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Pull-out behavior of deformed bars using high strength self-compacting concrete and high strength ordinary concrete

Comportamento da aderência em modelos de arrancamento utilizando concretos auto-adensáveis e concretos convencionais de alta resistência


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Abstract

The present research evaluates the bond behavior in pull-out tests using high strength self-compacting concrete and steel bars of 10 and 16 mm, and compares the results with similar pull-out tests in ordinary concrete, of same compressive strength. In the experimental study, the same materials were used for both cases, allowing a better evaluation of the pull-out models behavior. The tests results were analyzed from a statistical point of view, evaluating the variability of the response. As results, it was observed that the behavior of both models was similar, showing that the self-compacting concrete, besides promoting a series of advantages in its fresh state uses, it also guarantees a similar behavior in the hardened state.

Keywords: Self-compacting concrete, pull-out test, bond behavior, steel-concrete interface, ordinary concrete, comparison

Resumo

A presente pesquisa avalia o comportamento da aderência em modelos de arrancamento utilizando concreto auto-adensável de alta resistência e barras de aço de 10 e 16 mm, e compara com modelos similares de arrancamento em concreto convencional de mesma resistência à compressão. No estudo experimental foram utilizados os mesmos materiais para ambos os casos para melhor avaliação do comportamento dos modelos de arrancamento. Esses modelos foram avaliados do ponto de vista estatístico avaliando a variabilidade de sua resposta. Como resultados, o comportamento de ambos os modelos foi similar, mostrando que o concreto auto-adensável, além de promover uma série de vantagens em sua utilização no estado fresco, garante um comportamento similar no estado endurecido.

Palavras-chave: concreto auto-adensável, ensaio de arrancamento, aderência, contato aço-concreto, concreto convencional.

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1 Introduction

Since the beginning of the reinforced concrete use, the bond between steel and concrete has been object of several researchers' study. This interaction between both materials is the main mechanism that characterizes reinforced concrete, defining these structures behavior. The bond strength depends, besides the deformed bar properties, of the concrete properties and, therefore, its study goes by the knowledge of the materials that are involved in its production.
According to the literature, there is a concern about the bond behavior under flexure. However, this concern is limited to the usual variables, as development length, bar diameter, load type (monotonic or cyclical), cover thickness, confinement reinforcement, concrete compressive strength etc. Just in the last decades of the XX century, the presence of fibers and other innovative concretes became studied from the bond behavior point-of-view.
Nowadays, the use of high-performance concrete is more and more frequent due its economy and versatility. However, that concrete turns necessary the use of high reinforcement rates to guarantee the structure an appropriate ductility, provoking many difficulties in the cast operations. Then, it would be desirable to develop such a type of concrete mixture that the vibration operation could be spared.
So, SCC (self-compacting concrete) could be defined as a mixture that can be cast in any place of the formwork, just through the accommodation due to its own weight ([1], [2]). It is capable to flow inside of a formwork, going by the reinforcement and filling it out without the use of compacting equipments. Like this, the use of SCC increases the productivity, reduces the labor and it improves the final quality of the structure ([3]). The advantages of SCC can be summarized as: reduction of the construction time and of the structure cost, increase of the quality of the cast concrete, increase of the safety and of the workers' health, increase of the reinforcement rate and a significant increase of the constructive process.
When OC (ordinary concrete) is compared to SCC, for low compressive strength, it possesses similar bond strength, but with some peculiarities for SCC ([4]; [5]). Besides, in places with high reinforcement rate, the advantages of SCC previously mentioned stood out over OC ([6]).

1.1 Objectives and research significance

The main objective of this research is to compare the bond behavior of the steel-concrete interface in pull-out tests using SCC and OC. Besides, it was developed a study of the variability of the pull-out response, for both concretes.
The study of the bond between steel and concrete involves a great amount of variables, and some of them still have not their influence completely established. Among those, stand out: need of data regarding the bond behavior in high strength concrete; need of data about the bond behaviour under flexure; and need of data about SCC in Brazil, and its influence on bond behavior.

2 Materials

The Figure 1 shows the particle size distribution classified in agreement with [7].

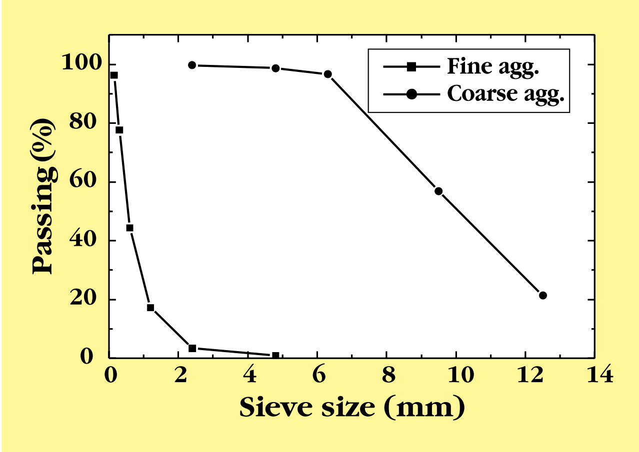

Figure 1 – Particles size distribution

The sand and the gravel had the characteristics shown in Table 1 ([8], [9]).

Table 1 – Characteristics of the aggregates

Properties	Sand	Gravel
Maximum grain size (mm)	1.2	12.5
Dry density (kg/m^3)	2,630.0	2,828.0
Coefficient of absorption (%)	9.9%	1.71%

The cement was Ciminas CP V ARI Plus and the limestone filler had a maximum grain size of 125 μm. The superplasticizer was GRACE ADVA@CAST (carboxylate), with density of 1.08 kg/dm^3 (30% solid content and 70% water content).

3 Designing of self-compacting concrete

There are many proposed methods to determine the SCC composition ([10], [11], [12] and [13]). The proposal to develop the SCC of this research was based on the research of [3].
The designing method for SCC was based on the optimization of the paste composition and of the granular skeleton. The paste is composed by cement, silica fume, filler, water

and superplasticizer, while the granular skeleton is composed by the void content for the used aggregates combination. Notice that the maximum coarse aggregate size should not pass 12 mm.
For the paste composition, must be established the relationships, in weight, for W/C, SF/C, SP/C and F/C. In the case of high-strength concretes SF/C is equals to 0.1 and the W/C is fixed as 0.4. Since then, that value is reduced until requested strength is obtained ([13]).
After the determination of W/C and SF/C, the superplasticizer and filler content (SP/C and F/C, respectively) could be determined.
The superplasticizer content is determined by the Marsh cone, with an opening of 8.0 mm for pastes and 12.5 mm for mortars. When the curve log (T_m) – SP/C (%)is obtained, the superplasticizer saturation point can be determined. This point is established as the point that has an internal angle of 140° ± 10° at the curve log (T_m) – SP/C (%) ([3]).
With the optimum superplasticizer content, next step is to determine the added filler optimum content for the cement/silica fume matrix. That filler content is determined by the mini-slump test ([14]). This test is summarized measuring the final spread diameter and the needed time to pass the 115 mm diameter (T_{115}). The obtained value must be inside the limit of 18 ± 1 cm and T_{115} has to be 3 ± 1 s ([13]; [3]).
Figure 2 shows the outlined methodology for the SCC optimization ([3]).
The paste content has a great importance for workability and cohesion of the resulting SCC ([5]; [15]). The mixtures can be evaluated by slump-flow test and L-box's test. The

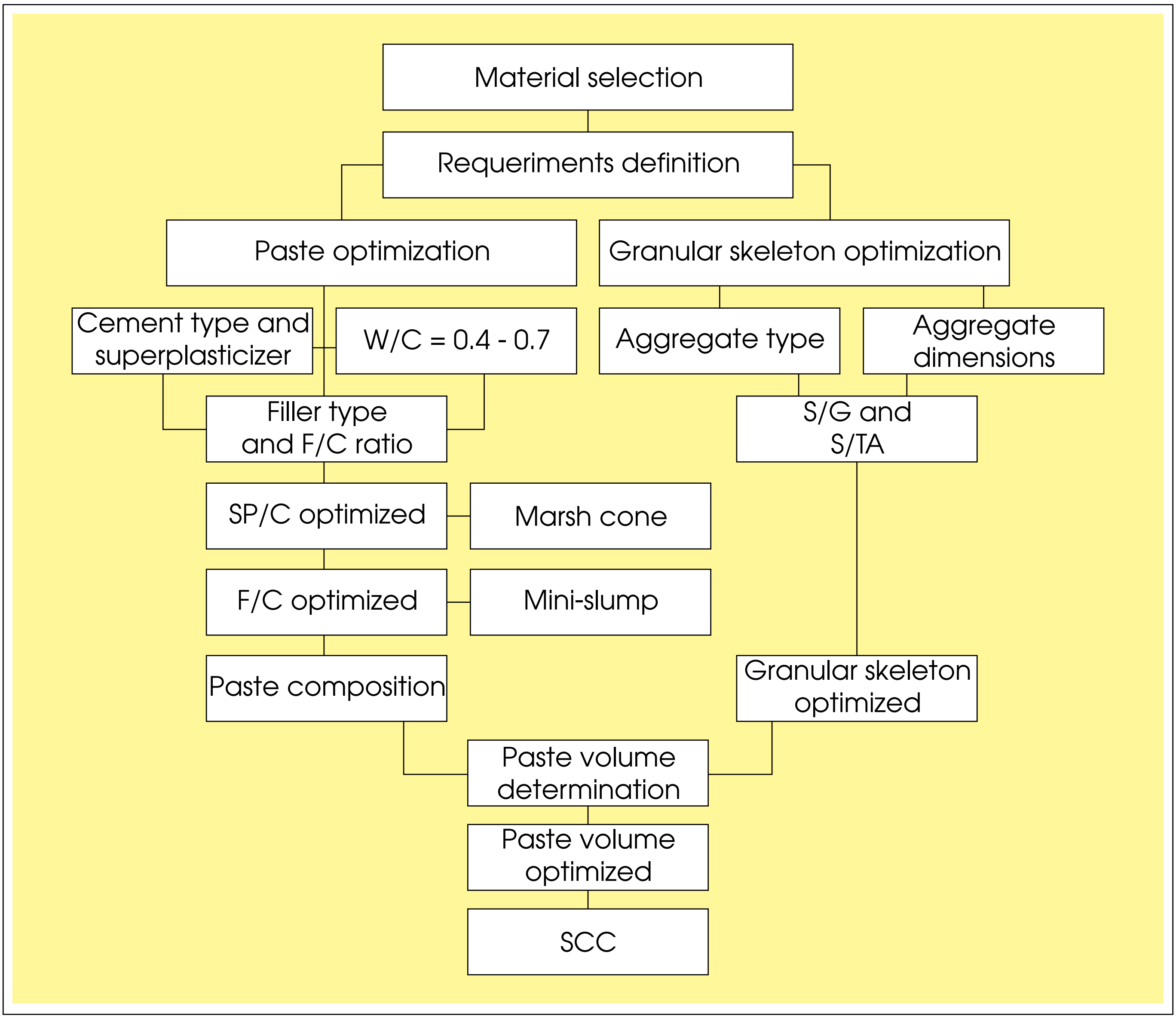

Figure 2 – Methodologies for SCC ([3])

last one can evaluate the SCC capacity of passing through reinforcement. In order to control the segregation, concrete cylinders could be opened to verify the coarse aggregate distribution.
The determination of the SCC composition was divided in three phases: paste, aggregate skeleton and concrete.

3.1 Paste phase

Four limestone filler content were adopted (10, 20, 30 and 40%) substituting cement, besides the substitution of the silica fume content (10%).
Figure 3 shows the variation of the saturation point for the W/C=0.4 (measured values 10 minutes after the mixture).

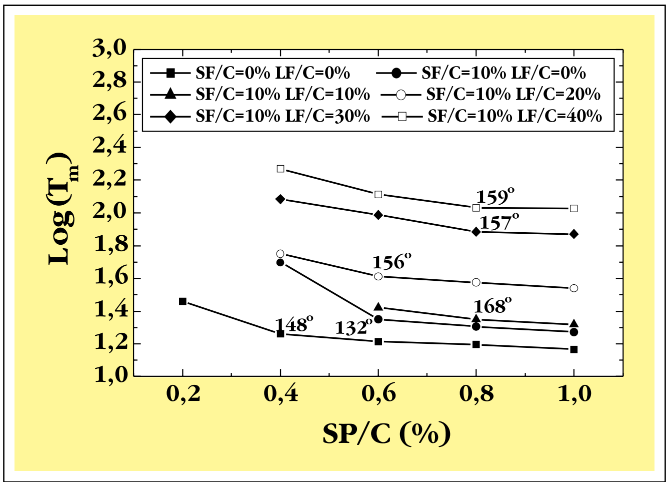

Figure 3 Variation of the saturation point (W/C=0.4)

Table 2 shows the results of flow and spread tests for limestone filler and silica fume contents. The obtained values for the optimum superplasticizer content were taken for the time of 10 minutes. When it was not possible to determine the saturation point, an interpolation was made ([3]).

Table 2 – Values for the flow and spread tests

SF/C (%)	0	10	10	10	10	10
LF/C (%)	0	0	10	20	30	40
SP/C (%)	0.40	0.60	0.78	0.55	0.65	0.75
Spread (cm)	18.5	13.0	17.8	14.5	16.9	18.0
T115 (s)	0.5	0.4	0.3	0.7	0.5	0.5

The measured values for T_{115} shown on Table 2 were very low and susceptible to measurement errors. Therefore, they could not be taking into account for paste validation. So, the criteria to determine the filler content, in this case, was the final spread diameter observed in two pastes, being them LF/C=0,1 and LF/C=0,4. In order to optimize the cement content of SCC, the second paste (LF/C=0,4) was adopted. Illustration 4 shows the influence of the limestone filler and superplasticizer contents in the behavior of the analyzed pastes. The adoption of a final spread above 20 cm leads to segregation ([3]).

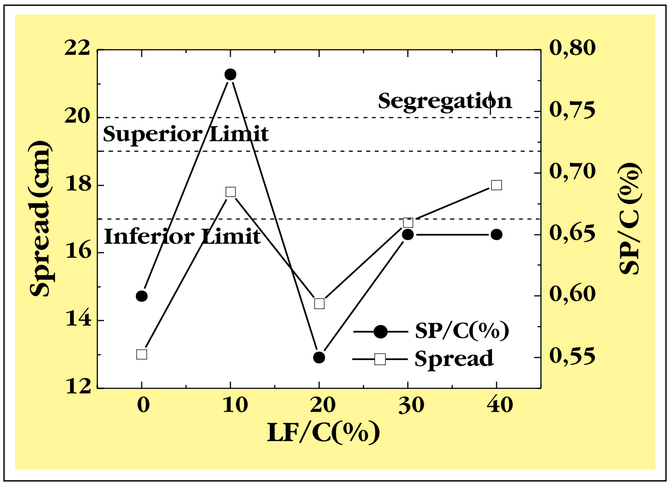

Figure 4 – Tests results for mini-slump final spread

3.2 Aggregate phase

In this phase, the aggregate content is optimized to the minor void content. After the characterization of the aggregates, the relationships among them (S/G and S/TA) should be determined ([17]).
Figure 5 shows the aggregate skeleton composition.

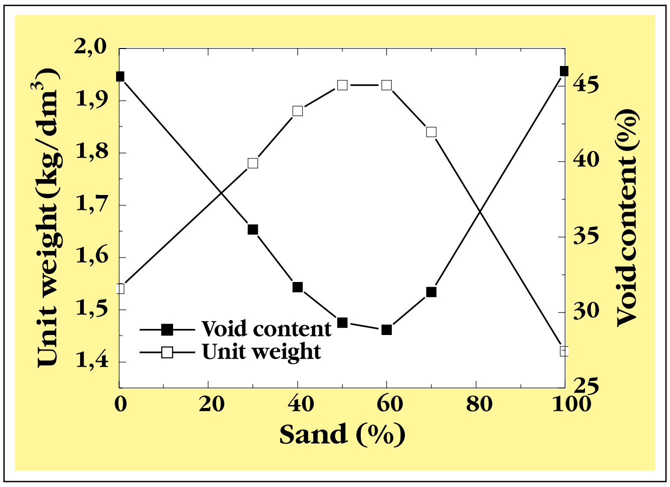

Figure 5 – Void content and unity weight of the granular skeleton

The influence of the amount of voids should be verified in the granular skeleton; for that, it should take place

the mixture test of the aggregates content, obtaining the mixture with smaller amount of voids. This procedure was based on the idea that the combination of aggregates with a low void content takes to lower paste consumption, reducing porosity and shrinkage ([3]; [18]).
So, for this research the same procedure adopted by [3] and [13] for the determination of the minimum void content was used.

3.3 Concrete phase

With the granular skeleton optimized and the paste composition defined, the concrete phase could be developed. That step consists of evaluating the SCC pre-established requirements (in this case spread and L-box tests).
The mixture procedure for SCC was: first, mix for 30 seconds coarse aggregate with 3/4 of the total water (water for paste and for aggregates); then, mix for 120 seconds the cement, the silica fume, the limestone powder, the superplasticizer and the remaining water; and finally, the fine aggregate is added and mixed for 120 seconds.
With the determination of the superplasticizer, filler, cement and aggregates contents, the procedure is to determine the concrete composition. The process to determine the SCC composition was the Okamura's Method ([2]; [3]; [15]).
In this process it is necessary to determine the paste unitary weight (in this case 1.843 kg/dm³ [16]).
For the determination of the cement aggregate contents, for 1 m³ of SCC, Eq. (1), (2) and (3) were used (more details in [3]).

$$\omega_c = \frac{V_p \cdot \rho_p}{1 + W/C + \frac{(SF/C + LF/C)}{100} + \frac{SP/C}{100}} \qquad (1)$$

$$\omega_g = \frac{(1 - V_p)}{\frac{S/G}{\rho_{sd}} + \frac{1}{\rho_{gd}}} \qquad (2)$$

$$\omega_s = \frac{(S/G) \cdot (1 - V_p)}{\frac{S/G}{\rho_{sd}} + \frac{1}{\rho_{gd}}} \qquad (3)$$

Table 3 shows the SCC content.

Table 3 – SCC content

Cement (kg)	368,6
LF/C (%)	40
SF/C (%)	10
Sand (kg) – Absorption (%)	815,3 (9,9%)
Grave (kg) – Absorption (%)	876,7 (1,71%)
SP/C (%)	0,75
Slump test	
T50 (s)	1,0
Spread (mm)	740
L-Box	
T40 (s)	1,0
RB	0,85
Compressive strength (kN/cm²)	
2 days	3,18
7 days	4,52
15 days	5,70
S.D. 15 days (kN/cm²)	0,21
Tensile strength (kN/cm²)	
2 days	0,23
15 days	0,37
Flexure strength (kN/cm²)	
15 days	0,48
Elasticity Modulus (kN/cm²)	
15 days	3272,80

Figure 6 shows the compressive strength of the SCC and OC.

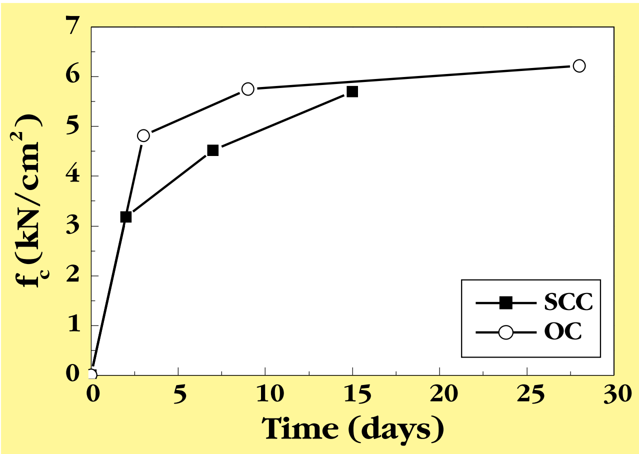

Figure 6 OC and SCC compressive strength

To verify if there was segregation, besides the spread and L-box test (Figure 7), cylinders tested under indirect tension were opened to verify the gravel distribution (Figure 8).

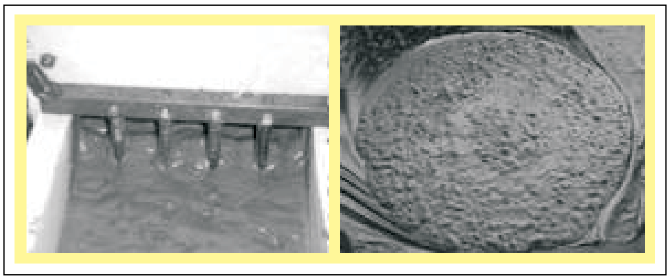

Figure 7 – Spread and L-box tests

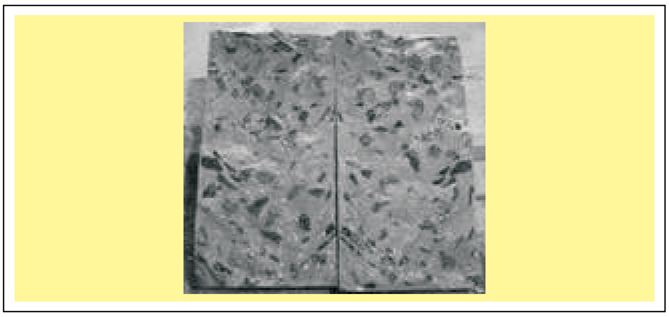

Figure 8 – Coarse aggregate distributions in cylinder specimens

4 Considerations about the pull-out specimens

The bond strength is equivalent to the shear force that acts parallel to the deformed bar on the contact zone between deformed bar surface and adjacent concrete, which varies along the deformed bar surface. This force is transferred to the adjacent concrete through radial forces along the deformed bar.
Nowadays, researches about bond behavior on pull-out models using SCC are just starting.
The behavior of a concrete element is ruled by the bond strength of the steel- concrete interface. Because of that, several researches about bond behavior using ordinary concrete were carried on. The more important factors affecting this behavior were determined, being they: the number of load cycles, the concrete composition, the cast direction, the specimen geometry, deformed bar surface and etc.
For the evaluation of the bond behavior, there are three different test models: The beam test, the axially tested specimen and the pull-out model ([21]).
Although the pull-out test is simple to execute, it has some disadvantages. The main one is the friction on the support base that avoids cracking and transverse expansion of the concrete prism. This effect causes a confinement over the reinforcement, giving non-representative results for structural elements in general, as beams, for example. However, those tests give satisfactory quantitative and qualitative results, through the simple observation of the main parameters affecting bond behavior.
Because of the model's limitations, several authors proposed different models with the objective of evaluating the bond behavior when the concrete is in tension ([22]; [23]; [24]). Those tests adopted a common procedure, placing two deformed bars at the concrete prism extremities, and pulling one of the deformed bars, which has a smaller embedment length.
There are tests that try to simulate the eccentricity effect of the deformed bar in the beam. That process can be called half-beam test. It consists of a concrete prism with a deformed bar eccentrically positioned in relation to the prism normal axis ([25]).
In agreement with SCC experimental analysis, it is expected that its use improves the concrete behavior under flexure, and also increases the load capacity of structural elements due to its best filling capacity. This increases directly the bond strength along the steel-concrete interface, and indirectly, the confinement effect of the stirrups.
There were a few experimental researches about the bond strength between steel-SCC using pull-out models ([4]; [5]; [26]) comparing them with similar specimens made with OC. As results, the referred authors concluded that there is certain ductility in the post-peak behavior of the bond strength, being characterized by sliding accompanied by small bond loss.

5 Experimental program

As commented previously, the used pull-out model was the standard model [21]. Figure 9 shows the geometry of the adopted pull-out model for deformed bars of 10 and 16 mm.

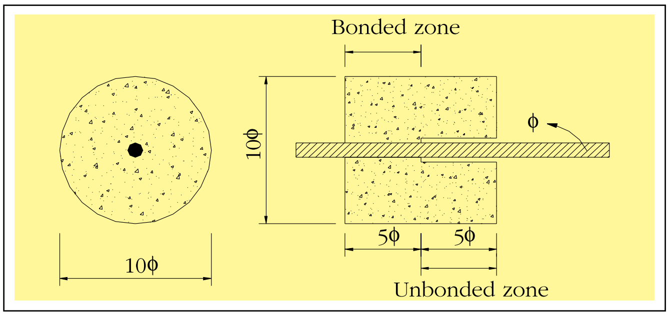

Figure 9 – Pull-out geometry

The position and the inclination of the deformed bars have a significant influence in the bond behavior. The specimens cast in the vertical direction present larger bond strength, while the specimens cast in the horizontal direction resent an inferior bond strength ([27]). In this case, the specimens were cast in the vertical direction and the pull-out load was applied at the op-

posite direction. The applied load was monotonic with a displacement rate of 0,005 mm/s until failure.
The test instrumentation is shown on Figure 10.

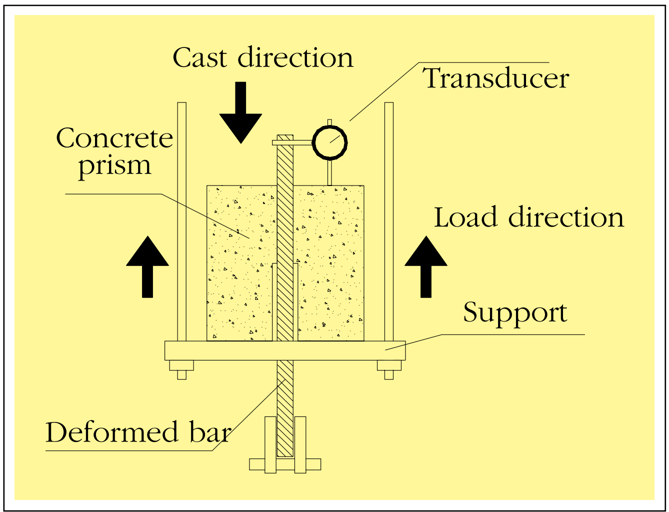

Figure 10 – Pull-out test layout

Although some authors have obtained values for the bond strength using strain gages ([28]; [27]), this procedure leads to a bond loss and it compromises the results.

5.1 OC specimens

The ordinary concrete (OC) reference specimens used the same materials of the SCC ones (cement and aggregates), with a compressive strength of 6.0 kN/cm² at 14 days.
The reference specimens were called A2-10 and A2-16, where A corresponds to pull-out model, 2 correspond to OC, and 10 or 16 correspond to the deformed bar diameter.
Table 4 shows the hardened properties for OC (average of 3 cylinders).

Table 4 – OC hardened properties

	Av. (kN/cm^2)	S.D. (kN/cm^2)	C.V.
$f_{c,14}$	6.10	0.14	2.33%
E_c	3261.4	6.80	0.21%
$f_{ct,sp}$	0.345	0.002	0.53%
$f_{ct,f}$	0.482	0.016	3.27%

Where $f_{ct,sp}$ is the tensile strength, $f_{ct,f}$ is the tensile strength under flexure, E_c is the elasticity modulus and $f_{c,14}$ is the compressive strength at 14 days.
In order to give some reliability to the obtained results, for each specimen, 4 additional specimens were tested.
For the reference specimens, compacting is essential. The vibration can result in loss of bond strength leading to problems in the structural performance of the element. For normal strength concretes, the compacting exaggeration (carefully to avoid segregation) or inadequate vibration does not affect the bond strength. The vibration practice is important but not crucial for concrete with small slump, for what cohesion prevents segregation or bleeding. However, for high-strength concretes, the compacting exaggeration or inadequate vibration can carry a bond strength loss up to 30% ([6]).
Figure 11 shows the OC pull-out behavior.

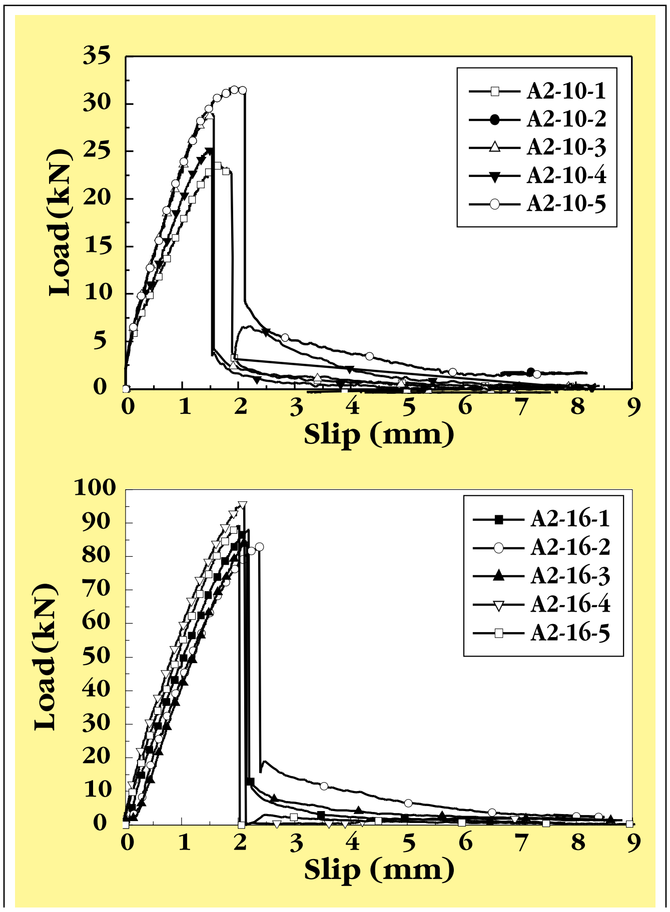

Figure 11 – OC specimens pull-out behavior

Figure 12 shows the OC pull-out specimens.

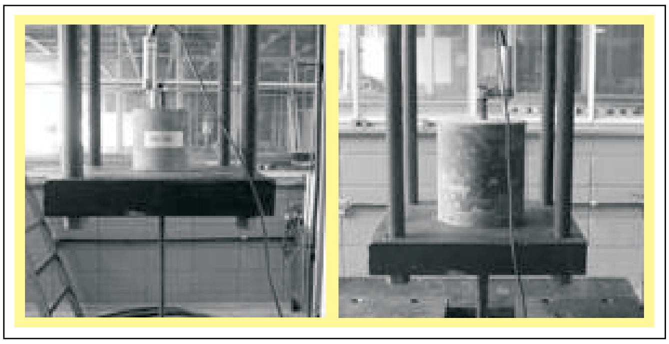

Figure 12 OC pull-out specimens at test

Figure 13 shows the OC specimens after test.

Figure 13 – Failure mode for OC pull-out specimens

All the OC specimens, for both deformed bar diameters, had concrete splitting failure.

5.2 SCC specimens

The SCC specimens were cast after the verification of the properties of pass ability (L-box), cohesion and fluidity (slump test). About the pull-out specimens, the application of any compactation should be avoided; therefore, this can lead to a loss of 10% or more of the bond strength ([6]).
The SCC specimens were called A1-10 and A1-16, where A corresponds to pull-out model, 1 correspond to SCC, and 10 and 16 correspond the deformed bar diameter.
Figure 14 shows the SCC pull-out behavior.

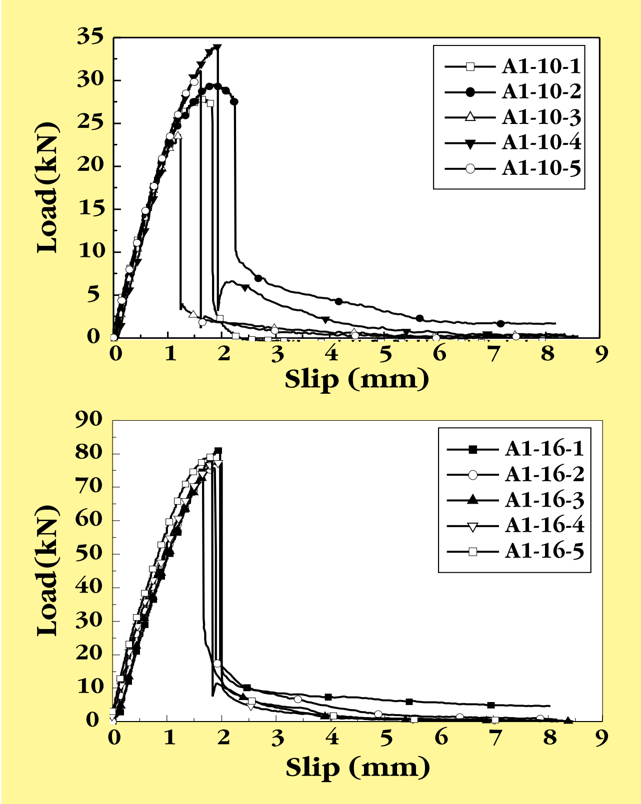

Figure 14 – SCC specimens pull-out behavior

Figure 15 shows the SCC pull-out specimens.

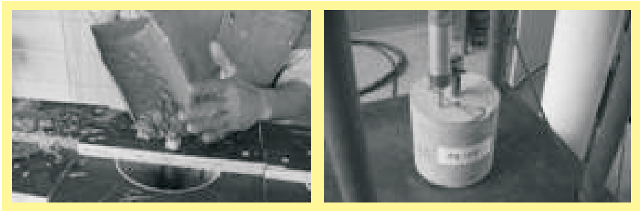

Figure 15 – SCC pull-out specimens at test

Figure 16 shows the failure mode for the OC pull-out specimens.

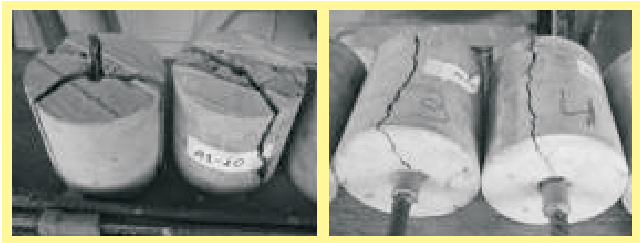

Figure 16 – Failure mode for SCC pull-out specimens

As expected, all the SCC specimens also had a concrete splitting failure.

6 Results analysis

The results of the pull-out tests presented a good similarity, mainly for the specimens with 10 mm deformed bars. For the specimens with 16 mm deformed bars, the OC presented a superior strength than the SCC ones (12.3%). That difference can be explained by the smallest compressive strength of the SCC (3.4%) and due the high cement content of the OC.
Table 5 and Table 6 show the variation of the results in the pull-out tests.

Table 5 – Pull-out load for specimens

Specimen	Pull-out load (kN)				
	1	2	3	4	5
A1-10	23.73	29.61	23.73	34.03	31.13
A1-16	81.30	76.00	72.80	77.50	79.10
A2-10	25.26	23.73	31.74	29.00	24.19
A2-16	88.05	83.09	84.70	95.99	89.27

Table 6 – measured slips					
Specimen	Slip (mm)				
	1	2	3	4	5
A1-10	1.65	1.86	1.21	1.90	1.61
A1-16	1.97	1.86	1.65	1.92	1.78
A2-10	1.51	1.65	1.85	1.55	1.62
A2-16	2.19	2.44	2.24	2.11	2.02

Figure 17 shows the pull-out behavior of the SCC and OC specimens.

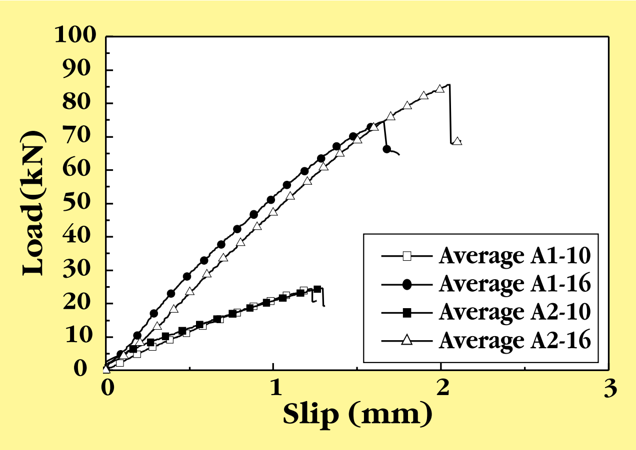

Figure 17 – Average results from the specimens

Figure 18 shows the variability of the SCC pull-out specimens according to the results average.

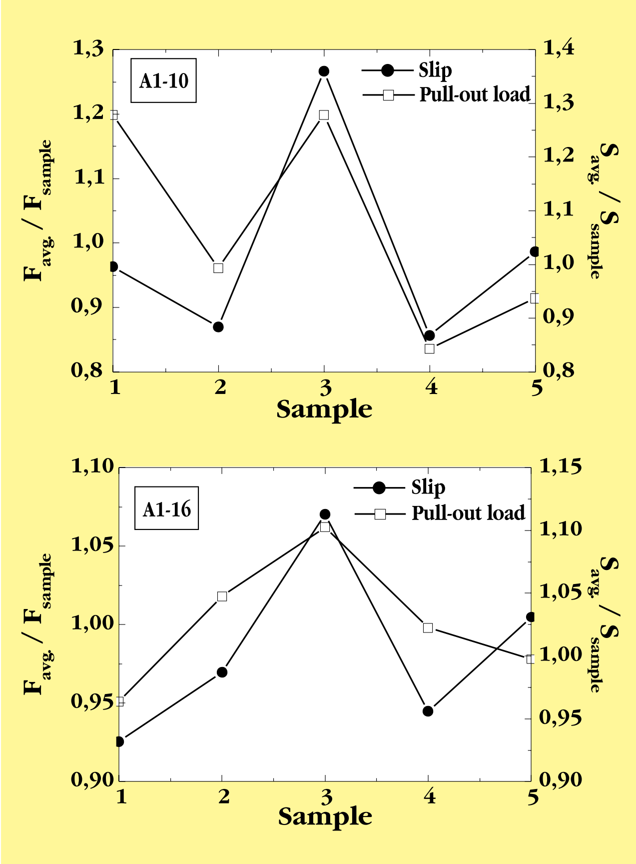

Figure 18 – Variability of the SCC pull-out specimens

Table 7 shows the variability of the results.
For the 10 mm deformed bar specimens, there was a great

Table 7 – Variability of the pull-out results						
Spec.	Average		S. D.		C.V.	
	F kN	S. mm	F kN	S. mm	F %	S %
A1-10	28.45	1.65	4.59	0.27	16.1	16.7
A1-16	77.34	1.84	3.21	0.13	4.2	6.8
A2-10	26.78	1.64	3.46	0.14	12.9	8.3
A2-16	88.22	2.20	5.00	0.16	5.7	7.3

variability for the failure loads and for the corresponding sliding values, for both concretes. This variability is due the use of inappropriate formwork.
Figure 19 shows the variability of the OC pull-out specimens according to the results average.

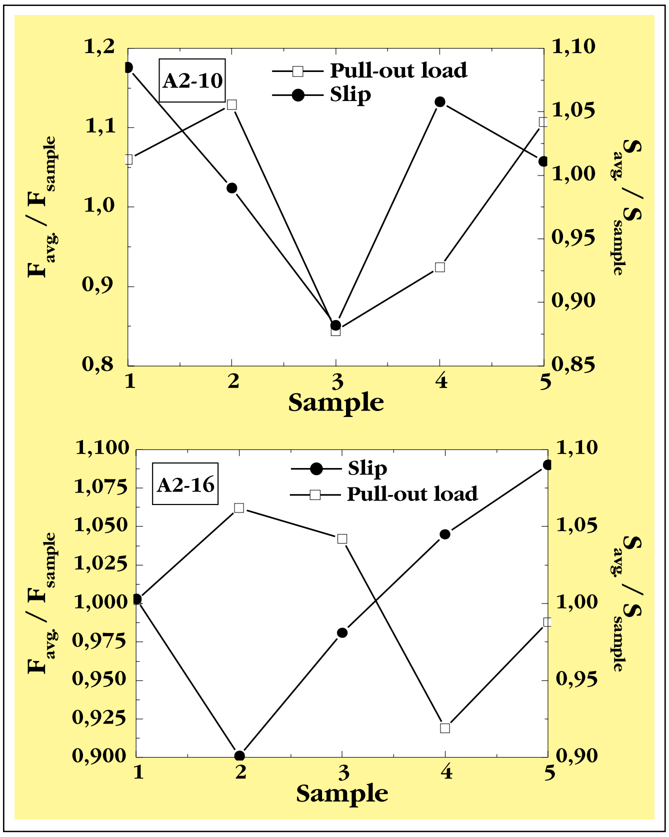

Figure 19 – Variability of the OC pull-out specimens

Another factor that should be taken into consideration is that few samples were accomplished for each deformed bar diameter. For a better statistical evaluation it should be necessary pull-out series with a significant amount of values. Figure 20 shows the comparison between the elasticity modulus (E_c) for SCC and OC.

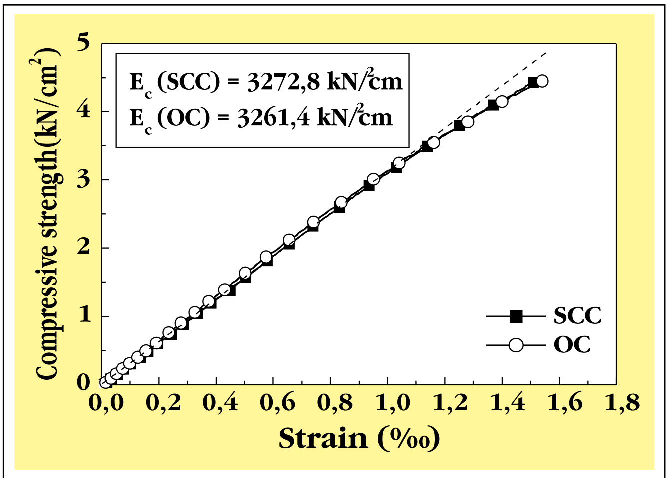

Figure 20 – Comparison of the elasticity modulus of SCC and OC

In a general, the SCC behavior in relation to OC was satisfactory, because it had similar characteristics to the OC bond strength behavior.

7 Conclusions

In this paper it was presented a preliminary experimental investigation about the evaluation of bond behavior considering deformed bars (10 and 16 mm) and self-compacting concrete.
For SCC fresh state evaluation, slump and L-box tests were used. For the segregation control, SCC cylinders were opened to evaluate the coarse aggregate distribution. In these tests, the parameters did not accomplished flow time from slump flow (T_{50}) and flow time from L-box (T_{40}), because SCC presented a very high fluidity. The cause of this high fluidity was the use of a carboxylate chains based superplasticizer, which is not quite appropriate for SCC (need of a viscosity increaser). However, the fresh properties such as pass ability, slump flow and segregation resistance were verified. In that way, it was obtained a highly fluid SCC, without loss of cohesion.
About the pull-out specimens, the following conclusions can be drawn:

- The failure mode, in both cases, was characterized by concrete splitting, which happens in high strength concretes. That fact can lead to a development length reduction, for high strength concretes;
- The pull-out specimens presented a good agreement with tests average response. Only the specimens with 10 mm deformed bars had a certain variability due to the used formworks;
- Although the ordinary concrete did not use silica fume, it presented a high cement content;
- The instrumentation and the load rate were appropriate to the tests;
- Another important point that deserves to be commented is the cast velocity. The SCC specimens had an average cast time of 48 seconds and the OC ones had an average cast time of 78 seconds, showing a great productivity for SCC;
- The OC pull-out specimens with 16 mm deformed bars (A2-16) had greater bond strength than the SCC specimens (A1-16). This can be explained by higher OC compressive strength (3.4%) and cement content.

Then, it can be stated that the SCC behavior, in the hardened state, was similar to the ordinary concrete.
Further studies about the steel-SCC interface with a larger amount of specimens are still needed to have a better evaluation of the bond strength.

8 Notation

W/C = Water/cement ratio;
SF/C = Silica Fume/cement ratio;
F/C = filler/cement ratio;
SP/C = Superplasticizer/cement ratio;
S/G = Fine/coarse aggregate ratio;

S/TA = Fine/total aggregate ratio;
V_p = Paste volume (%);
ω_s = Dry weight of fine aggregate (kg/m³);
ω_c = Weight of cement (kg/m³);
ω_g = Dry weight of coarse aggregate (kg/m³);
ρ_p = unit weight of the paste (kg/m³);
ρ_{sd} = Dry density of fine aggregate (kg/m³);
ρ_{gd} = Dry density of coarse aggregate (kg/m³).

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