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Experimental investigation on shear resistance of self-consolidating concrete beams

Análise experimental da resistência ao cisalhamento de vigas de concreto autoadensável

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Abstract

Self-consolidating concrete stands out for its high fluidity and stability, which are obtained by the reduction of the coarse aggregate dimensions and content in the mixture and also by the addition of superplasticizer and viscosity modifiers. An experimental test program was carried out to evaluate the influence of these particularities of self-consolidating concrete mixtures on the shear capacity of beams with shear reinforcement. Four mixtures of self-compacting concrete and two mixtures of conventionally vibrated concrete with different coarse aggregate size and volume were used for the production of beams to be tested under flexure. The experimental results were compared to those estimated by the ACI-318, CAN A23.3, EC-2 and NBR 6118 design codes. The results demonstrated that the reduction of coarse aggregate dimensions and content in self-compacting concrete mixture did not significantly influence the ultimate shear strength. The shear strengths obtained experimentally were considered adequate to codes estimates, for both concrete types.

Keywords: self-consolidating concrete, shear resistance, aggregate interlock, beams.

Resumo

O concreto autoadensável se destaca pela alta fluidez e estabilidade, sendo estas propriedades obtidas com a redução da granulometria e volume de agregado graúdo da mistura, adição de materiais finos e a utilização de aditivos superplastificantes e modificadores de viscosidade. Um programa experimental foi realizado para avaliar a influência destas particularidades de dosagem do concreto autoadensável na resistência ao cisalhamento de vigas de concreto com armadura transversal. Quatro misturas de concreto auto adensável e duas misturas de concreto convencionalmente vibrado com dimensão máxima e volume de agregado graúdo diferenciados foram utilizados para produção de vigas a serem ensaiadas a flexão com o intuito de comparar os resultados obtidos com os os estimados pelas normas de dimensionamento de estruturas ACI-318, CAN A23.3, EC-2 e NBR 6118. Os resultados demonstraram que a redução da granulometria e volume de agregado graúdo no concreto autoadensável não influenciaram significativamente na resistência última ao cisalhamento. Entretanto, verificou-se um aumento da parcela de resistência atribuída ao concreto e mecanismos alternativos nas vigas de concreto autoadensável em relação ao concreto convencionalmente vibrado. As resistências ao cisalhamento obtidas experimentalmente foram consideradas adequadas às estimativas das normas, tanto para o concreto convencional quanto para o autoadensável.

Palavras-chave: concreto autoadensável, resistência ao cisalhamento, engrenamento de agregados, vigas.

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1. Introduction

In the late 1980s, the reduction of skilled workers and the need to increase the durability of reinforced concrete structures led researchers at the University of Tokyo to develop a high-performance concrete characterized by the ability to spread readily by its own weight, passing by the reinforcement without the necessity of mechanical vibration.This high-performance concrete was called self consolidating concrete (SCC) [1]. The high fluidity is a consequence of the addition of superplasticizers, of the smaller size and reduction of volume fraction of coarse aggregate in the mixture as well as the increase of the volume fraction of fine aggregate. In addition, viscosity and cohesion are ensured by additions of fine materials, such as fly ash, rice husk ash, blast furnace slag, silica fume, and limestone or quartz fillers [2].

These modifications in the mix design together with being a relatively new material, brought about a certain restriction in the use of SCC. There is a need for skilled workers for production and also absence of data regarding the structural performance of this material [3].

According to Domone [4], the tensile and compressive strengths of self consolidating concrete are similar to conventional concrete, however the modulus of elasticity can be up to 40% lower in self consolidating concrete with compressive strength close to 20 MPa, and 5% lower in high strength concrete, above 90 MPa, as compared to conventional concrete. This reduction of the elasticity modulus of self consolidating concrete is caused by the lower volume fraction of coarse aggregates and the increase of the mortar volume fraction.As a consequence, excessive deflections are expected for structures affecting their serviceability limit state [5] [6].

In addition, uncertainties about the shear strength of self consolidating concrete and the lack of specification in the current standards for the design of reinforced concrete structures are still a hindrance for this material to be used by designers in practical applications [3].

Recent studies with conventional concretes have demonstrated that the maximum-size coarse aggregate directly influences aggregate interlock at crack surfaces. Depending on the mixture, the shear strength may be higher for concretes produced with larger aggregates [7] [8]. Since self consolidating concrete requires a smaller content of coarse aggregate with smaller size in its mixture, it may present a reduction on shear strength when compared to conventional concrete [3]. However, this reduction is not a consensus among researchers.

Using direct shear tests, Desnerck et al. [5] verified higher shear strength of self consolidating concrete as compared to conventional concrete.This higher strength was attributed to the improvements in the concrete matrix provided by the use of a greater amount of fine materials, increasing the friction between the surfaces of the cracks, and consequently supplying the reduction of coarse aggregates. On the other hand, Kim et al. [9] verified higher aggregate interlock for conventional concrete in relation to self-consolidating concrete. Shear resistance increased with the increase of the coarse aggregate content in the mixture, regardless of the type of aggregate.

Thus, although self consolidating concrete was developed three decades ago, there is no exact definition of its behavior under shear stresses.Therefore, it is necessary to evaluate the influence of self consolidating concrete mixtures with reduced volume fraction of coarse aggregates of smaller sizes on the shear strength of beams with this material. This work intends to contribute to reduce the uncertainties about the structural performance of self consolidating concrete in relation to shear strength, through the formation of a database of experimental tests and comparison with expected values from international standards.

2. Materials e experimental program

The experimental program was designed to compare the shear strength of conventional vibrated and self consolidating concretes beams with transverse reinforcement tested under four-point bending tests.

2.1 Concrete mixtures and casting of beams specimens

Six concrete mixtures were obtained from a conventional concrete mixture proportion.Two maximum size coarse aggregates and two coarse aggregate volume fractions were used.The mixtures were identified by letters corresponding to concrete type, conventional (CC) or self consolidating (SCC), by the maximum coarse aggregate size, 9.5 mm (0) or 19.0 mm (1), and also by the coarse aggregate volume fraction, normal (N) or reduced by 30% (R). For concrete mixtures with reduction of coarse aggregate volume fraction, the mixture was complemented with fine aggregate.Furthermore, self-consolidating concretes received addition of limestone filler, in order to increase their viscosity, and superplasticizer admixture based on polycarboxylate, to increase their flowability.

Table 1
Mixture proportions for CC and CA mixtures (kg/m³)

Concrete	Cement (kg)	Filler (kg)	Natural sand (kg)	Artificial sand (kg)	Coarse aggregate 0 (kg)	Coarse aggregate 1 (kg)	Water (kg)	Superplasticizer (kg)
CC1	385.18	—	418.54	417.41	—	964.59	200.29	—
CC0	385.18	—	418.54	417.41	961.10	—	200.29	—
CA1N	385.18	214.77	312.88	312.04	—	964.59	200.29	0.87
CA0N	385.18	214.77	312.88	312.04	961.10	—	200.29	0.77
CA1R	385.72	215.08	456.45	455.23	—	676.02	200.57	1.15
CA0R	385.72	215.08	456.45	455.23	673.58	—	200.57	1.11

Table 2
Fresh and hardened properties of CC and CA mixtures

Concrete	Slump (mm)	Slump flow (mm)	Density (kg/m³)	V-funnel (s)	L-box (mm)	f_{cm} (MPa)
CC1	90	—	2424	—	—	47.0
CC0	85	—	2391	—	—	41.2
CA1N	—	73.5	2391	19.63	0.87	48.2
CA0N	—	70.5	2391	21.52	0.81	42.7
CA1R	—	79.5	2367	11.94	0.87	47.7
CA0R	—	78.5	2421	10.42	0.83	47.4

Brazilian Portland cement CP V-ARI-RS, similar to ASTM Type V, with high initial strength and sulphate resistant was used.Form removal was performed after 24 hours of casting. The fine aggregate used was a mixtureof 50% quartz sand, with a fineness modulus of 2.23 and specific mass of 2.67 kg/dm³, and 50% granitic rock crushing sand, with fineness modulus of 3.8 and specific mass of 2.68 kg/dm³. Granite coarse aggregates with maximum sizes of 9.5 mm and 19.0 mm and a specific mass of 2.67 kg/dm³ were used. A calcitic limestone filler, from the metropolitan region of Curitiba-PR, composed mainly of CaO with 90% of material passing through the 74 μm sieve was also added to the SCC mixes. The mix proportions for the production per m³ of concrete are summarized in Table 1.

All concrete mixes were produced with water cement ratio of 0.52. Superplasticizer admixture was initially added at 0.3% of the cement mass, however during concrete production this value was later corrected according to the flowability requirements of each self consolidating concrete mixture. The final values lied between 0.2% and 0.3% of the cement mass.

Self consolidating concretes with normal aggregate volume, CA1N and CA0N, were obtained from conventional concrete mixtures, CC1 and CC0, respectively, by replacing 25% of fine aggregate mass by limestone filler. The same content of filler was used in the self consolidating concretes with reduced aggregate volume, CA1R and CA0R.For these latter mixtures 30% of the coarse aggregate volume was replaced by fine aggregate thus maintaining the proportion of fine materials around of 600 kg/m³ of concrete for all self consolidating concrete. CA0N, CA1N, CC0 and CC1 presented 56% of mortar content whereas for CA1R and CA0R this content increased to 69% due to the reduction of aggregate volume by 30% and complementation with small aggregates.

Concrete mixture were evaluated considering its workability according to the slump test, as specified by ABNT NBR NM 67 standard [10], for conventional concrete.For SCC mixtures, their flowability, passing ability and viscosity were evaluated according to the tests defined by ABNT NBR 15823 [11]. The compressive strength of the concrete used to cast the beams specimens was obtained from using cylindrical specimens (10 cm in diameter and 20 cm in height), according to ABNT NBR 5739 [12].The results are presented in Table 2.

Both SCC and CC mixtures were mixed in a 150 L capacity batch mixer with three beams and three cylindrical specimens cast with each concrete mixture. Formworks made of medium density fiberboard were used for beams specimens where concrete was placed manually.Conventional concrete beams were vibrated with a 25 mm diameter immersion vibrator.

After 24 hours of casting, the beams and cylindrical specimens were demolded and stored under plastic canvas.These specimens were moistened daily during the first seven days.They remained under laboratory conditions, with a mean temperature of 22.5 °C and relative humidity around 75.4%.All experiments were performed at 28 days of age.

2.2 Details of beams specimens and test set up

The concrete beams were design to fail by shear when transverse reinforcement yield was reached. The beams had a rectangular cross section of 10 cm x 25 cm, total length of 150 cm, with the distance between the supports of 130 cm. Four point bending tests were performed through load point located at a 50 cm distance from the supports.The shear span and the effective height of the cross section (a/d) was close to 2.25, according to the scheme shown in Figure 1.

All beams were reinforced with two 16 mm diameter CA-50 reinforcing bars, placed at the bottom of the cross section, corresponding to a longitudinal reinforcement ratio of 1.61%.Two 5 mm diameter CA-60 reinforcing bars were positioned at the top of the cross-section. The transverse reinforcement consisted of rectangular stirrups spaced 20 cm along the entire beam, as shown in Figure 2.

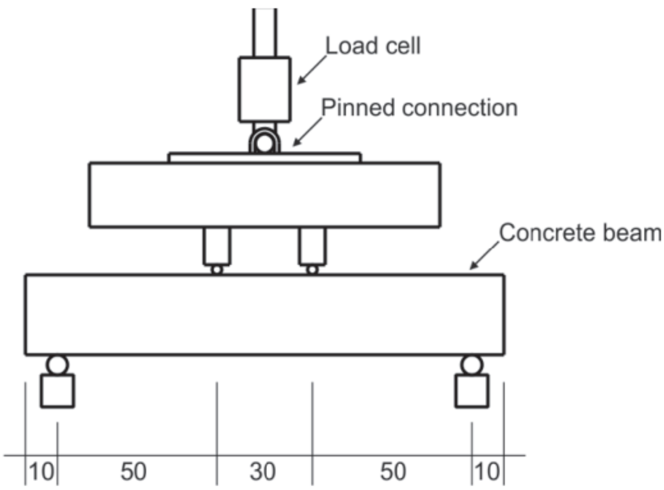

Figure 1
Four-point bending test set-up (dimensions in cm)

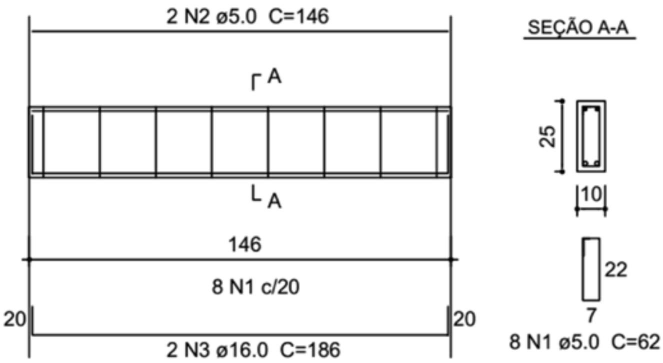

Figure 2
Beam dimension and reinforcement

Loading was applied using a hydraulic jack coupled to a load cell with a capacity of 200 kN, at a constant rate of 500 N/s until failure. During loading, at loads of 30 kN, 60 kN and 90 kN the number and position of cracks were identified. These load values were defined from the theoretical load capacity of the beams, aiming to evaluate the behavior of the beams before and after its cracking resistance.
In order to measure the vertical displacement at middle span of the beam, two linear variable displacement transducers (LVDTs) with a measuring capacity of 10 mm were used.The LVDTs were fixed in aluminum bars installed on the sides of the beams, which were supported on rollers at the ends of the beams.The LVDTs were referenced on steel angles screwed at the neutral axis. Shear crack openings were measured in the two shear spans using LVDTs installed 15 cm from the load application points, fastened with screws on the upper side of the beam face and in a channel section steel bar screwed on the bottom of the beam.The positions of the LVDTs are shown in Figure 3.

3. Results and discussion

3.1 Cracking pattern and shear resistance

All beams tested presented a similar behavior regarding cracking. The first flexural crack appeared in the middle of the span, before 30 kN load.The formation of shear cracks happened when the shear force was near to 35 kN. The shear crack width at failure was greater than 1.0 mm.
Figures 4 to 6 detailed the observed cracks pattern for all beams at failure. The load, in kN, indicates the corresponding load step while the letter R represents the cracks that occurred between 90 kN and failure. The dotted lines correspond to the inclination of the shear crack, presented at the upper part of the beam. The inclination of the shear crack presented values between 26.0° and 54.1°.There was not an observed direct relationship between its inclination and the ultimate shear strength of the beams, as have also occurred in previous tests of beams without transversal reinforcement presented by Savaris and Pinto [13].
During the tests of two beams, CA1N V1 and CA1R V3, there were failures in the mechanism of load application and the data logger. Thus, these samples were discarded. Among the mixtures studied, there was no distinction in the cracking pattern of the beams, with similar cracks between the mixtures and also a great variation in the inclination of the shear crack. Beams CC0 V3 and CA0N V2 presented failure of the transverse reinforcement at the end of the shear crack, near the longitudinal reinforcement.In these cases, this crack presented inclination greater than 45° without crossing the transverse reinforcement. Due to this distinct behavior the results obtained for these beams were also disregarded.
Table 3 shows the ultimate shear forces (V_u) resisted by the beams and the mean values for each concrete mix.
Concrete mixtures showed small variation in compressive strength, with values between 41.2 MPa and 48.2 MPa, demonstrating that the changes in the mix design had not significant influence on the ultimate shear strength of the beams. The reduction of coarse

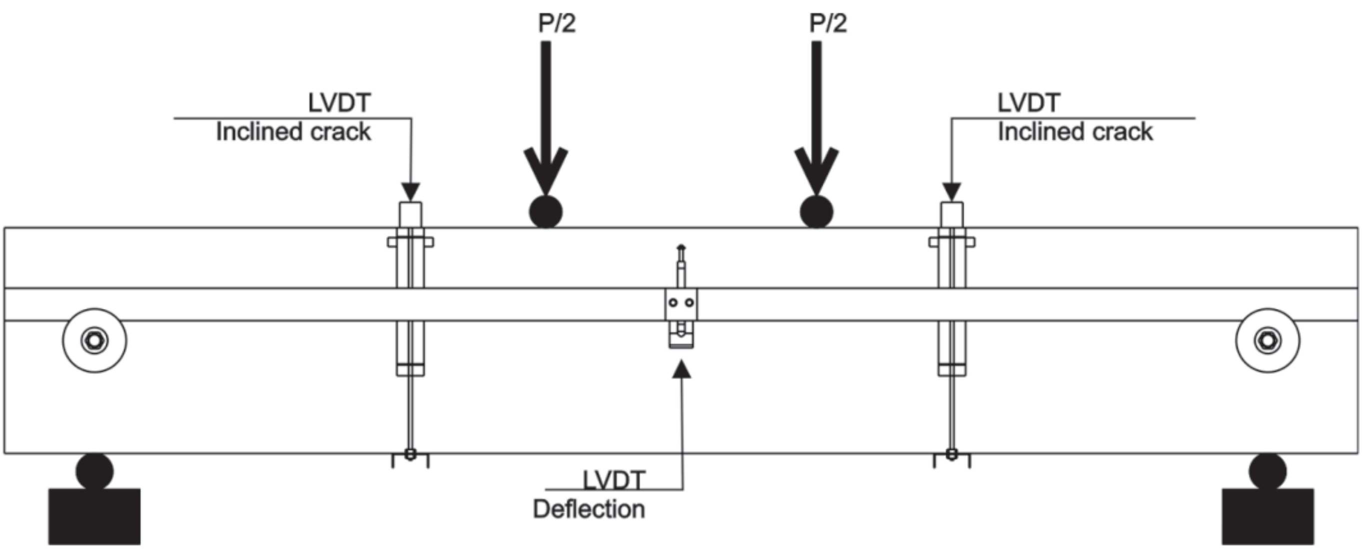

Figure 3
Beam instrumentation

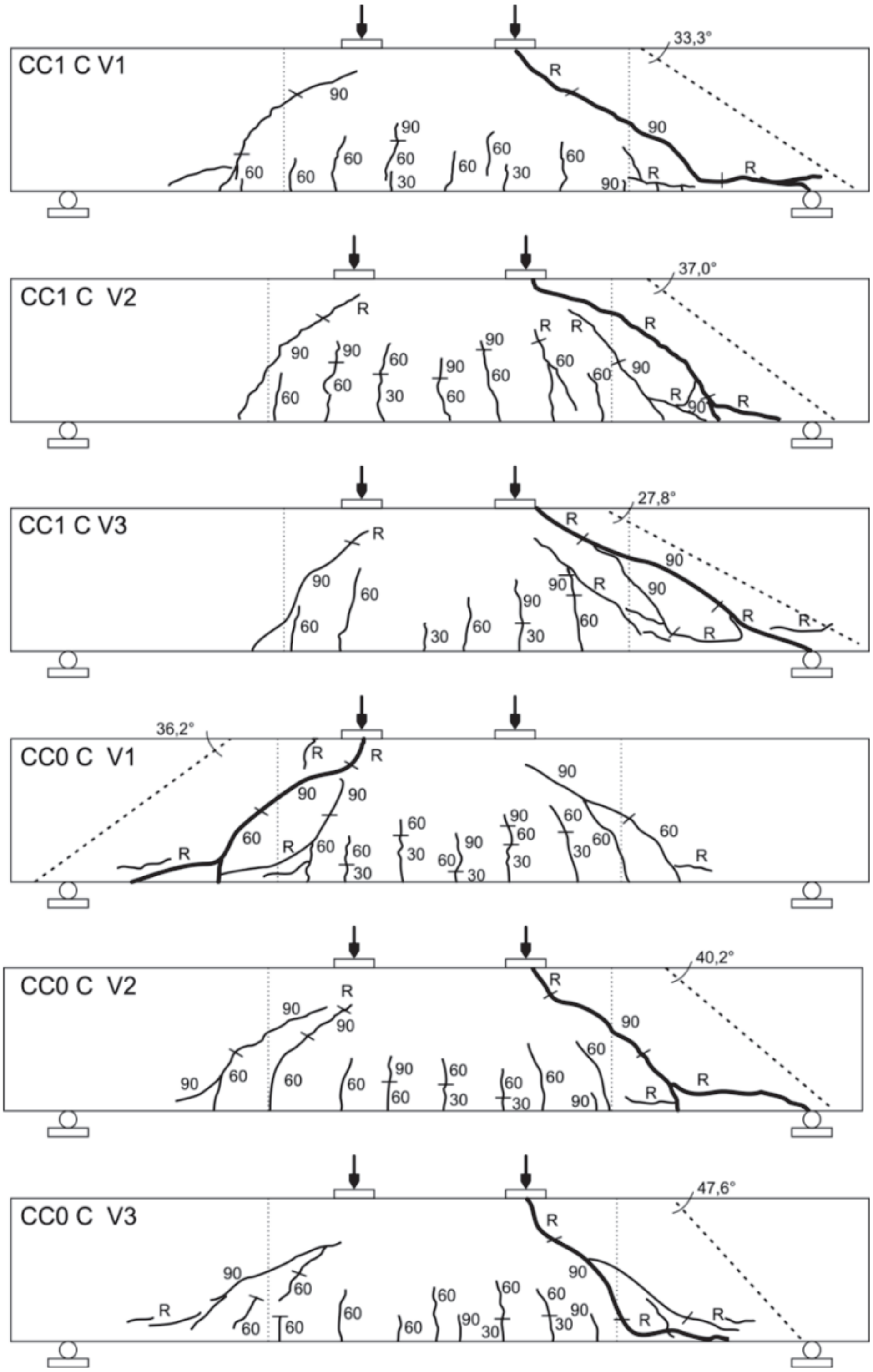

Figure 4
Crack patterns of conventional concrete beams

aggregate maximum size from 19 mm to 9.5 mm showed a greater influence on the shear strength of the conventional concretes, with a reduction of 10.2%, than for self-consolidating concretes, where this variation was smaller than 5%. The reduction of coarse aggregate volume fraction in self consolidating concretes did not show a significant effect on shear strength, with variations smaller than 3%.

3.2 Transverse reinforcement effect on shear resistance

In experimental tests of beams without shear reinforcement, Savaris and Pinto [13] verified that beams produced with conventional concrete showed higher shear strength than beams made with self consolidating concrete.The reduction of the shear resistance of self consolidating concrete beams was attributed to the higher content of fine materials in their composition and lower aggregate content, thus reducing the aggregate interlock mechanism.

In order to evaluate the effect of the presence of the transverse reinforcement on the shear strength of the beams tested in this work, the results obtained were compared with the results from Savaris and Pinto [13], since these beams presented the same geometric characteristics, longitudinal reinforcement ratio and concrete mix

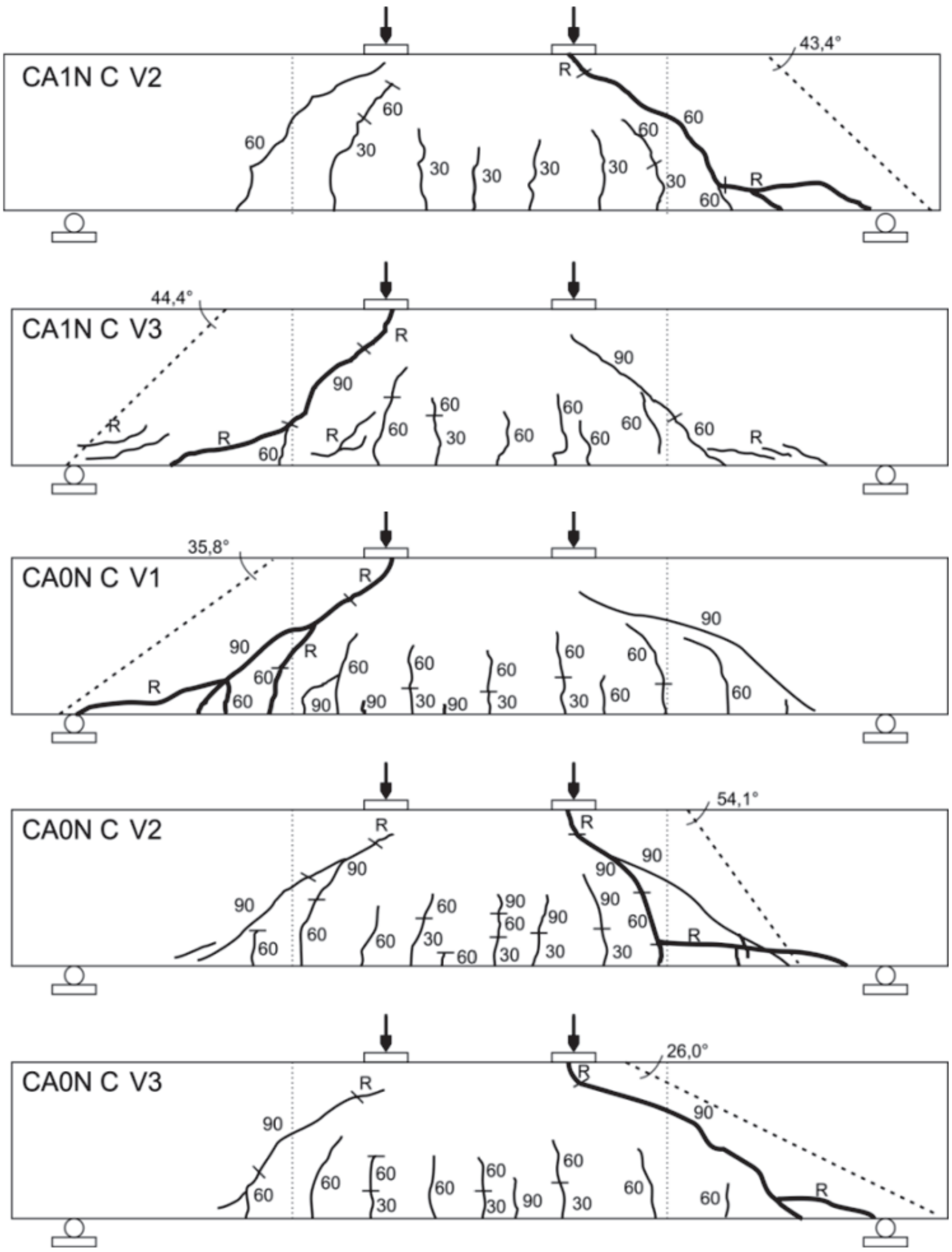

Figure 5
Crack patterns of self consolidating concrete beams with normal amount of coarse aggregate

proportions. Thus, the shear force resisted by the transverse reinforcement (V_{sw}) was calculated using Equation (1), resulting in 25.64 kN.This value was subtracted from the experimental shear force (shown in Table 3), resulting on the shear resistance attributed to concrete and alternative resistance mechanisms (V_c).

$$V_{sw} = f_{yw} A_{sw} \tag{1}$$

where:
V_{sw}: shear resistance provided by transverse reinforcement;
f_{yw}: specified yield strength of transverse reinforcement, equal to 658 MPa, obtained by tension tests;
A_{sw}: area of shear reinforcement, equal to 38.96 mm².

In order to consider the difference on the compressive strength of the concrete mixes used in the beams with and without transverse reinforcement, the shear resistance V_c was normalized, i.e., the value was divided by the square root of the compressive strength of the concrete. Table 4 presents the final normalized shear force resisted by the concrete and alternative resistance mechanisms of the beams with transverse reinforcement ($V_{C\_C,n}$), of the beams without transverse reinforcement ($V_{C\_S,n}$) and the relationship between these values for each concrete mixture.
Table 4 indicates that shear strength values were similar for beams

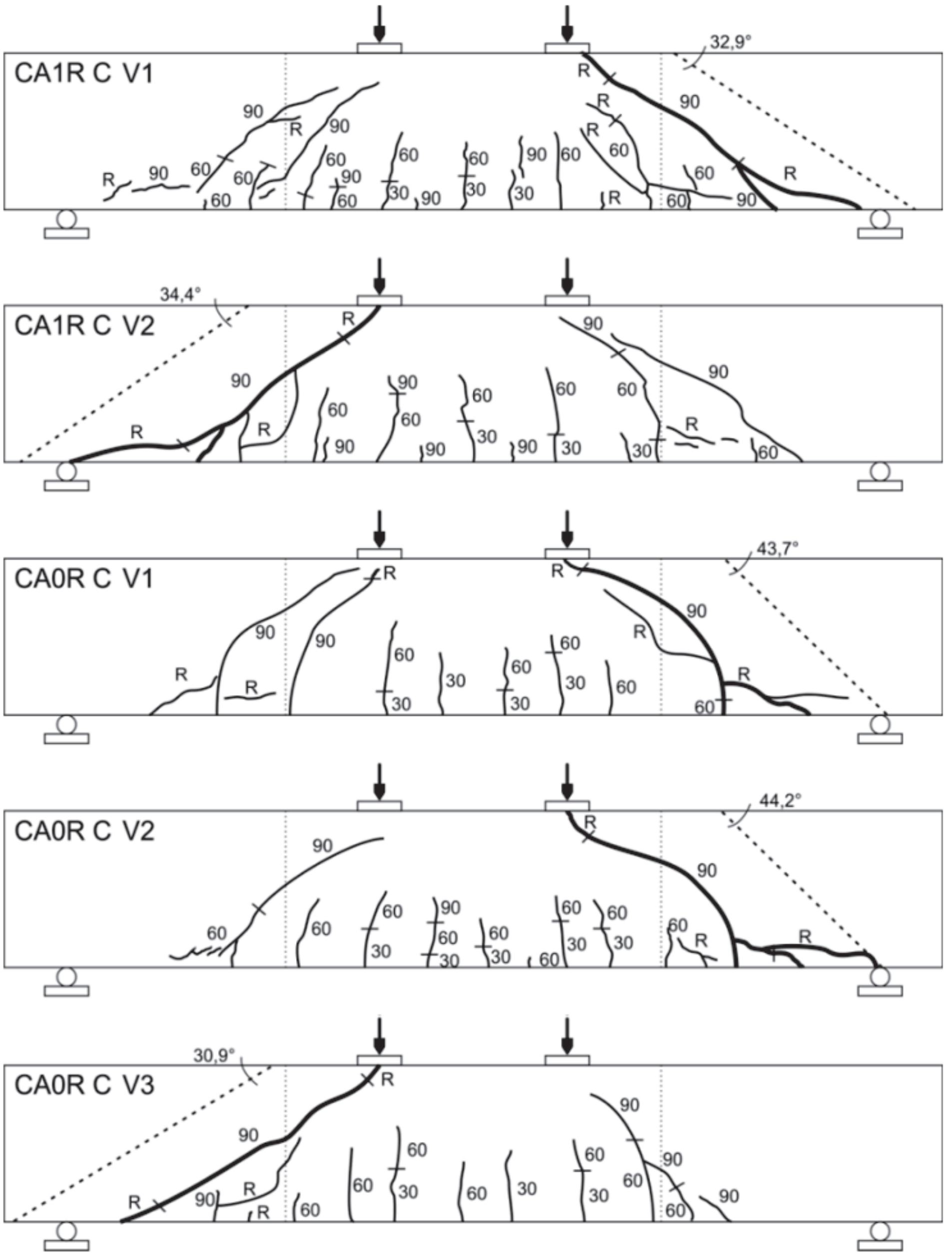

Figure 6
Crack patterns of self consolidating concrete beams with reduced amount of coarse aggregate

produced with conventional concrete with and without transverse reinforcement. However, the self consolidating concrete beams with transverse reinforcement presented V_{C_Cn} between 22% and 32% higher than the strength of the same beams without transverse reinforcement. This increase of the V_c was responsible for reducing the variation of the ultimate strength for beams with transverse reinforcement, supplying the lower resistance observed in self consolidating concrete beams without this reinforcement, as previously presented by Savaris and Pinto [13].

These results can be attributed to the higher bond of the self-reinforcing concrete to the reinforcement, caused by the use of filler, as demonstrated at Almeida Filho et al. [14], Desnerck et al. [5] and Helincks et al. [15], resulting in small shear crack opening and consequently higher aggregate interlock. It should be noted that the beams tested in this work presented a transverse reinforcement ratio close to the minimum required by Brazilian building code, indicating that a greater increase in shear strength can occur in self consolidating concrete beams in relation to the

Table 3
Ultimate shear capacity of beams with transverse reinforcement

Concrete	V_u (kN)	$V_{u,m}$ (kN)	Standard deviation (kN)
CC1 – V1	72.6		
CC1 – V2	70.5	72.6	2.05
CC1 – V3	74.6		
CC0 – V1	63.6	65.1	2.19
CC0 – V2	66.7		
CA1N – V2	71.8	74.5	3.89
CA1N – V3	77.3		
CA0N – V1	76.5	70.8	8.06
CA0N – V3	65.1		
CA1R – V1	70.4	72.5	2.90
CA1R – V2	74.5		
CA0R – V1	68.5		
CA0R – V2	68.4	70.6	3.78
CA0R – V3	75.0		

Table 4
Normalized shear resistance attributed to concrete of beams with and without transverse reinforcement

Concrete	$V_{C\_C,n}$ ($kN.MPa^{-0.5}$)	$V_{C\_S,n}$ ($kN.MPa^{-0.5}$)	$V_{C\_C,n}/V_{C\_S,n}$ ($kN.MPa^{-0.5}$)
CC1	6.84	6.71	1.02
CC0	6.15	5.95	1.04
CA1N	7.04	5.39	1.31
CA0N	6.91	5.22	1.32
CA1R	6.78	5.34	1.27
CA0R	6.53	5.37	1.22

Table 5
Code based equations to prediction of shear resistance of beams

Code	Concrete attributed resistance	Reinforcement attributed resistance
ACI 318	$V_c = \frac{\sqrt{f_c}\, b_w\, d}{6}$	$V_s = \frac{A_{sw}\, f_{yw}\, d}{s}$
CAN A23.3	$V_c = \beta \sqrt{f_c}\ b_w d_v$ $\beta = \frac{0.4}{(1+1500\,\varepsilon_x)}\frac{1300}{(1000+S_{ze})}$ $\varepsilon_x = \frac{M/d_v + V}{2\, E_s\, A_{sl}}$ $d_v \geq \begin{cases} 0.9\, d \\ 0.72\, h \end{cases}$ Em elementos sem armadura transversal: $s_{ze} = \frac{35\, d_v}{15 + a_g}$ Em elementos com armadura transversal: $s_{ze} = 300$	$V_s = \frac{A_{sw}\, f_{yw}\, d_v\, cotg(\theta)}{s}$ $\theta = 29 + 7000\, \varepsilon_x$
EC-2	$V_c = 0.18\, k\, (100\, \rho_l\, f_c)^{1/3}\, b_w\, d$ $k = 1 + \sqrt{\frac{200}{d}}$	$V_s = \frac{A_{sw}\, z\, f_{yw}\, cotg(\theta)}{s}$ 21.8° ≤ θ ≤ 35°
NBR 6118 Model I	$V_c = V_{c0} = 0.6\, f_{ct}\, b_w\, d$ $f_{ct} = 0.21\, f_c^{\,2/3}$	$V_s = \frac{A_{sw}\, f_{yw}\, 0.9\, d}{s}$
NBR 6118 Model II	$V_c = V_{c0}\frac{V_{Rd2} - V_{Sd}}{V_{Rd2} - V_{C0}}$ $V_{Rd2} = 0.54\left(1 - \frac{f_{ck}}{250}\right) f_{ck}\, b_w\, d\, sen^2\theta\, cotg\theta$	$V_s = \frac{A_{sw}\, f_{yw}\, 0.9\, d\, cotg\theta}{s}$

Table 6
Ultimate shear load from experiments, code based prediction and these values ratio

Beam	$V_{u,exp}$ (kN)	$V_{u,exp,m}$ (kN)	Code based prediction – $V_{u,teo}$ (kN)					Ratio $V_{u,teo}/V_{u,exp}$				
			ACI 318	CAN A23.3	EC 2	NBR 6118 MI	NBR 6118 MII	ACI 318	CAN A23.3	EC 2	NBR 6118 MI	NBR 6118 MII
CC1 – V1	72.6	72.6	53.6	46.2	63.5	61.8	72.3	0.74	0.64	0.87	0.85	1.00
CC1 – V2	70.5											
CC1 – V3	74.6											
CC0 – V1	63.6	65.1	51.9	47.6	63.5	58.8	70.1	0.80	0.73	0.98	0.90	1.08
CC0 – V2	66.7											
CA1N – V2	71.8	74.5	53.9	45.8	63.5	62.4	72.6	0.72	0.61	0.85	0.84	0.97
CA1N – V3	77.3											
CA0N – V1	76.5	70.8	52.4	46.1	63.5	59.6	69.8	0.74	0.65	0.90	0.84	0.99
CA0N – V3	65.1											
CA1R – V1	70.4	72.5	53.8	46.4	63.5	62.2	72.8	0.74	0.64	0.88	0.86	1.00
CA1R – V2	74.5											
CA0R – V1	68.5	70.6	53.7	46.9	63.5	62.0	73.0	0.76	0.66	0.90	0.88	1.03
CA0R – V2	68.4											
CA0R – V3	75.0											

conventional concrete beams when using higher transverse reinforcement ratio.

3.3 Comparison of experimental resistance and codes estimates

The expressions presented by codes to estimate the shear strength of concrete beams when designing structures must result in approximate values to those obtained experimentally.Thus, the safety of buildings is guaranteed with the introduction of resistance factors for materials strength and factored loads

The experimental results obtained for the beams were compared with predictions from ACI 318: 2011 [16], CAN3 A23.3: 2004 [17], EN 1992-1-1: 2004 [18] and ABNT NBR 6118: 2014 [19] codes.The equations presented in Table 5 were used considering resistance factors of 1.0.

The ultimate shear resistance of beams with transverse reinforcement was calculated by the sum of the portions of concrete and complementary mechanisms (V_c) and steel (V_{sw}), except for EN 1992-1-1: 2004 [18] where the concrete and complementary mechanisms contribution are disregarded, assuming that shear force is resisted only by the transverse reinforcement (V_{sw}).

Table 6 depicts the ultimate shear forces obtained experimentally, the predictions calculated by code based equations and also the relation between these values for beams with transverse reinforcement. Inclination of strutof 21.8° and 30° were adopted in order to estimate the portion of shear force resisted by the reinforcement in equations from EN 1992-1-1:2004 [18] and Model II of ABNT NBR 6118:2014 [19], respectively, resulting in higher values.

The ratio between the ultimate experimental and estimated shear forces presented values between 0.61 and 1.08. Despite the differences in the flowability, coarse aggregate volume fraction and size, the results did not indicate the influence of these factors in relation to the safety of the code predictions for beam design.

Concrete beams produced with coarse aggregate of smaller size presented lower shear strength and, in the majority of cases, less conservative prediction by the codes equations.However, the variation in the results cannot be considered significant.

In spite of adopting a more refined theoretical model, based on compression fields, which takes into account the longitudinal reinforcement area, the magnitude of the bending moment and the shear force acting, and the spacing between the cracks, the results of CAN3 A23.3: 2004 [17] were conservative in relation to the other codes, with a ratio between prediction and experimental results between 0.61 and 0.73.

EN 1992-1-1:2004 [18] does not consider the shear force resisted by the concrete, nevertheless this code presented results close to those estimated by the model I of theABNT NBR 6118: 2014 [19], around 90% of the ultimate shear force obtained experimentally.

The values estimated by the Brazilian code presented a better approximation with the experimental results, especially when using the model II with a strut inclination angle of 30°, with ratio between 0.97 and 1.08.

It should be noted that, although some code predictions have presented values similar or higher than the values obtained experimentally, this does not reflect unsafety of the codes, since the American and Canadian codes consider the specified yield strength of transverse reinforcement limited in 400 MPa while in the European and Brazilian standards this value is 435 MPa.The value obtained for yield strength at tensile tests of reinforcement used was 658 MPa, so there is a safety margin in the reinforcement resistance around 50%.

Figure 7 shows the predictions of ultimate shear force of the codes as a function of the compressive strength of the concrete, indicating the values corresponding to the ultimate shear force of the tested beams for each concrete mixture. The equations of CAN3 A23.3: 2004 [17] and Model II of NBR 6118: 2014 [19] codes require parameters referring to the acting shear force.thus, values of β and θ were considered for Canadian standard, equal to 0.12 and 40°, respectively obtained by the arithmetic mean of the values

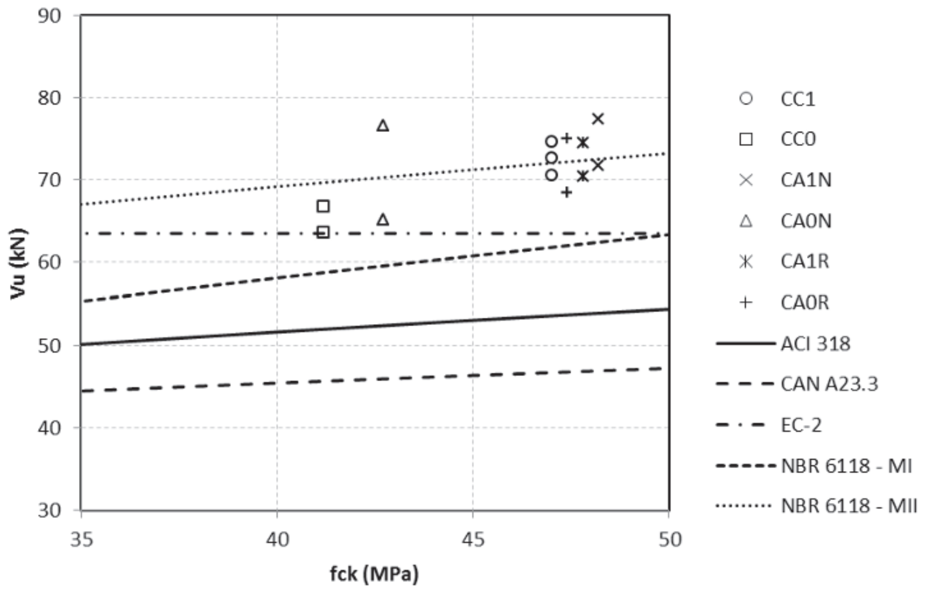

Figure 7
Code based prediction and experimentally measured of ultimate shear force vs. concrete compressive strength

calculated for the beams tested.For model II of the Brazilian code, which considers a reduction of the portion V_c when the acting shear force approximates the resistance of the struts of concrete, it was considered that V_c equals to 77% of V_{c0}.

In relation to ACI 318: 2011 [16], CAN3 A23.3: 2004 [17], EN 1992-1-1: 2004 [18] and model I of NBR 6118: 2014 [19] codes, it was observed that all the beams tested showed ultimate shear strength higher than the codes predictions. The model II of NBR 6118: 2014 [19] presented a better approximation of the results, with values approximately 8% higher than the values obtained experimentally. However, this variation does not represent a lack of safety of the model, since this code determines that the yield strength of reinforcement that must be used is equal to 435 MPa, as discussed before.

Among the codes, a direct relationship between the ultimate shear force and the compressive strength of concrete was verified, similar to the behavior of the experimental results, except for EN 1992-1-1:2004 [18], where prediction of shear strength was constant. Its equation considers only the strength of the reinforcement, becoming more conservative as the strength of concrete increases.

4. Conclusions

In this work the shear strength of concrete beams with transverse reinforcement was evaluated.The behavior of beams made with conventional and self consolidating concrete was compared.The main goal was to reduce the uncertainties about the structural performance of self consolidating concrete.

The results showed that the reduction of coarse aggregate volume fraction and maximum size, necessary to produce self consolidating concrete, did not result in a significant reduction on the shear strength of SCC concrete beams with transverse reinforcement.

Comparing the strength of beams with transverse reinforcement to the results of beams without this reinforcement, there was an increase on the resistance attributed to the concrete and alternative mechanisms of self consolidating concrete beams in relation to the conventionally vibrated concrete.This increase may be due to an improve on the concrete-reinforcement bond; however, more tests must be performed to assert this statement.

The shear strength estimates, regardless of the safety coefficients of the ABNT NBR 6118: 2014 model II, presented values closer to the results obtained experimentally than the ACI 318: 2011 [16], CAN3 A23.3: 2004 [17], EN 1992-1-1: 2004 [18] and model I of ABNT NBR 6118: 2014 [19], which are considered conservative.All these codes demonstrated to be safe in the design of self consolidating concrete beams.

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