that slump values between 5 and 12 cm were obtained.

2.1 Cement

A Portland-limestone blended cement with density equal to 3150 kg/m³ was utilized, classified as type CP II-Z 32 according to the NBR 11578 specifications [10].

Table 1 – Physical properties of the crushed aggregate and sand

Characterization	Medium sand	Coarse 12.5 mm
Bulk density (g/cm³)	2.611	2.650
Unit weight in a loose condition (g/cm³)	1.449	1.381
Unit weight in a compacted condition (g/cm³)	-	1.456
Thickness modulus	2.492	-
Absorption (%)	0.60	0.82

2.2 Aggregates

A crushed limestone aggregate of granitic origin (maximum size of 12.5 mm) and natural sand (maximum size of 2.4 mm), classified as medium sand according to NBR 7211 [11], were employed. Table 1 lists the characteristics of the crushed aggregate and the physical properties of the sand. Figure 1 contains the gradation curves.

2.3 Mineral Addition

A limestone powder originated from marble and granite beneficiation waste (MGBW) was applied as a mineral addition.
This kind of waste is generated during the cutting and polishing operations of marbles and granite slabs and end up normally deposited in "lagoons" located around industries, as showed in Figure 2. The waste released into the lagoons is basically composed of rock powder, water, hydrated lime, and steel grit.
The waste material used in the research was removed from a lagoon, and it acquired mud consistency after an evaporation process. In the laboratory, the collected material was dried by exposure to the sun and later stored in barrels. Thereafter, the larger particles that remained from the drying process were broken, as shown in Figure 3, and sieved on a # 0.3mm mesh. Finally, the powdery material was stored in sealed containers for later use as mineral addition.
The MGBW is considered to be predominantly a non-active addition, thus contributing to higher compactness of the internal structure of the cementitious material mainly through physical action, also known as filler effect. Figure 4 illustrates the gradation of the MGBW.

Figure 1 – Crushed aggregate and sand gradation curves

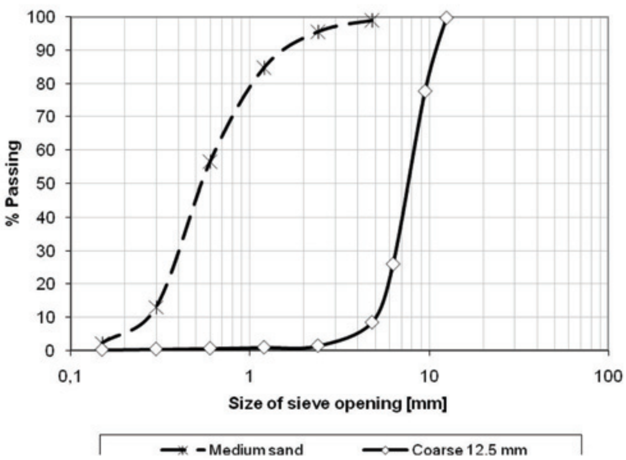
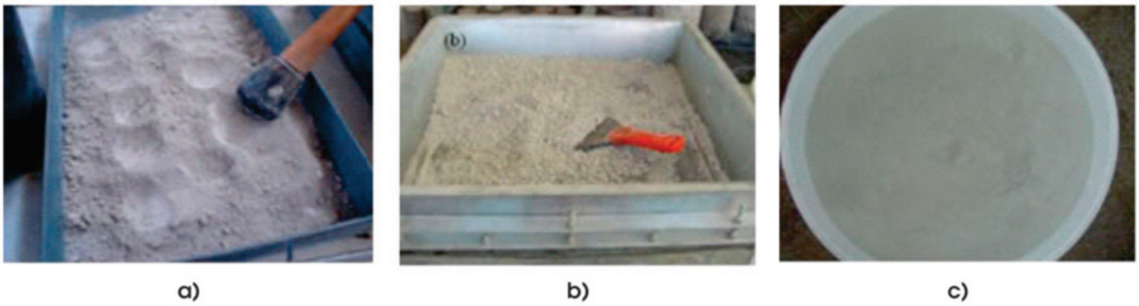


Figure 2 – Marble and granite beneficiation waste disposal in a lagoon

2.4 Admixtures

A superplasticizer (SPC) was used in the self-compacting concrete mix, and a plasticizer (PC) was employed in the reference concrete mix, to promote adequate workability.
Plasticizers are normally employed to reduce water contents between 5% and 10%, reaching 15% in high workability concretes, according to Neville [12]. As explained by Mehta and Monteiro [13], plasticizer use leads to higher fluidity without increasing water content.
Tensoactive agents are the main active components of these admixtures, which in the case of plasticizers will be concentrate at the interface between two phases immiscible, modifying the physical-

Figure 3 – a) Breaking of the larger particles; b) Sieving; and c) Storage of the MGBW

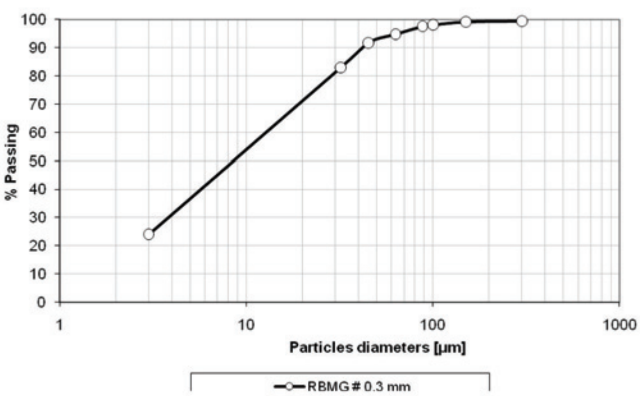


chemical forces that act in this interface. These substances are adsorbed by cement particles giving a negative electrical charge which results in repulsion between the particles. Thus, the particles gains higher mobility and the water molecules are not trapped and are therefore able to lubricate the mix and increase the workability (Neville [12]).
The superplasticizers are a special category of water reducing agents which are formulated from components that allow water content reduction between 25% and 35% (Neville [12]), resulting in extreme workability to the concretes where they are incorporated. The tensoactive agents of the superplasticizer involves the cement particles, charging them negatively, causing electrostatic repulsion of them, which results in cement particle dispersion causing a reduction in viscosity (Dal Molin [14]). Superplasticizer usage in SCC is practically inevitable. Its use is responsible for one of the main properties of this concrete, the fluidity. Without superplasticizer it would impossible to get self-compacting concrete.

2.5 Water

The water used for concrete production in this study was obtained from of the supply system of the Federal University of Alagoas.

Figure 4 – Gradation curve of MGBW



2.6 Fibers

Steel bars with tensile strength of 500 MPa and diameters of 6.3 mm, 5.0 mm, and 12.5 mm were used as reinforcement in the beams. The density of the steel was 7850 kg/m³.
Commercially available hooked-end straight steel fibers measuring 30 mm in length and 0.6 mm in diameter, as depicted in Figure 5, with tensile stress around 1100 MPa, were employed.
According to NBR 15530 [15], the steel fiber used in this study corresponds to the A-I type.

3. Experimental Program

3.1 Concretes mixtures

Firstly, the sand and crushed aggregate were placed in the mixer, which was allowed to work for about 30 (thirty) seconds, for incorporation of adsorbed water. Next, the mixer was interrupted, cement and MGBW were introduced into it, and the mixture was further mixed for about 30 seconds. Part of the mixing water (80% of water-to-cement ratio) was then added to the equipment, and the mixing was allowed to proceed for about 90 seconds. The mixing process continued for about 120 seconds after addition of the admixture (superplasticizer in the case of SCC and plasticizer for RF) and the remaining mixing water (20% of water/cement ratio),. When the mix process was complete, steel fibers were added and mixed for another 60 seconds in the cases of SFRSCC and SFRRC only.
Table 2 summarizes the main differences in terms of the dosages employed in this research.
The volume content of steel fibers in the SCC was based on the

Figure 5 – Geometric profile of the steel fiber employed in this study

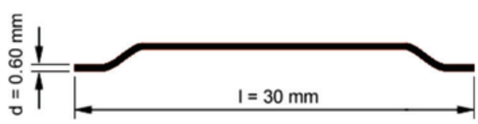


Table 2 – Main differences in terms of the dosages employed in this research

Type of Concrete	D_{max} coarse aggregate (mm)	MGBW	SPC	PC	Steel fibers	Compacting
SCC	12.5	Yes	Yes	No	No	Self-compacting
SFRSCC	12.5	Yes	Yes	No	Yes	Self-compacting
RC	12.5	No	No	Yes	No	Vibrated
SFRRC	12.5	No	No	Yes	Yes	Vibrated

recommendations of Tviksta [16], according to whom the dosage of steel fibers per volume in a steel fiber-reinforced self-compacting concrete (SFRSCC) can be obtained from an existing SCC with a slump value between 650 mm and 700 mm.

The need for changes in the SCC dosage when steel fibers are added to the mixture can be assessed by the fiber factor (F_{sf}), according to Eq. (1):

$$F_{sf} = \frac{m_f}{78,5} \cdot \frac{l_f}{d_f} \quad (1)$$

where m_f is the mass of added fiber (kg/m³); l_f is the length of the fiber; and d_f is the diameter of the fiber.

On the basis of the recommendations of Tviksta [16] and preliminary tests, it is possible to add steel fibers up to a 1% volume ratio (78.5 kg/m³), with no alterations in the properties of fresh SCC. Table 3 displays the concretes mixes prepared for this study.

3.2 Fresh concrete experiments

The filling ability of the self-compacting concrete with and without steel fibers was evaluated by means of the slump flow test. Attention was focused on measurement of the slump flow (D_f), which is the mean value of two perpendicular diameters measurements (d_1 and d_2) obtained after release of a standard slump cone in the concrete. The time, in seconds, necessary for a mean diameter gain of 500 mm to be achieved is designated T_{50}. This is the most commonly employed test both in the laboratory and in the construction site, due to its easiness and quickness. Additionally, it uses the same equipment that is often used for conventional concretes. Moreover, the slump flow test enables controlling the segregation tendency of the coarse aggregate. Figure 6 brings both an illustration and pictures regarding execution of the test.

In this work, the self-compactability acceptance test was employed in order to investigate the ability of SCC to pass through obstacles. The self-compactability test was developed by Ouchi [18] and is normally used in construction sites for evaluation of the self-compactability of the SCC before it is placed in the structure formworks. To enable the use of this test in the lab, a device was constructed on the basis of the same principles of the Ouchi's apparatus [18], but in a reduced scale. In the lab, the test equipment was positioned so that all the concrete placed into the formwork could be assessed. Figure 7 depicts both an illustration and a picture concerning execution of the test, where one can observe the equipment and its positioning in relation to the beam formwork.

Incorporated air content was determined for all studied concretes by means of the pressure method, according to NBR NM 47 [19].

Table 3 – Mix proportions used in the study

Type of concrete	Cement (kg/m³)	w/c	Water* (kg/m³)	Aggregates (kg/m³)		MGBW (kg/m³)	SPC (kg/m³) (spc/c = 0,6%)	PC (kg/m³) (pc/c = 0,162%)	Steel fibers (kg/m³)
				Fine	Coarse				
SCC	400	0.5	194.4	785	790	200	8.0	0	0
SFRSCC	400	0.5	194.4	785	790	200	8.0	0	78.5
RC	400	0.5	198.9	875	895	0	0	1.8	0
SFRRC	400	0.5	198.9	875	895	0	0	1.8	78.5

*The water present in the chemical admixture was discounted.

Figure 6 – Execution of the slump-flow test and determination of the final spread diameter

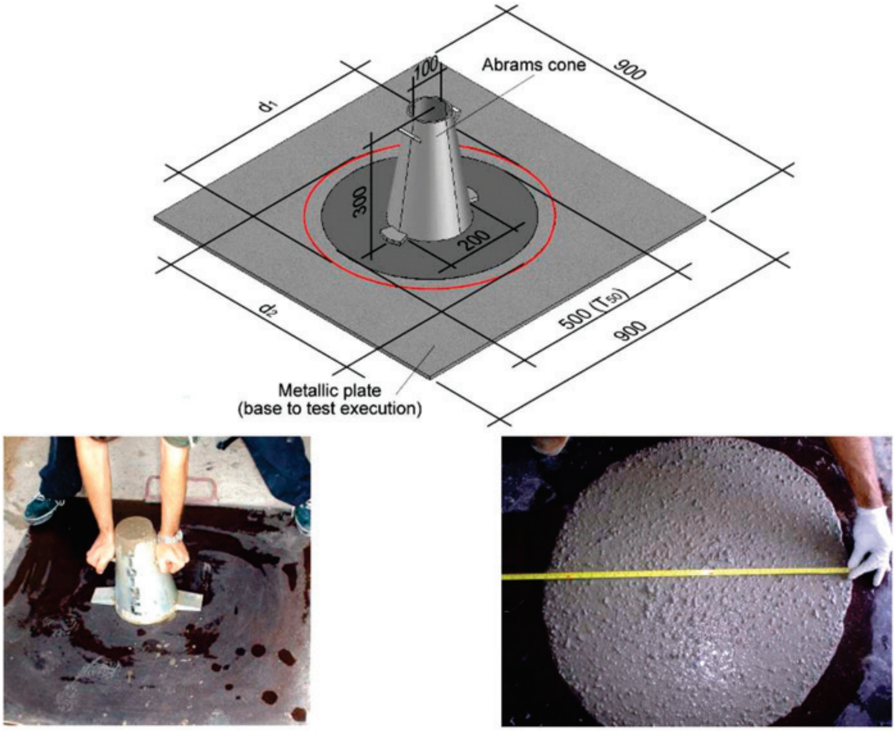


Figure 7 – Execution of self-compactability acceptance test in the lab

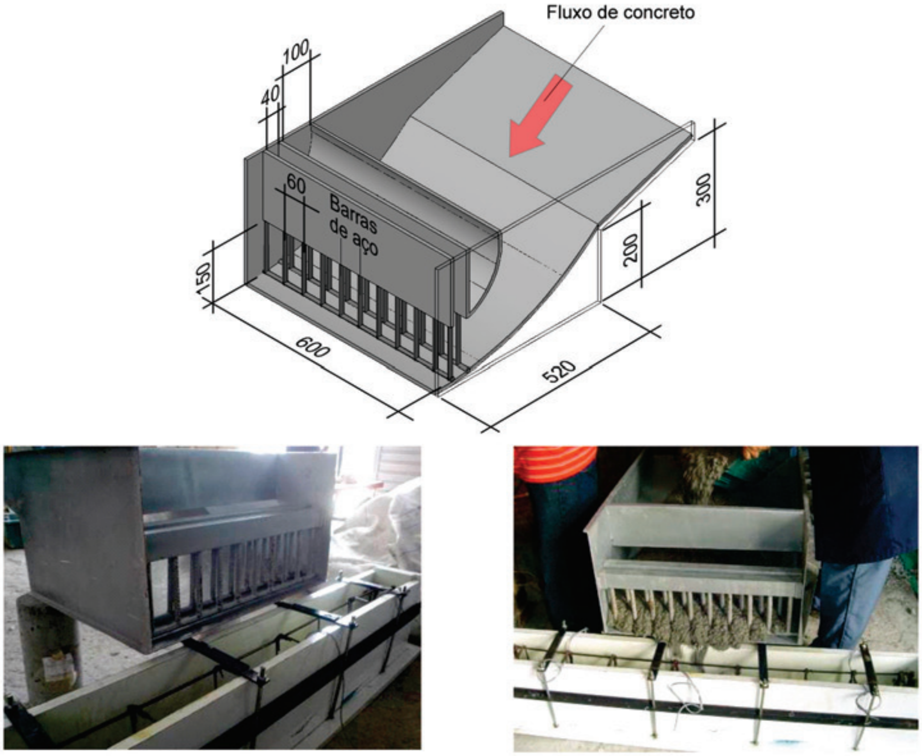
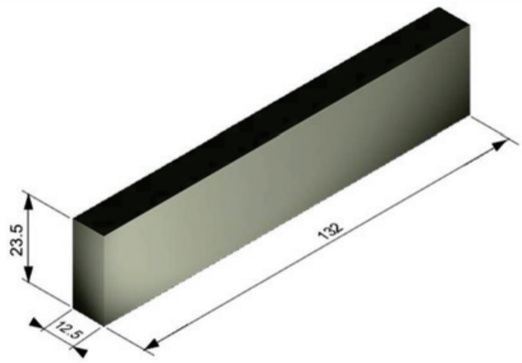


Figure 8 – Dimensions (in cm) of concrete beams



The type B measurer recipient used was filled with concrete and placed as in the case of the molding of the specimens. Thus, when the self-compacting concrete was evaluated, the filling of the recipient was accomplished by only placing the concrete at once, without any kind of vibration. As for reference concretes, with and without fibers, the recipient was filled in two layers, being each of them compacted by immersing a rod vibrator.

3.3 Molding the specimens

For each concrete produced herein, one reinforced concrete beam with 12.5 cm width, 23.5 cm height, and 132 cm length was cast , as displayed in Figure 8.
The molding of beams varied, depending on the compacting process undergone by each type of concrete employed in this work. In the case of the SCC and SFRSCC , as the name suggests, there was no need for vibration of any kind for it to be compacted in the formworks (Figure 9a). On the other hand, RC and SFRRC were compacted by mechanical vibration in a vibrating table (Figure 9b).

3.4 Curing of the specimens

After demolding, which was carried out after 48 hours of completion of the molding process, the beams were subjected to wet curing, for which the beam was placed on a sand bed and covered with cotton waste. The wetting of the beams was conducted once or twice a day, depending on the environment temperature. Such curing was repeatedly accomplished until the test age of 28 days.
Some beams were demolded at 24 hours after completion of the molding process. Then, the cylindrical specimens, employed in the compression and modulus of elasticity tests, and the prismatic specimens, used in the bending test, were cured by immersion in water, where they remained until the test age of 28 days.

3.5 Four-point bending test of reinforced concrete beams

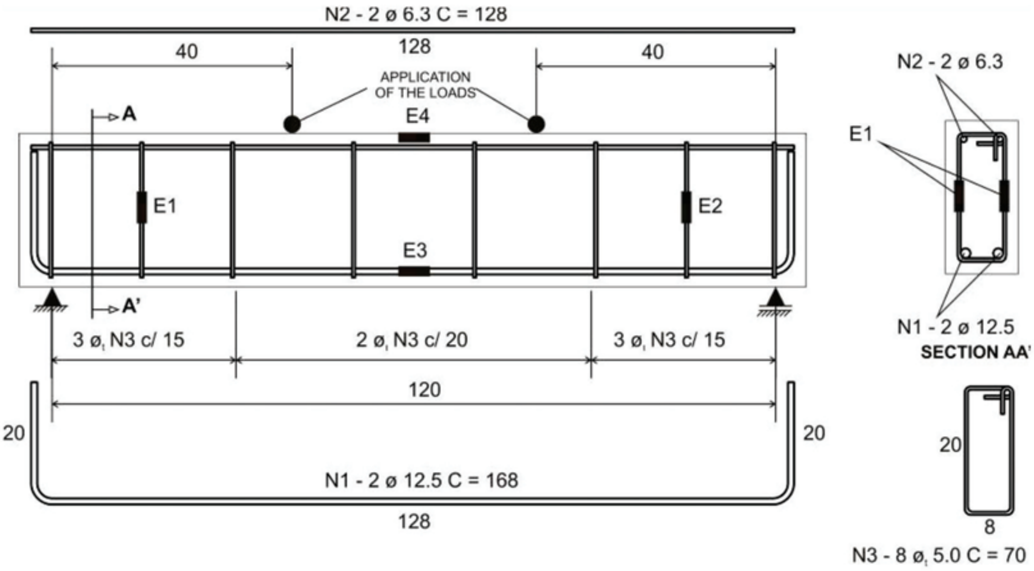
Figure 10 corresponds to the beam reinforcement employed in the four-point bending test and the positions of the strain-gauges relative to the measurements of the deformations in the longitudinal reinforcement (E3 position), transversal reinforcement (E1 and E2 positions), and compressed region (E4 position) of the concrete. The beams were designed to have insufficient transversal reinforcement, in order to induce shear rupture and increase the demand on the stirrups.
The longitudinal reinforcement was composed by two steel bars of 12.5 mm diameter each (N1), whereas the transversal reinforcement consisted of eight stirrups made with 5-mm diameter steel (N3). Furthermore, two steel bars with 6.3 mm diameter were used as stirrups guide only (N2). The beam span was 120 cm, being the two loads equidistantly applied at 40 cm from the supports.
Two types of uniaxial strain-gauges with 120 Ω resistance and 5-mm grid length were utilized for measurement of the stirrups deformations. Other strain-gauges with 10-mm grid length were used

Figure 9 – a) Casting of the SCC beam; b) Compacting of beams in the vibrating table (RC and SFRRC)

a)

b)

Figure 10 – Beam reinforcement details and positions of the strain-gauges



in the longitudinal reinforcement and in the region of compressed concrete. The fixation of strain-gauges in the reinforcements was performed 24 hours before casting of the beam.

The fixation of the strain-gauges in the region of compressed concrete, the fixation of a flat steel bar on the top of the beam for measurement of displacements, and the demarcation of a rectangular mesh, measuring 4.7 cm by 5 cm, along the beam web height for mapping of the cracks were done 24 hours before the tests were performed, as shown in Figure 11. The assessment of the evolution of cracks in the beams as a function of the load increase was carried out using force load increments of 1 ton.

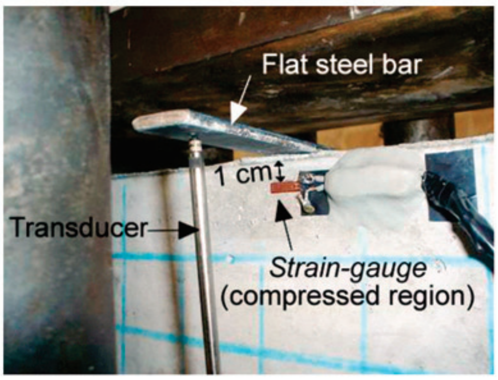
A pair of strain-gauges were positioned in each point of interest for measurement of deformations (E1, E2, E3, and E4), according to Figure 12.

4. Results and discussions

4.1 Assessment of the concretes in the fresh state

Table 4 lists the results achieved for the tested concretes in the fresh state.

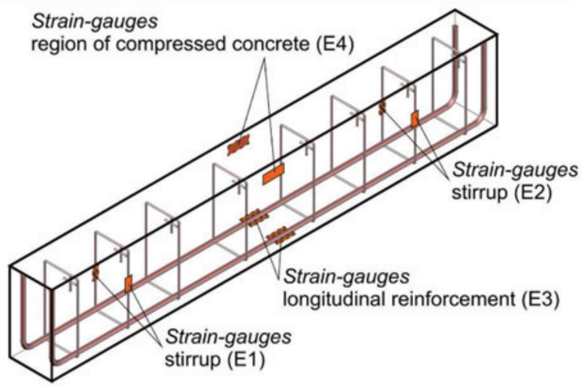
Figure 11 – Bending test for the reinforced concrete beam: a) Detail of the strain-gauge placement in the region of compressed concrete and b) Rectangular mesh for the mapping of cracks



a)

b)

Figure 12 – Strain-gauges fixation points



Observation of Table 4, reveals that the addition of steel fibers at a 1% volume fraction did not result in significant slump reduction in the case of the reference concrete (RC). As for SCC, the addition of steel fibers caused 10.6% decrease in the fluidity of this cement, as verified from the D_f values presented in Table 4. Steel incorporation into SCC also promoted greater concrete cohesion, as observed from the increase in T_{50}.
Despite the reduced flow spread and larger T_{50} compared with SCC, the SFRSCC attended to the self-compacting characteristics in the slump-flow test, since in the technical literature it is recommended that D_f should lie between 600 and 750 mm, and that T_{50} should be in the range of 3 to 7 seconds.

In general, the reference concretes RC and SFRRC presented higher levels of air voids compared with the values found for the self-compacting concretes SCC and SFRSCC. This is probably due to the use of a plasticizer in the former cases, which could have led to the appearance of air bubbles during mixing of the fresh concretes RC and SFRRC. Moreover, the greater volume of fine particles present in the SCC composition may have generated lower amounts of air voids, compared with those obtained in the case of the reference concretes.

4.2 Mechanical properties of the studied concretes

Table 5 summarizes the mechanical properties of the studied concretes, at 28 days of age. Compression (f_c) and elasticity modulus (E_c) tests (NBR 8522 [20]) were conducted on cylindrical specimens with 10-cm diameter and 20-cm height. The concretes bending strength (f_{ctM}) was also determined in accordance with NBR 12142 [21], by using prismatic specimens with 15-cm width, 15-cm height, and 50-cm length. Four cylindrical specimens were molded for each produced concrete for the compression test, 04 cylindrical specimens were produced for evaluation of the elasticity modulus, and 03 prismatic specimens were made for the bending test.
Despite the decrease in the elasticity modulus after addition of the steel fiber, the SCC presented a 10.3% rise in its compression average strength and 141.6% elevation in the bending resistance in the case of prismatic specimens (Table 5). In contrast with some literature reports on fiber-reinforced material, the increased SCC compression strength observed after addition of steel fibers has also been verified in other works (Marangon [22]). Therefore, this point must be further investigated in future studies.
The four-point bending test conducted in the concrete beams is described in Figure 13, which shows the beam dimensions, the

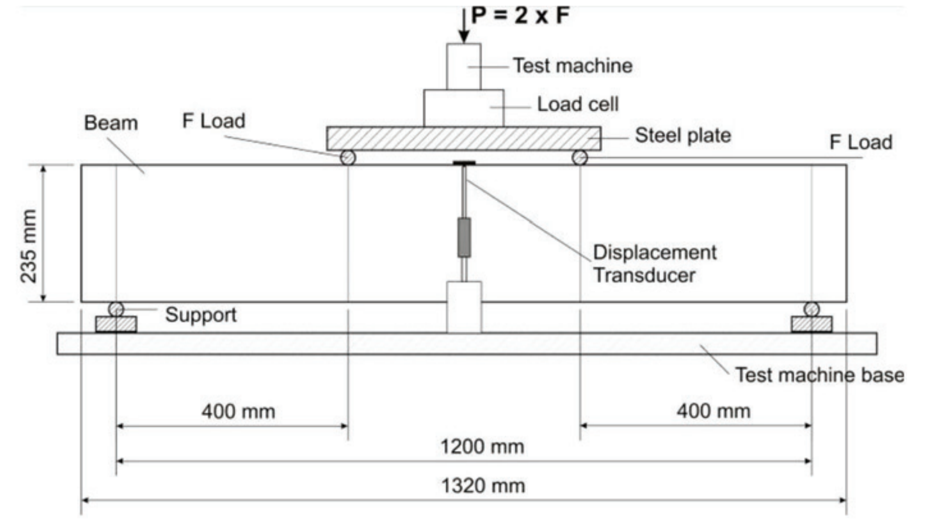
Table 4 – Results achieved for the tested concretes in the fresh state

Type of concrete	Slump (cm)	Final spread (mm) - D_f	T_{50} (s)	Air voids (%)
SCC	---	705	3.7	2.5
SFRSCC	---	630	5.0	2.5
RC	13	---	---	3.5
SFRRC	12	---	---	3.0

Table 5 – Mechanical properties of the studied concretes at 28 days of age

Concrete types	f_c (MPa)	E_c (GPa)	E_c/f_c (%)	f_{ctM} (MPa)
SCC	42.9	39.6	9.23	4.4
SFRSCC	47.3	35.4	7.48	10.6
RC	39.9	39.9	10.00	4.6
SFRRC	39.1	36.4	9.30	5.2

Figure 13 – Illustration of the four-point bending test on reinforced concrete beams



distance between supports and applied loads, as well as the position of the employed instrumentation.

Figure 14 displays the results from the deformation measurements performed in the region of compressed concrete.

According to Figure 14, for the same level of loading the addition of steel fibers yielded smaller deformations in the region of beam compression in the case of SFRSCC, compared with the SCC beam. But the effect of the fibers was lower in the final stage of beam load capacity, where there was superposition of the curves corresponding to SCC and SFRSCC.

With regard to RC, the introduction of steel fibers considerably improved the behavior of the concrete in the region of beam compression, as verified by comparison with the curve relative to SFRRC. In the final stage of load capacity, the SFRRC beam exhibited better behavior.

As for the fiber-reinforced concretes SFRSCC and SFRRC, the slowing down of the development of cracks due to the presence of the steel fibers may have placed the neutral line of the upper border of the beam cross-section further away, compared with concretes without added fibers, SCC and RC. This might have led to an enlargement of the beam compression zone, consequently favoring the appearance of fewer deformations in the compressed concretes. This can be clearly observed in Figure 14, by comparing RC with SFRRC and SCC with SFRSCC.

The measurements accomplished in the longitudinal reinforcement of the beams are presented in Figure 15. Some problems occurred during the execution of the tests: the strain-gauges fixed in the

Figure 14 – Results from specific deformation measurements performed in the region of compressed concrete in the beams

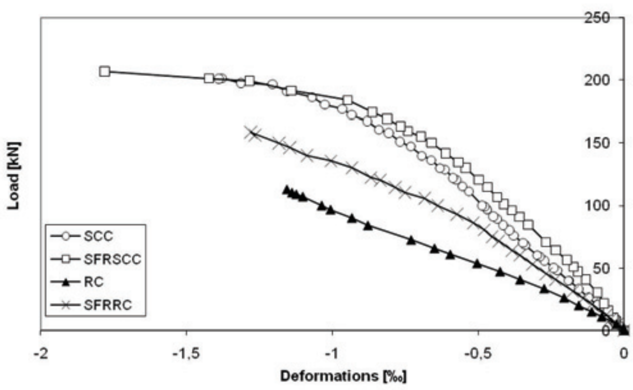


Figure 15 – Specific deformation measurements in the longitudinal reinforcement

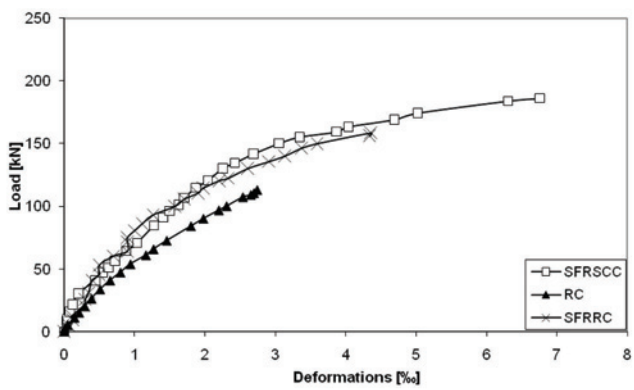
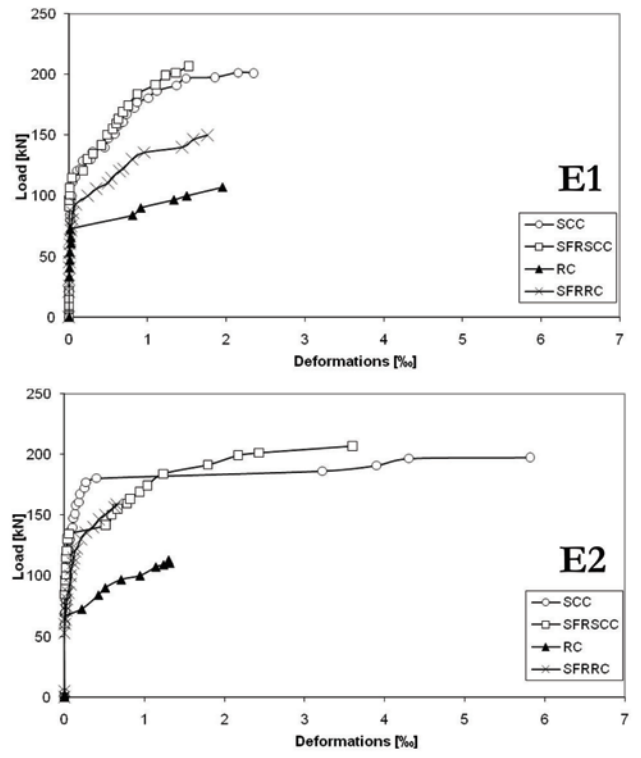


Figure 16 – Specific deformation measurements in the stirrups



longitudinal reinforcement were released, and some channels of the data acquisition system did not work correctly, which did not allow for the measurement of deformations in the longitudinal bars of the SCC beam.

As shown in Figure 15, the addition of steel fibers provided the RC with greater tensile load-capacity, which is developed during the bending of the beam . This culminates in smaller deformations of the longitudinal reinforcement of the SFRRC beam, compared with the RC beam, showing that part of the tensile stress was resisted by the steel-fiber reinforced concrete, thereby relieving the action of the longitudinal reinforcement.

The behaviors of SFRRC and SFRSCC were similar, at least up to a load of approximately 100 kN. This is because the SFRSCC beam displayed slightly better performance with increasing load, compared with the SFRRC beam. This enabled the achievement of greater loading levels with smaller deformations in the longitudinal reinforcement It is noteworthy that the strain-gauges fixed in the longitudinal reinforcement of the SFRSCC beam were released when the load was 186.2 kN, corresponding to 6.75‰ deformation. Thus, the curve depicted in Figure 15 does not describe the complete behavior relative to the deformation of the SFRSCC beam longitudinal reinforcement.

The curves represented in Figure 16, indicate smaller stirrups deformations in the self-compacting concrete beams SCC and SFRSCC, as observed from the load levels reached by the concretes. However, the addition of steel fibers to SCC did not imply an evident benefit in terms of counteracting the action of shear stress acting on the beam. Perhaps, this result is due to the favorable behavior of the matrix, which generates a better concrete-steel bond (Almeida Filho [6]). Therefore, there was no significant gain in shear strength after addition of the fibers.

On the other hand, the shear stress was considerably counteracted when steel fibers were incorporated into the RC. This is an indication that the steel fibers act on the region of shear resistance, with direct action on inclined cracks (in a similar way to stirrups) that appear in the beam regions located between the load and the support.

The measurements of the mid-span deflections of the beams are presented in Figure 17. In the aforementioned figure, the load versus deflection curves evidence (see the legend of the curves) the load at which the first crack occurred in each of the beams.

According to the curves in Figure 17, taking into account the same loading level, SFRSCC was the material that underwent the smallest deflections. Probably, the better concrete-steel bond obtained in this case by using steel fibers as well as the denser internal structure of SCC, achieved through use of a high volume of fine particles in the mix, provided a greater beam deformation capacity. Similarly to SCC, the RC also presented larger load capacity after incorporation of steel fibers. As observed previously, results from the longitudinal reinforcement deformation studies demonstrated that the addition of steel fibers to RC reduced the demand for longitudinal reinforcement, indicating that SFRRC was able to counteract part of the tensile stress developed in the bending. Indeed, the data from Figure 17 reflect this behavior, evidencing greater SFRRC beam ductility compared with the RC beam.

In relation to the appearance of the first crack, there was a 100% increase in the load at which the first crack was detected in the SFRSCC, compared with the SCC beam. On the other hand, the incorporation of steel fibers into the RC provided a 200% rise in the load that caused the first crack.

The development of cracks in the beams is illustrated in Figures 18 to 21 for each of the concretes, from the first crack until failure. The loads that generated the cracking stages are also presented.

The development of cracks in the SCC beam can be observed in Figure 18.

The development of cracks in the SFRSCC beam is shown in Figure 19.

Figure 17 – Load x deflection curves of each beam

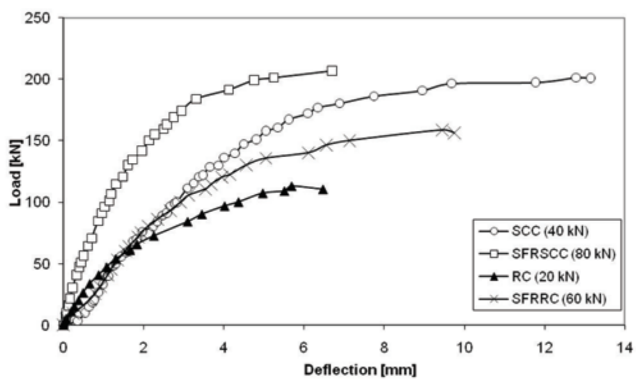


Figure 18 – Crack development pattern in the SCC beam

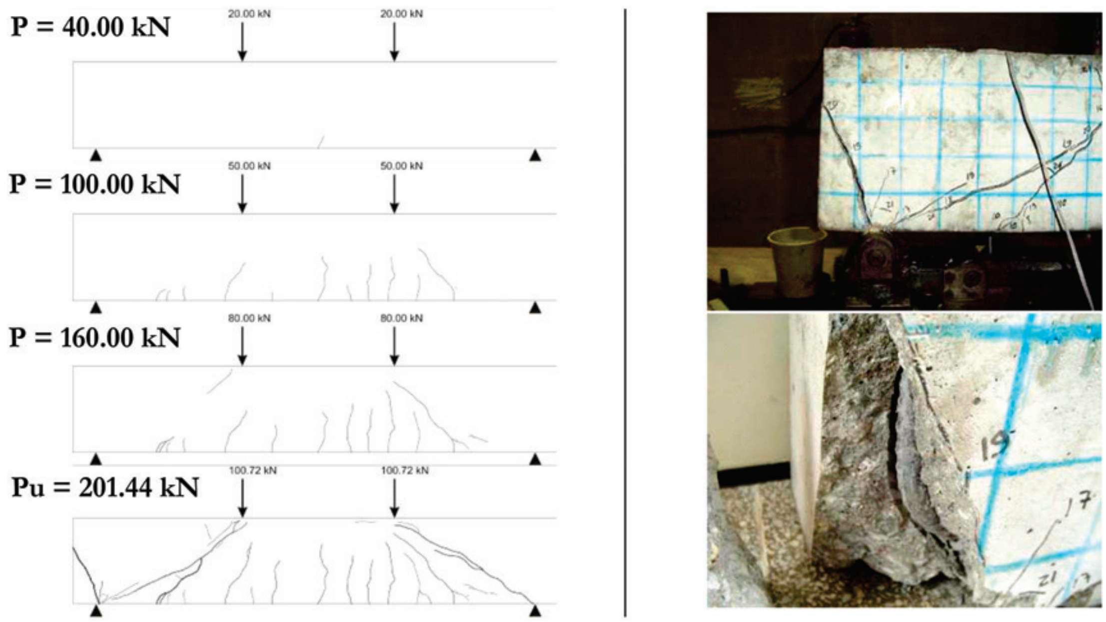


Figure 19 reveals that the incorporation of steel fibers into the SCC avoided slipping of the longitudinal reinforcement in the beam support region, in contrast with what occurred in the case of the SCC beam (Figure 18). This gives evidence of some kind of fiber reinforcement in this sense. As for the RC beam, the development of cracks progressed as represented in Figure 20.

Figure 19 – Crack development pattern in the SFRSCC beam

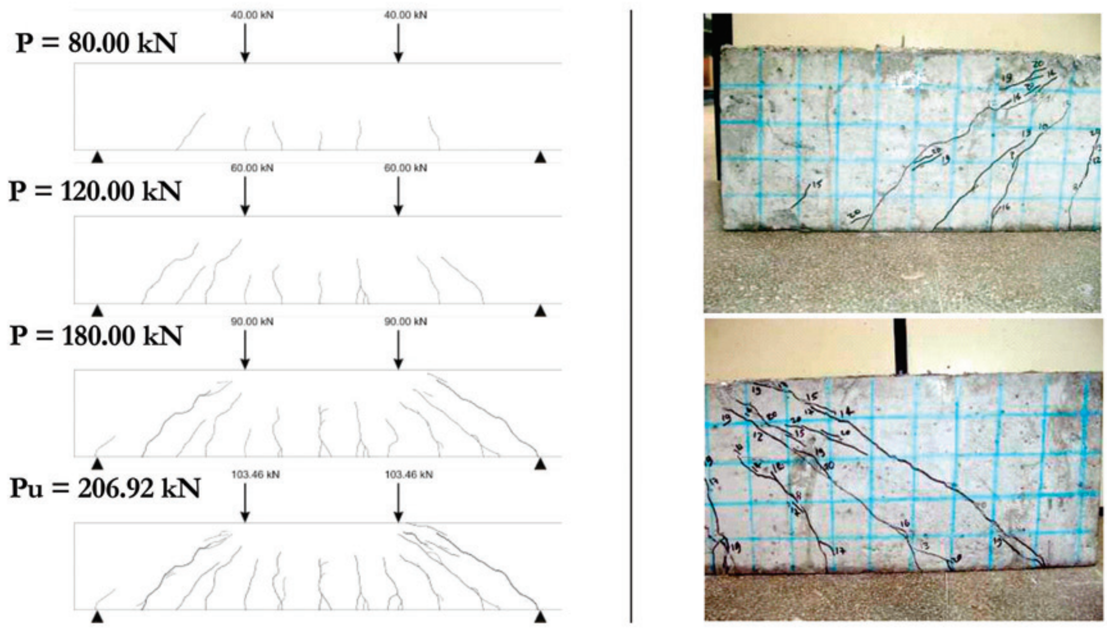
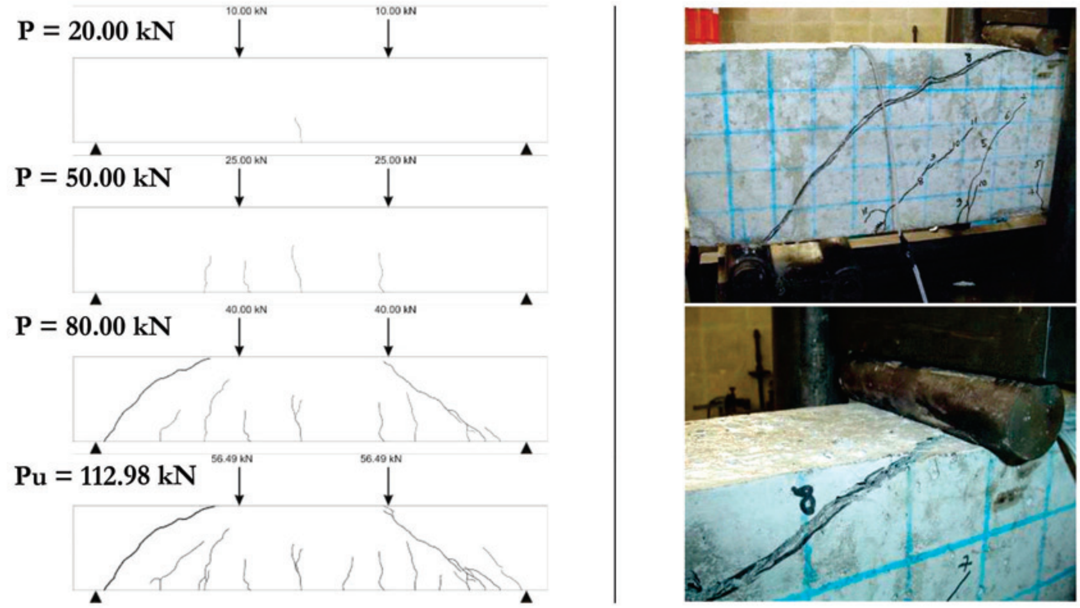


Figure 20 – Crack development pattern in the RC beam



Finally, the mapping of cracks in the SFRRC beam is displayed in Figure 21.

5. Conclusions

The conclusions presented in this study were obtained from initial investigations on steel fiber-reinforced self-compacting concrete, and therefore indicate a trend of the possible behavior of this concrete after addition of steel fibers to its mixing, both in the fresh and hardened states.
Complementary studies are underway, in order to examine the effect of volume fractions, types and characteristics of the fibers, and self-compacting concrete dosages on the behavior of composite concretes. Additionally, research targeting the SCC-steel fiber bond using tests and a number of samples that is sufficient for the statistical analysis of the obtained results is being conducted.
Thank to improved control of cracks, the SFRSCC beam containing 1% steel fiber in its volume fraction exhibited better structural behavior, affording a greater load-capacity with smaller deformations in the stirrups, longitudinal reinforcement, and region of compressed concrete in the upper border of the beam cross-section. However, despite the better behavior of the SFRSCC, the steel fibers were more beneficial in the case of the SFRRC beam, where the amount of deformations in the reinforcement and compressed regions was more significantly reduced compared with the corresponding concrete without added steel (RC beam).
The steel fibers in SFRSCC did not give rise to evident benefits regarding the reinforcement of the SCC beam. Indeed, the advantages of introducing steel fibers into SCC included only the slowing down of the appearance of the first crack and the presence of smaller deflections, compared with the SCC beam. The stronger concrete-steel bond due to the denser internal structure of SCC was able to promote enhanced beam behavior, compared with RC and SFRRC. In other words, the addition of steel fibers to SCC at 1% volume fraction did not significantly reinforce the SCC concrete. In fact, this behavior had not been expected for the SFRSCC beam considering the results from the bending tests performed on prismatic specimens. However, it was verified that at least two beams should have been produced for each analyzed concrete type, in order to aid observations of variations in concrete behavior. This in turn should allow for better analysis of each of the dosages. The use of different volume fractions of steel fibers should also be interesting, so that changes in the behavior of the beams due to the addition of different increments of fiber could be verified.

6. Acknowledgements

The authors gratefully acknowledge FAPEAL, CNPq, CAPES, LEMA of the Technological Researches Nucleus (NPT) of the Federal University of Alagoas (UFAL), the beneficiation companies of marble and granite of Alagoas, the cement factories ZEBU and POTY, the factory of chemical admixtures MBT – Master Builders Technologies, and the companies BRITEX and IMCREL.

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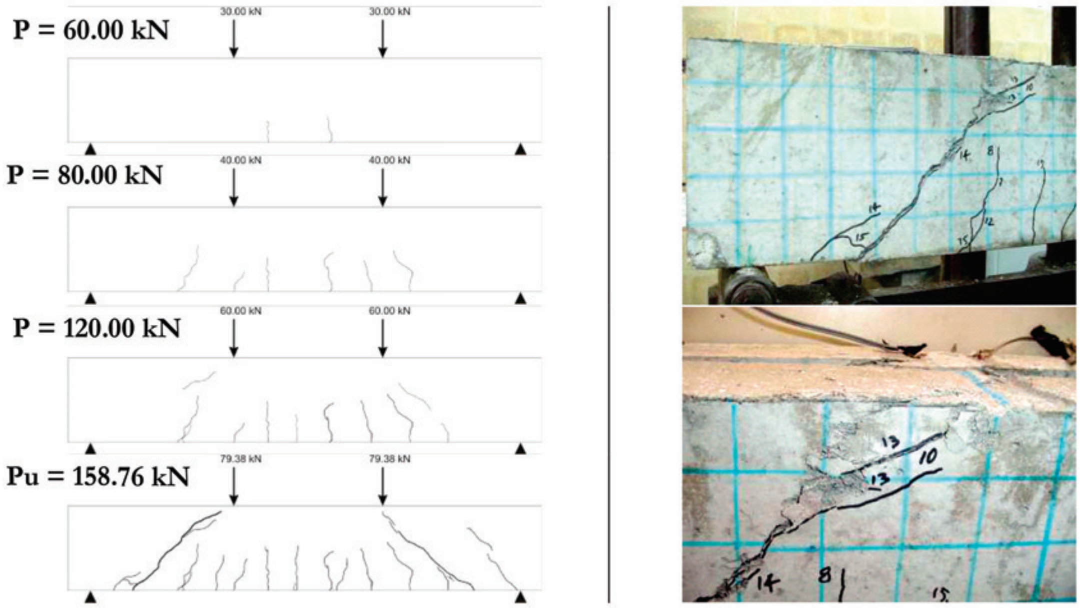
Figure 21 – Crack development pattern in the SFRRC beam



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