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Study of the compressive and tensile strenghts of self-compacting concrete with sugarcane bagasse ash

Estudo das resistências à compressão e à tração de concreto autoadensável com cinza do bagaço da cana-de-açúcar

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Abstract

In this work, the axial compressive strength at 3, 7 and 28 days of age and the tensile strength at 28 days of age of specimens of two self-compacting concrete (SCC) compositions were evaluated. The difference between them was the presence of the sugarcane bagasse ash (SCBA) in the substitution rate of 10% of the sand mass in the second trace. The traces were developed based on the rheological parameters of the NBR 15823 Brazilian standard. The strengths at 28 days were evaluated by the confidence interval of the Student's t-test with α of 5%. The results in the fresh state have proved that the rheological performances between the SCC'S are similar. Moreover, the SCC with SCBA obtained equivalent performances in the compressive and tensile strengths at all ages when compared to the SCC without SCBA, with an effective reduction of 87 Kg of sand per cubic meter of concrete.

Keywords: self-compacting mortar, rheology of concrete, mechanical strength of concrete, sustainability.

Resumo

Neste trabalho foram avaliadas as resistências à compressão axial aos 3, 7 e 28 dias de idade e a resistência à tração aos 28 dias de idade, de corpos de prova de duas composições de concreto autoadensável (CAA). A diferença entre ambas, era a presença da cinza do bagaço da cana-de-açúcar (CBC), na taxa de substituição de 10% da massa da areia no segundo traço. Os traços foram desenvolvidos com base nos parâmetros reológicos da norma NBR 15823 da Associação Brasileira de Normas Técnicas. As resistências aos 28 dias foram avaliadas pelo intervalo de confiança do teste t de Student com α de 5%. Os resultados no estado fresco comprovaram que os desempenhos reológicos entre os CAA's são similares. Destaca-se também que o CAA com CBC obteve desempenhos equivalentes nas resistências à compressão e à tração em todas as idades, quando comparado ao CAA sem CBC, com a redução efetiva de 87 Kg de areia por metro cúbico de concreto.

Palavras-chave: argamassa autoadensável, reologia do concreto, resistência mecânica do concreto, sustentabilidade.

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1. Introduction

The self-compacting concrete (SCC) is a category of concrete that is capable of flowing, self-compacting by its own weight, filling molds and passing through obstructions (reinforcements, curves, inserts) with success, quality and reliability. During these events, the mixture must remain homogeneous, in the stages of mixing, transportation, placement and finishing, in order to characterize efficient results in the control of its segregation [1, 2].

The methodologies and techniques to obtain SCC are associated with challenges inherent to the rheological study in its fresh state, with a special focus on the control of the fluidity, cohesion and segregation resistance aspects. To this end, these methodologies usually perform preliminary studies of the paste and/or the mortar, and of the granular structure of the aggregates and fine materials [3, 4, 5, 6]. However, even though this concrete has special focus of development in its fresh state, with an intense program of rheological analysis, it must also present characteristics appropriate in its hardened state, as all the other concrete classes with structural purposes.

The high consumption of fine aggregates and fine materials, which promote the cohesion with the desired controlled viscosity among other factors, is a determining factor in the SCC composition. In this study, the incorporation of fines was performed adding calcitic limestone filler and sugarcane bagasse ash (SCBA). The SCBA particles contributed to the expected rheological control, where about 73% of the particles had a size between 150 and 250 micrometers, typical of fine sand phases. According to EFNARC [3], the remaining 27%, with dimensions smaller than 150 micrometers, added mass as fine materials.

The SCBA is a by-product from de burning of the sugarcane bagasse in the process of energy cogeneration. In general, it is predominantly composed of silica (SiO_2), as well as the sand, and depending on the burning conditions, it may be in the amorphous or crystalline state [7, 8, 9].

According to CONAB [10], about 38.7 million tons of sugarcane are expected in the current harvest (2017/2018) only in the state of Paraná. This volume can generate more than 240,000 tons of SCBA, based on the rate of ash generation by burning the bagasse reported in FIESP/CIESP [11]. With the same data base and considering the same logic of calculation, it is estimated that the expected volume of 645,000,000 tons of sugarcane in the national harvest in 2017/2018 would be able to generate more than 4,000,000 tons of SCBA, if all the bagasse was used in processes of energy cogeneration. It is emphasized that such volume generated would be able to decelerate the same sand consumption of natural extraction.

In the last years, several researches have advanced significantly in the use of the SCBA in civil construction products. Cordeiro et al. [7] obtained excellent performances in the rheological tests on concretes produced by using the SCBA as a mineral mixture (replacement rate of up to 20%). In this work, a very low change of the plastic viscosity in these materials was observed. In this same line, Crespi et al. [8], Bahurudeen and Santhanam [9] and Castaldelli et al. [12] verified the existence of pozzolanic properties in the sugarcane bagasse ash, besides the bond properties of the concrete mortars.

Câmara et al. [13] showed that it is viable to use the SCBA in mixtures with cement when the purpose is to accelerate the hydration of the first ages with projections of better results of the compressive strengths of mortars over time. Lima et al. [14] had also emphasized this information for concretes made with the SCBA and cement CP II E 32, which presented better results of compressive strength than the ones without SCBA.

Other authors have evaluated the performance of the mechanical strength of the SCBA in concretes, such as Moretti et al. [15], who have proved that concretes with SCBA can achieve values of compressive strength very close to concretes without the ash. Sampaio et al. [16] and Bahurudeen et al. [17] emphasized that the initiative in using the SCBA in concretes is a good destination for the agro-industrial residues, since it promotes improvement of the performance of the mechanical properties of the compound.

The need for high levels of fine materials in the SCC composition aroused the interest in studying the effect of the SCBA as an aggregate. This fact is due to the great availability of material and the targeting of this by-product (residue) in a sustainable way. Therefore, in this work, the SCBA was used as a partial replacement for the sand. Thus, it is projected that the characteristic results of the self-compacting parameters in the fresh state, and subsequently, of the strength properties in the hardened state, are not changed in relation to the concrete without the SCBA. The comparative mechanical evaluations were conducted on the performance results of the axial compressive strength at 3, 7 and 28 days and the tensile strength (diametral compression) at 28 days.

2. Materials and experimental program

The SCC without the SCBA and the SCC with the SCBA, named as $SCC_{SCBA10\%}$, were produced and validated by the experimental methods, specifications and parameters of NBR 15823-1 [1], Gomes and Barros [2] and Okamura and Ouchi [5]. For the study of the compressive and tensile strengths at 3, 7 and 28 days age, 8 cylindrical specimens of (Ø 10 cm x 20 cm) were produced for each of the investigations carried out, that is, 64 specimens in total.

2.1 Materials

The first unitary trace was composed only of sand as fine aggregate and the second one had 10% of SCBA in replacement for the sand, in mass. The materials and their respective unitary compositions are shown in Table 1.

Table 1
Unitary traces of the concretes

Components	Unitary composition 1 SCC	Unitary composition 2 $SCC_{SCBA10\%}$
Cement	1	1
Calcitic limestone filler	0.4000	0.4000
Sand	2	1.8000
SCBA	0	0.2000
Gravel	2.1200	2.2100
Water	0.4500	0.4500
Superplasticizer	0.0055	0.0055

Reference: Molin Filho [18]

Table 2
Sand and gravel characterizations

Characteristics	Units	Sand	Gravel
Specific mass (ρ)	kg/m³	2642.5	2877.1
Absorption of the aggregate (ABA)	%	0.1	1.9
Unbound mass (U.M)	kg/m³	1491.6	1464.2
Compressed unitary mass (C.U.M)	kg/m³	1656.6	1649.3
Maximum characteristic diameter (ϕ_{max})	mm	0.6	12.5
Fineness modulus (F.M)	%	1.7	6.8

Both unitary traces (table 1) presented a mortar volume (Vscm) at 70% (0.7) in relation to the mass. This proportion of mortar in the concrete was able to promote an amount of fines from 380 kg/m³ to 600 kg/m³ as foreseen by the EFNARC [3] recommendations.
All the materials used in the production of the SCC are described below:
Cement: Portland CPII E-32, characterized by NBR 13069 [19] and NBR 7215 [20]. It had initial setting time at 67 minutes and final setting time at 212 minutes. Its characteristic strengths at 3, 7 and 28 days were of 18 MPa, 21 MPa and 40 MPa, respectively.
Fine aggregate and coarse aggregate: quartz sand and basalt gravel, respectively. Both were from the region of Maringá in the state of Paraná. Their main characteristics, evaluated by the standards NBR NM 30 [21], NBR NM 45 [22], NBR NM 52 [23], NBR NM 53 [24]; NBR NM 248 [25] and NBR 7211 [26] are presented in Table 2.
Superplasticizer additive (sp): Glenium 51 from the manufacturer Basf, which was liquid, white in color and cloudy in appearance. It is classified as a third generation additive for concrete, has the polycarboxylic ether as reference and has also total water solubility. The sp had a solid content of 28.5% to 31.5% of the total mass and a pH between 5 and 7, for a viscosity around 1067 g/cm³.
Limestone filler: calcitic origin and produced by the manufacturer Cazanga. It is composed with the presence at least 51.8 % of CaO, 37% of Ca, 1% of MgO and 0.63% of Mg. More than 94% of its particles are smaller than 0.045 mm (45 µm). The water used was from the water supply system of the city of Maringá, which was in accordance with the requirements of NBR 15900 [27].
SCBA: from Iguatemi Sugarcane Mill (Maringá, Paraná, Brazil) of Usaçúcar Group. It had a specific mass of 2640 Kg/m³ and specific area of 5356 m²/Kg [18]. The highest proportion of its particles, around 73%, had a size between 150 and 250 micrometers [28]. It is important to emphasize that the SCBA was used *in natura,* being only sieved in the mesh 0.595mm (#30), in order to remove the organic impurities (Figure 1).
Table 3 shows the SCBA composition studied by X-Ray fluorescence (XRF).
In Table 3, it is possible to observe the predominant presence of silicon dioxide (SiO_2)[25]. Figure 2 presents the X-Ray Diffraction (XRD) patterns.
The diffraction signals are identified as quartz crystalline phases (ICDS 07-346 standard). Finally, it is highlighted that the solid materials were dry and/or with moisture controlled.

Figure 1
Sugarcane bagasse ash (SCBA) sample

2.2 Method and self-compacting parameters

The preparation of the SCC's was performed as described by Molin Filho [18]. The self-compacting parameters were proved by tests of self-compactibility recommended by NBR 15823-1 [1] (Slump-flow, J-Ring, V-Funnel and L-Box Tests) and by Gomes and Barros [2] the segregation resistance test by U-Pipe. It is important to emphasize that the method described by NBR 15823-6 [29] for determination of the segregation resistance by

Table 3
X-Ray fluorescence (XRF) results of SCBA composition

Elements	% by mass
SiO_2	86.2
Al_2O_3	2.8
K_2O	2.4
CaO	1.5
Fe_2O_3	2.9
P_2O5	1.6
TiO_2	1.9
Other elements	0.7

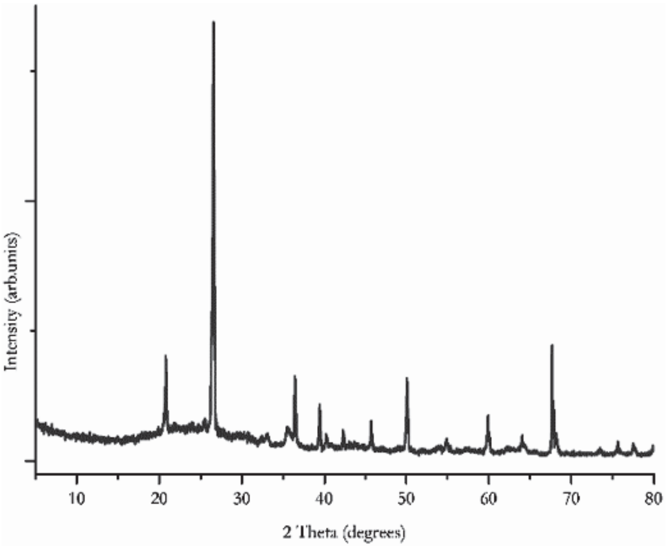


Figure 2
X-Ray diffraction

the segregation column and the sieve methods was replaced by the segregation analysis of Gomes U-Pipe method [6], which presents the same demand and precision level. The classification parameters are shown in Table 4.
It is highlighted that the main acceptance criterion of the respective parameters was the recommendation of NBR 15823-1 [1]. In the cases there were specifications of the standard, the criteria of Gomes and Barros [2] were only considered as acceptance criteria if there was disapproval by the standard.

2.3 Scheme for evaluations of the compressive and tensile strengths

For the study of the compressive strength at 3, 7 and 28 days age, 8 cylindrical specimens (Ø 10 cm x 20 cm) were produced for each of the investigations carried out, that is, a total of 48 specimens for the two traces. For the tensile tests, 8 specimens of each SCC type were also produced, totaling 16 specimens in this type of test. The failures schemes in the 100-ton hydraulic press can be seen in Figure 3.
Panel "a" of Figure 3 presents a schematic image of the rupture by axial compression, for a compressive strength analysis, while panel "b" presents the rupture scheme by diametral compression for a tensile strength analysis. The moldings of the specimens did not use any energy of self-compactibility and followed the other specifications of the NBR 5738 [34]. The test recommended by NBR 5739 [35] was performed specifically for the analysis of the axial compressive strength. For the analysis of the tensile strength by diametral compression, the test recommended by NBR 7222 [36] was carried out, which was later evaluated by NBR 6118 [37]. At the end, both concretes were classified by NBR 8953 [38].

3. Results and discussions

This topic consists of two stages. At first, a synthesis of the self-compacting tests is presented, and after, the results of the mechanical tests of the compressive and tensile strengths.

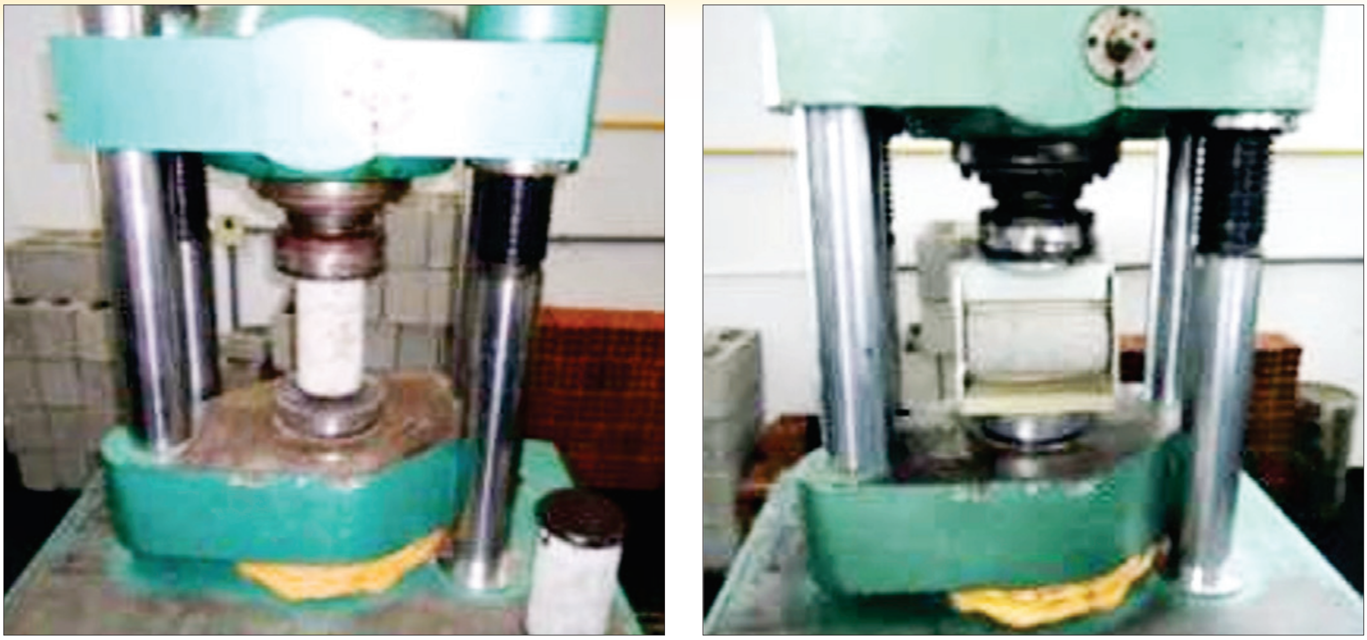
3.1 Obtaining self-compacting traces

The self-compacting properties of the concretes studied were evaluated by verifying the rheological characteristics of fluidity,

Table 4
Range of self-compacting parameters

Test method	Investigated property	Parameters			
		Class	Units	NBR 15823-1 [1]	Gomes and Barros [2]
Slump-flow test NBR 15823-2 [30]	Slump-flow	SF 1	mm	550 to 650	600 to 800
		SF 2		660 to 750	
		SF 3		760 to 850	
	Apparent plastic viscosity t_{500} under free flow	VS 1	s	≤ 2	2 to 7
		VS 2	s	> 2	
J-Ring test NBR 15823-3 [31]	J-Ring passing ability	PJ 1	mm	0 to 25	–
		PJ 2	mm	25 to 50	–
	Blocking step	BS_J	mm	–	0 - 10
L-Box test NBR 15823-4 [32]	Flow time T_{L20}	T_{L20}	s	–	≤ 2
	Flow time T_{L40}	T_{L40}	s	–	≤ 4
	L-Box passing ability	PL 1	(H2/H1)	≥ 0.8	≥ 0.8
		PL 2	(H2/H1)	≥ 0.8	≥ 0.8
V-Funnel test NBR 15823-5 [33]	Apparent plastic viscosity by V-Funnel	VF 1	s	< 9	6 to 15
		VF 2	s	9 to 25	
U-Pipe test	Resistance to segregation by U-Pipe analysis (RS 1. RS 2. RS 3)	RS	%	–	≥ 0.9

Fonte: Adaptado da norma NBR 15823-1 [1] e de Gomes and Barros [2]



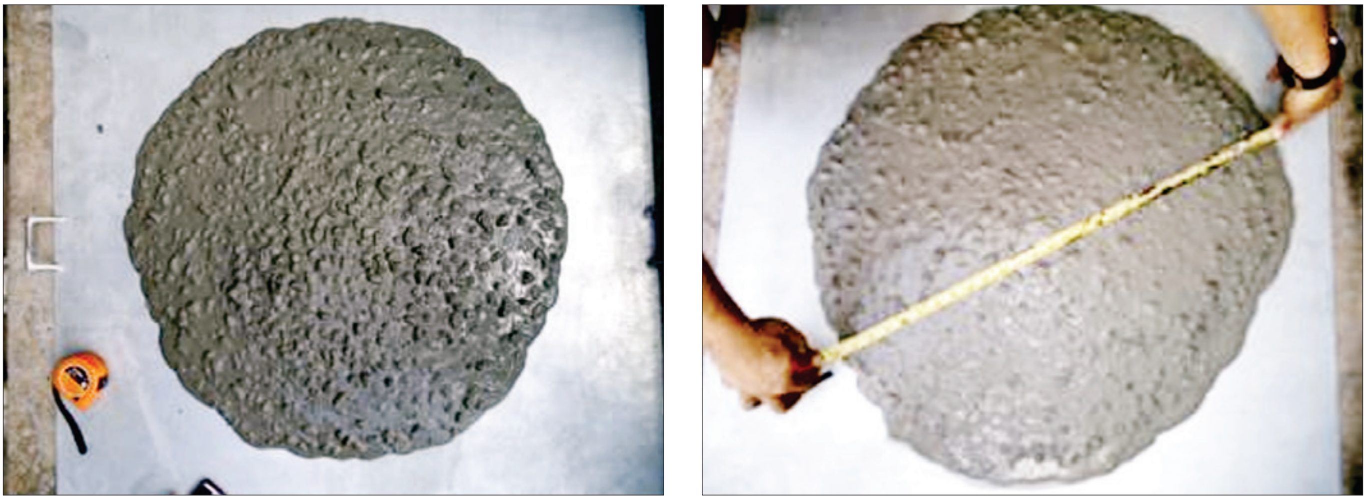
(a) Axial compression **(b)** Diametral compression

Figure 3
Specimens in failure position

Table 5
Results of the self-compactibilty tests

Test method	Propriedade investigada	Units	SCC			$SCC_{SCBA10\%}$		
			Values	**NBR 15823-1 [1]**	**Gomes and Barros [2]**	**Values**	**NBR 15823-1 [1]**	**Gomes and Barros [2]**
Slump-flow test	Slump-flow	mm	745	SF 2	ok	702	SF 2	ok
	Apparent plastic viscosity t_{500} under free flow	s	1.0	VS 1	didn't atend	2	VS 1	didn't atend
J-Ring test	J-Ring passing ability	mm	125	didn't atend	–	2	PJ 1	–
	Blocking step	mm	9.5	–	ok	3	–	ok
L-Box test	Flow time T_{L20}	s	0.2	–	ok	0.4	–	ok
	Flow time T_{L40}	s	0.8	–	ok	0.7	–	ok
	L-Box passing ability	(H2/H1)	0.9	PL 2	ok	0.9	PL 2	ok
V-Funnel test	Apparent plastic viscosity by V-Funnel	s	5.3	VF 1	didn't atend	5.1	VF 1	didn't atend
U-Pipe test	Resistance to segregation by U-Pipe analysis (RS 1. RS 2. RS 3)	%	0.92	–	ok	1.10	–	ok
			0.95	–	ok (RS)	1.00	–	ok (RS)
			0.93	–	ok	1.10	–	ok
Specific mass	Normal specific mass without compaction	kg/m³	2399			2405		
Cement consumption	Cement consumption per m³ of concrete	kg/m³	405			396		

Note: The fields with the dash (-) indicate that no tests occurred or there were no relevant classifications according to Table 4



(a) Concrete without SCBA

(b) Concrete with 10% of SCBA

Figure 4
Illustrations of the slump-flow tests

cohesion and segregation resistance in their fresh state. The results achieved are shown in Table 5.

It was verified, by evaluating the results presented in Table 5, that both concretes received technical approvals in all the tests of self-compactibility of NBR 15823-1 [1]. Although the concrete without SCBA has not fulfilled the J-Ring test according to the parameters of NBR 15823-1 [1], it had partial approval by the auxiliary parameter of J-Ring, the "*Blocking step*", recommended by Gomes and Barros [2]. Figure 4 shows illustrations of the Slump-flow test of the two concretes.

It was considered at this moment that both concretes studied fulfilled the requirements of self-compactibility demanded for the category of SCC. Therefore, under these conditions, the specimens were produced for the study of the mechanical properties. The materials consumption for both concretes are demonstrated in Table 6.

In Table 6, it is highlighted that the consumption ranges of both concretes components meet the specifications of EFNARC [3], including the cement consumption very close of the expected average ranges of 350 Kg to 450 Kg per cubic meter of SCC. It is also observed, in the same Table, the evident effective reduction of 87.63 kg/m^3 of sand with the direct use of 79.30 Kg of SCBA in the concrete trace $SCC_{SCBA10\%}$. Considering also the analysis of the fresh state, it was possible to affirm, by the parameters of fluidity and flow, apparent plastic viscosity, passing ability and segregation resistance, that both the $SCC_{SCBA10\%}$ and the SCC without SCBA present the same technical recommendations of application in accordance with the criteria of NBR 15823-1 [1]. By the annexes of this standard, it is possible to affirm that both are appropriate to be applied in most constructions works, such as walls, beams, pillars and others.

3.2 Evaluations of the compressive and tensile strength

The results of the compressive strengths are presented in Table 7. These are the average values of the specimens of each concrete trace, as well as the respective calculations of the characteristic compressive strength values (fck).

At the age of 3 and 7 days, a greater difference, about 8%, in the results of the characteristic compressive strength (fck) was observed, considering the hardening stages. However, only a small difference of 3 % in the characteristic axial compressive strength at 28 days was observed, which is the classificatory stage of NBR 8953 [39].

Table 6
Materials consumption for 1 m³ of concrete

Components	SCC (kg/m³)	$SCC_{SCBA10\%}$ (kg/m³)	Variation in kg
Cement	400.51	396.33	4.18
Calcitic limestone filler	160.22	158.55	1.67
Sand	801.00	713.37	87.63
SCBA	0.00	-79.30	79.30
Gravel	849.10	875.90	26.80
Water	180.20	178.32	1.88
Superplasticizer	2.20	2.18	0.02

Table 7
Axial compressive strengths at 3, 7 and 28 days

Concretes	Age	Average compressive strength (f_{cm}) (MPa)	Batch standard deviation (σ)	Characteristic resistance to compression (f_{ck}) (MPa)
SCC	3 dias	25.48	0.80	24.15
$SCC_{SCBA10\%}$		23.41	0.71	22.24
Variation		8%	–	7.9%
SCC	7 dias	29.71	2.01	26.40
$SCC_{SCBA10\%}$		27.95	2.27	24.20
Variation		5.9%	–	8.3%
SCC	28 dias	40.8	1.35	38.6
$SCC_{SCBA10\%}$		40.9	0.69	39.8
Variation		0.25%	–	3%

The tests results of the axial compressive strength for both concretes placed them in the same level of mechanical resistance by the classification of NBR 8953 [39]. Therefore, both of them belong to group I and to class C35 of strength. It is also worth emphasizing, by the Student's *t*-test with significance level α of 5%, that the average values of the compression failures have confidence intervals with a lower and upper limit of 37.47 MPa and 39.73 MPa (error of ± 1.13 MPa), respectively, for the SCC, and of 40.38 MPa to 39.22 MPa (error of ± 0.58) for the $SCC_{SCBA10\%}$. Consequently, it is possible to reproduce again the two compositions of SCC with a 95% confidence level with values capable of providing resistance results within group I for the class C35.
The results obtained in the characteristic axial compressive strength at 28 days, of 39.90 MPa for the $SCC_{SCBA10\%,}$ are similar to the 3 traces obtained by the modification of the SCBA preparation performed by Sampaio et al. [16], which were of 38.6 MPa, 39.19 MPa and 38.64 MPa for the same replacement rate. Already, Lima et al. [14] obtained 27.98 MPa and 28.72 MPa for the concrete with 30% and 50%, respectively, of replacement of sand by SCBA.
The results of the tensile strength at 28 days are shown in Table 8, where the average values of the specimens of each concrete trace and their respective characteristic values are presented.
In order to analyze the tensile strength, Table 9 was elaborated by the determination of the characteristic compressive strength (fck) and the support of NBR 6118 [37].
In general, the characteristic tensile strenght values (fctk,sp), presented in Table 9, are adjusted between the characteristic average and minimum values proposed by the calculation of the characteristic compressive strength (fck) by NBR 6118 [37], with a minimum variation of 2% between the SCC's developed. It is important to highlight, by the Student's *t*-test with significance level α of 5%, that the average values of the tensile failures have confidence intervals with a lower and upper limits of 2.54 MPa and 3.56 Mpa (error of ± 0.51 MPa), respectively, for the SCC, and of 2.47 MPa to 3.37 MPa (error of ± 0.45 MPa) for the $SCC_{SCBA10\%}$. Therefore, it is possible to reproduce the two compositions of SCC with a 95% confidence level with values capable of providing desirable results between fct,m and fctk,inf. Figure 5 shows two SCC specimens ruptured by the diametral compression test.
It is observed in Figure 5 that there are good coverings of the mortars in relation to the gravels in both specimens. Moreover, there is a homogeneous distribution of the coarse aggregates along the vertical and radial extension, which is a typical and necessary characteristic for SCC's.

Table 8
Tensile strength by diametral compression at 28 days

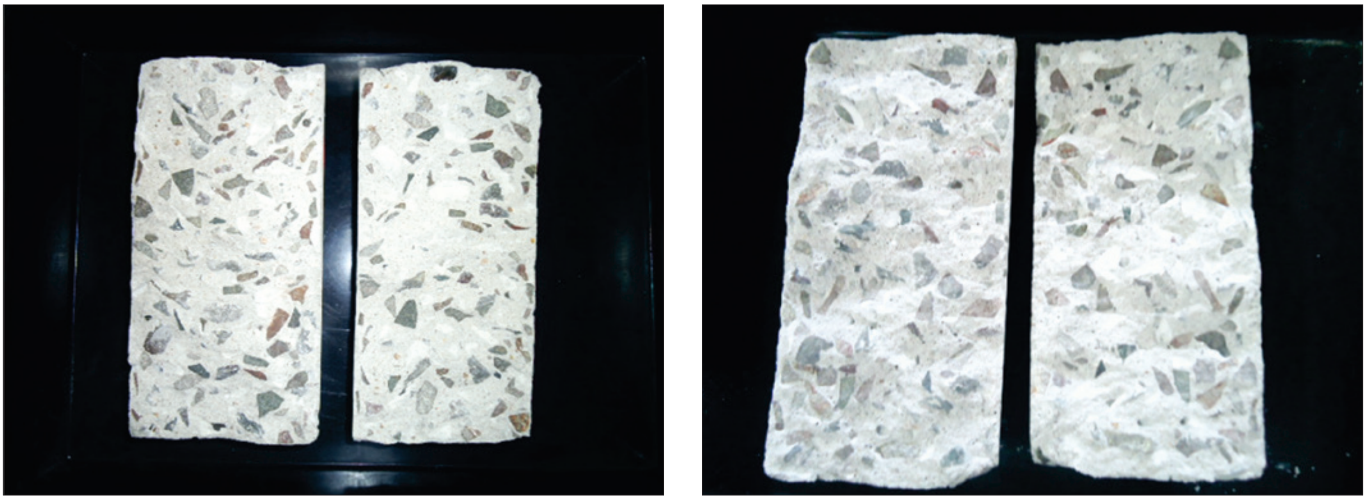
Concretes	Average resistance to diametral compression ($f_{ctm.sp}$) (MPa)	Batch standard deviation (σ)	Characteristic resistance to diametral compression ($f_{ctk.sp}$) (MPa)
SCC	3.05	0.20	2.71
$SCC_{SCBA10\%}$	2.92	0.24	2.52
Variation	6.2%	–	8.2%

4. Conclusions

This work obtained two SCC traces, with and without SCBA, for the study of the mechanical performances of compressive and tensile strengths. In particular, the highlights were:
1. The rheological parameters of fluidity and flow, apparent plastic viscosity, passing ability and segregation resistance,

Table 9
Tensile strength analysis

Concretes	NBR 7222 [36]	NBR 6118 [37]	
	Characteristic tensile strength ($f_{ctk,sp}$) (MPa)	Expected average tensile strength ($f_{ct,m}$) (MPa) $f_{ct,m} = 0,3\ f_{ck}^{2/3}$	Minimum tensile strength ($f_{ctk,inf}$) (MPa) $f_{ctk,inf} = 0,7\ f_{ct,m}$
SCC	2.71	3.43	2.40
$SCC_{SCBA10\%}$	2.52	3.50	2.45
Variation	8.2%	2.1%	2.0%



(a) SCC

(b) $SCC_{SCBA10\%}$

Figure 5
Specimens ruptured by diametral compression

obtained by the SCC without SCBA and the SCCSCBA10, showed that both of them achieved the previous recommendation to be used in several structural applications following the standards of NBR 15823-1 annexes.[1];

2. In general, it was possible to classify, by NBR 8953 [38], both SCC's as belonging to group I and to class C35 of strength, with a 95% confidence level of reproducibility;
3. It is emphasized that the SCCSCBA10% maintained the same levels of materials consumption, which are in accordance with the values ranges of this concrete technology and also contributed to the reduction of 87 kg/m³ in the effective consumption of sand;
4. In a direct evaluation on the SCC performance in the fresh state in relation to the SCCSCBA10%, it is noted that the 10% replacement rate of sand by SCBA, in mass, do not change the rheological properties for the SCC's in the aspects of fluidity, cohesion and consistency;
5. Still performing a direct comparison, the results indicated that it is possible to use the SCBA in the SCC production with no significant variations in the mechanical properties of compressive strength at 3, 7 and 28 days of age and of tensile strength at 28 days.

Finally, it is worth noting that this paper considered as important the advances in the development of new materials for the civil construction industry, which directly reduce the extraction of natural resources in favor of the respect for the social and environmental values.

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