ABSTRACT

Self-compacting concrete (SCC), was developed in 1986 with the purpose of obtaining more durable structures independently from worker skills. This concrete is characterized by simultaneously having high flowability and high segregation resistance, which originates the self compacting of the concrete without the need to use external means to achieve it, even in the presence of narrow spaces or highly dense steel reinforcing bars.

The first stage of this work was a bibliographical research on the state-of-the-art in Self-compacting concrete, focusing essentially in the mix design methods, characterization and property analysis of the fresh state (rheology and workability).

After this research a Self-compacting concrete mix was formulated based on the methodology proposed by Okamura, commonly denominated “General Method”, followed by a experimental campaign with the objective of producing SCCs for characterization in fresh and hardened states, at the end obtained results where put under analysis for interpretation.

Keywords: Self Compacting Concrete, high flowability, segregation resistance, compaction.

1. Introduction

It is currently known that no matter how much studding and control a traditional vibrated concrete has its final quality in the hardened state (durability and resistance) will always seriously depend on the application at the construction site, especially regarding the compacting through vibration that is very dependent on the worker’s skills. For these reasons, in 1986 professor Okamura and his associates introduced in Japan the concept o Self Compacting Concrete (SCC), with the final objective of ensuring a greater concrete homogeneity and increase structural durability independently from worker skills.

This new technology presents several advantages when compared to traditional vibrated concrete, namely: the ability to fill in complex shapes and pass through densely reinforced places just through its own weight, allows a faster and more efficient construction process, allows cost reduction regarding manual labor and finally reducing noise levels at construction sites.

SCC concrete is currently looked at as very promising technology, which in many ways replaces the traditional vibrated concrete. In the last decade this technology is being used in several countries, especially Japan, Sweden and Holland. It is usually used in bridges, tunnels and great structure buildings. In Portugal its application is still very sparse, most of the times it is only used for repairing structural elements where the introduction of a vibrator is not possible.

2. Self compacting concrete (SCC) definition

SCC is defined, as a concrete that is capable of passing among dense steel reinforcement and filling out the empty spaces of the formwork through its self-weight, maintaining its homogeneity and without the need for any additional compaction, meaning that neither segregation nor aggregate blockage occurs. [European Guidelines, 2005].

3. Classification of the SCC

Self-compacting concrete may be classified in three types: **the powder type** that is characterized by the use of large amounts of powder; **the viscosity agent type**, in which a viscosity agent is added; and the **combination type**, which consists of a combination of the two previous methods. [Nepomuceno, 2005; Nunes, 2001; Oliveira, 2003].

4. Fresh concrete properties

4.1 Rheology

The rheological behavior of SCC is characterized by having simultaneously a low yield stress value (high fluidity) and an adequate plastic viscosity (resistance to the segregation).

4.2 Workability

The self-compactability as property of the fresh concrete is characterized essentially by three functional requirements: filling ability, resistance to segregation and passing ability [Skarendahl et al., 2000].

4.2.1 Filling ability

The filling ability consists in the capacity of the concrete to deform and change its shape very well under its self-weight. The meaning of the filling ability includes simultaneously, the deformation capacity (how far from the discharge the concrete can flow), and the velocity of deformation (speed which concrete flows) [Skarendahl et al., 2000].

To reach an appropriate filling ability in SCC it owes: **to increase the deformability of the paste** through the superplasticizing admixtures introduction and controlling the water/powder ratio; **to reduce inter particle friction** by reducing the volume of coarse aggregates and optimizing the graded powder relative to aggregates and cement used [Skarendahl et al., 2000].

4.2.2 Resistance to segregation

The segregation in the fresh concrete is characterized by the heterogeneity in the distribution of their constituent materials. The concrete can show segregation tendency under certain movement conditions, for instance when it flows through heavily reinforced sections [Skarendahl et al., 2000].

To achieve appropriate resistance to the segregation it owes: **to reduce the separation of the solids,** through the limitation of aggregate content, the reduction of the maximum size of coarse aggregate, the reduction of water/powder ratio and a viscosity agent's introduction; **to minimize the bleeding water**, through the reduction of the volume of water and water/powder ratio, the introduction of powders with high specific surface area and a viscosity agent [Skarendahl et al., 2000].

4.2.3 Passing ability

SCC it should possess simultaneously flowability and resistance to segregation to work in an efficient way. In most of the situations it is necessary to possess an extra requirement, which consists in the capacity for the concrete to flow in reduced spaces, without the occurrence of blockage of coarse aggregates. It is necessary to make compatible the size and the proportion of coarse aggregate with the spacing of the reinforcing bars and the openings in the formwork. In a SCC mixture with good passing ability and resistance to the segregation, blockage only happens if maximum size of coarse aggregates is too big and/or if the content of coarse aggregates is too high [Skarendahl et al., 2000].

To reach an appropriate passing ability, the following actions should be considered: **enhance cohesiveness to reduce aggregate segregation**, lowering the water powder/ratio and introducing viscosity agents; **make the free spacing compatible with the characteristics of coarse aggregates**, reducing the content of coarse aggregates and maximum size of coarse aggregates [Skarendahl et al., 2000].

5. Mix design procedure of SCC

The conventional methods for determining the mix design of traditional vibrated concrete is not applicable for SCCs, because it possesses values for the consistence class that are greater than the highest class foreseen in NP EN 206-1. Therefore it was necessary to adopt a new mix design procedure for SCCs.

A number of SCC design methods have been developed, although all have some inherent limitations. One of the methods that stands out is the "General Method", proposed by Okamura and co-workers, this is a relatively simple step by step method, another is the one proposed by JSCE which stands out for the fact of being the only one that includes provision for the use of viscosity agents in the mixture [Nepomuceno, 2005; Skarendahl et al., 2000].

This document only has summarized the “general method” mix-design, because it was the method used for obtaining of the SCCs used in the experimental campaign.

The “General Method” asserts that the mix proportions should be defined by [Nepomuceno, 2005; Nunes, 2001; Skarendahl et al., 2000]:

The **air content** (V_v) is that required for the exposure condition, being usually between 4 and 7%.

The **coarse aggregate content** (V_g) is set as 50% of the dry rodded weight in the concrete volume excluding the air content (defined in the previous point).

The **fine aggregate content** (V_s) is set at 40% of the resulting mortar volume. This method considers fine aggregate all of the particles with dimensions between 0.09 and 5 mm, and all less 0.09 mm as powder. From the grading analysis of the fine aggregates it is possible to determine the percentage of particles (by volume unit) with size smaller than 0.09 mm, this percentage is designated by k_{sf}. To simplify in this work K_{sf} was considered as < 0.149 mm.

The **water/powder ratio** (V_w/V_p) and **superplasticizer dosage** (Sp/p) are determined by testing mortars with the flow and V-funnel tests. The flow test measures the spread diameter which is converted to a relative flow area, according to:

$$G_m = \left(\frac{D_m}{D_o}\right)^2 - 1$$

Where D_m is the average value for the dispersal diameter (mm), and D_o is the initial diameter, equal to 100 mm.

The V-funnel tests measures the flow time for the mortar (t), this time can be converted to a relative flow time according to:

$$R_m = \frac{10}{t}.$$

In this way the superplasticizer dosage and water/powder ratios of the mortar are adjusted to obtain simultaneously $G_m = 5$ and $R_m = 1$. Figure 1 represents the equipments used for the mortar tests.

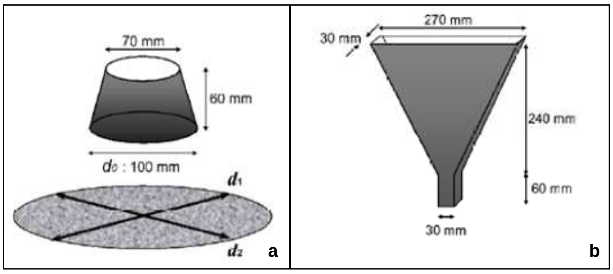

Figure 1 (a) Mortar flow test; (b) Mortar funnel test.

After correctly defining mortar parameters, it is possible to proceed with the trial concrete mixes. Attending to the fact that the superplasticizer has a different effects in concrete, so the dosage must be adjusted until the slump flow is ≥ to 650mm, and the flow time in the V - Funnel test is between 10 and 20 seconds, by last the “General Method” recommends a U-box test where the filling height (H_u) should be at least 300 mm [Nepomuceno, 2005; Nunes, 2001; Skarendahl et al., 2000].

After the initial development of the “General Method” several modifications where done aiming to produce more efficient mixes in terms of paste content, this work used the Domone (University College London) modification. This modification suggests the reduction of the paste volume (powder volume) by:

1. Increasing the volumetric ratio of fine aggregate/mortar;
2. Increasing the volume of coarse aggregate as a consequence of reducing their maximum size [Nepomuceno, 2005; Skarendahl et al., 2000].

Table 1 Calculation limits for SCCs as proposed by Domone [Skarendahl et al., 2000].

	Aggregate size 5 – 20 mm		**Aggregate size 5 – 10 mm**	
Coarse aggregate content [kg/m^3]	0,5 x dry rodded unit weight		0,5 – 0,54 x dry rodded unit weight	
Max. water powder content [kg/m^3]	200			
Water powder ratio by weight (w/p)	0,28 – 0,40		0,28 – 0,50	
Water/(powder + fine aggregate)	0,12 – 0,14		0,12 – 0,17	
Paste volume (m^3/m^3 concrete)	0,38 – 0,42			
Volume sand/volume mortar (V_s/V_m)	**w/p**	**V_s/V_m**	**w/p**	**V_s/V_m**
	<0,30	0,40	<0,30	0,40
	0,30 – 0,34	0,4-0,45	0,30 – 0,34	0,40 – 0,45
	0,34 – 0,40	0,45-0,47	0,34 – 0,40	0,45 – 0,47
	0,40 – 0,50	Do not use	0,4-0,5	> 0,45

6. Testing of fresh concrete

To evaluate the self-compacting properties of the concrete new tests where developed because the tests used for traditional vibrated concrete can not be applied. The most commonly used tests are the slump-flow test, V-funnel test, L-box test and the U-box test.

6.1 Slump- flow test

This test is a useful index for the concrete's deformation capacity. This test consists in filling the Abrams cone with concrete, with out compaction. After this the cone is raised and when all concrete movement has ceased the average diameter is calculated using two perpendicular measurements. During the deformation faze that ocurres after lifting the cone, the T_{500} time can be measured, this time is the time interval that goes from the cone lifting until the spread diameter is equal to 500mm. The T_{500} time is used to evaluate the viscosity of the fresh concrete. Basically slump-flow test is used to evaluate the concrete's filling ability. The acceptance criteria's are: spread diameter ≥ 650 mm and T_{500} between 2 to 5 seconds [European Guidelines, 2005; Skarendahl et al., 2000]. The figure 2 illustrates the test equipment and its dimensions.

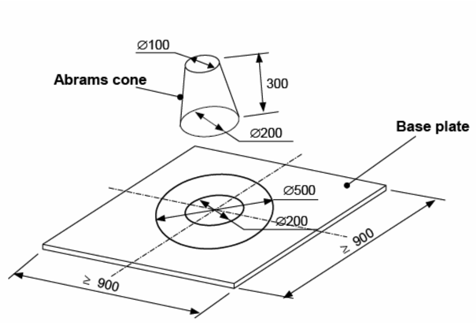

Figure 2 Slump flow test. Base plate and Abrams cone. All dimensions in mm. [De Shutter, 2005].

6.2 V-Funnel test

This test is used with the purpose of evaluating the viscosity and filling capacity of SCCs.

The test equipment consists of a V shaped funnel with an opening in the bottom, according to figure 3. This test consists in filling the funnel with fresh concrete and registering the time (T_{funnel}) between the opening and the end of the flow, so the flow time is defined as that to daylight first appearing trough the concrete when viewed from above. The acceptance criteria is a time between 10 to 20 seconds [European Guidelines, 2005].

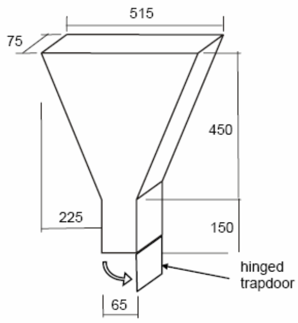

Figure 3 V-funnel test. All dimensions in mm [European Guidelines, 2005].

6.3 U-Box test

The U-Box test was developed to evaluate the concrete's capacity to pass throw narrow passages. This test reflects the deformability capacity and resistance to blockage of the SCCs. This test is also referred as the self-compactabillity test works as illustrated in figure 4, in first step "A" compartment is filled, afterwards the partition gate is opened and the fill height H_u in compartment "B" is measured, this value should be ≥300mm [Nepomuceno, 2005; Oliveira, 2003; Skarendahl et al., 2000].

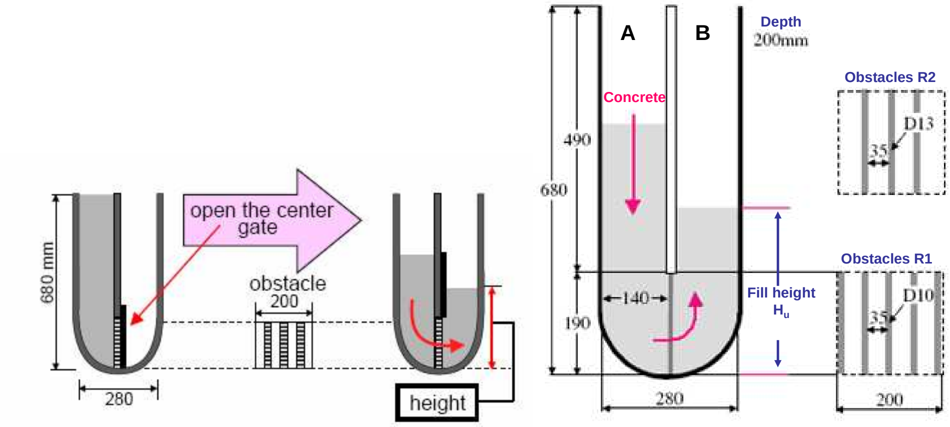

Figure 4 U shaped apparatus testing method. All dimensions in mm [Okamura et al., 2003; [Shindoh et al., 2003].

6.4 L-Box test

This test's objective is to evaluate the filling and passing abilities, this test works in a similar way to the U-Box test. The test consists in filling the box's "A" compartment afterwards the partition gate is opened, during the concrete flow the time to reach 200mm (T_{200}) and 400 mm (T_{400}) are often measured, once the flow has ended H_1 and H_2 must be measured and the blocking ratio is calculated according to: PA=H2/H1, and should have values ≥0,8 [Nepomuceno, 2005; Skarendahl et al., 2000].

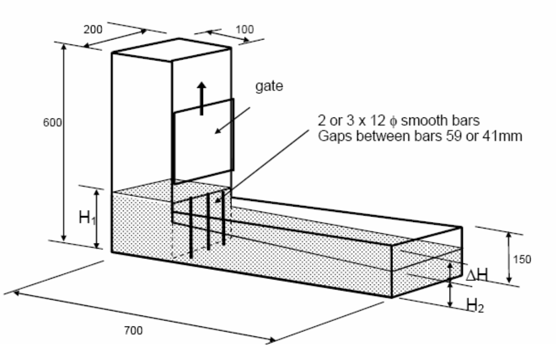

Figure 5 L-box test. All dimensions in mm [European Guidelines, 2005].

7. Result presentation and analysis

The production of concretes and mortars in the lab was done using the existing materials exception to the superplasticizer that was offered by SECIL. Table 2 displays some of the characteristics of the used materials: aggregate grading (maximum size-D_{max}), K_{sf} parameter, loose bulk density (B), and density.

Table 2 Characteristics of the materials used to produce mortars and concretes.

Components	D_{max} [mm]	k_{sf} [%]	B [kg/m^3]	Density [kg/m^3]
Cement II/A-L 42,5R	-	-	-	3100,0
Fly ash	-	-	-	2250,0
Coarse aggregate	12,70	0,43	1540	2650,0
Fine aggregate - A	2,38	1,52	1620	2600,0
Fine aggregate - B	1,19	0,72	1560	2600,0
Superplasticizer (Sp)	-	-	-	1045,5
Water	-	-	-	1000,0

As previously explained, the "General Method" states that to determine the optimal dosages of superplasticizer trial tests should take place using mortars, specifically by doing the flow tests and V-funnel tests. Since the IST construction lab does not posses a V funnel in order to determine the optimal dosage of superplasticizer (Sp), the volumetric ratio of water/powder was set as = **0,95** (≈ 0,31 by weight) and the Sp quantity was trialed until Gm = 5. In the concrete production its was observed that the desired rheology and workability characteristics where only achieved for a G_m value approximately 6.3. According to this the superplaticizer's optimal quantity was determined throw mortar flow tests trials until a G_m value of 6.3 was obtained, this value was obtained for a spread of 270 mm of diameter. The mortar composition is identical to the concretes excluding the coarse aggregates.

In this work four different SCC mixes where done. Table 3 shows the methods flowed and the mix compositions for each of the four SCCc that were produced in the experimental campaign.

Table 3 Lab SCC's composition.

Mix design		General Method		Domone's modification	
Concrete designation		BR	BV	BRr	BVr
Components		SCCs composition [kg/m^3]			
Aggregates	Coarse aggregate	746,9	746,9	746,9	746,9
	Fine aggregate - A	483,2	483,2	543,6	543,6
	Fine aggregate - B	241,6	241,6	271,8	271,8
Powder	Cement	650,8	528,8	595,4	483,8
	Fly ash	-	122,0	-	111,6
Water		199,4	199,4	182,5	182,5
Superplasticizer (Sp)		15,6 1)	13,0 2)	17,9 3)	13,7 4)

1) For Sp = 2,4%; 2) For Sp = 2,0%; 3) For Sp = 3,0%; 4) For Sp = 2,3%

BR and BV have the same mix (obtained using the "General Method") but are differentiated by the powder materials that where used:

- BR has a dosage of cement equal to 650,8 kg/m^3;
- BV has 528,8KG/m3 of cement and 122,0 kg/m^3 of fly ash (18,75%), adding up in a total of 650,8 kg/m^3.

BRr and BVr also have the same mix (obtained using the "General Method" and the Domone modification) and are also differentiated by the powder materials used in them:

- BRr has a dosage of cement equal to 595,4 kg/m^3;
- BVr has 483,8 kg/m^3 of cement and 111,6 kg/m^3 of fly ash (18,75%), adding up in a total of 595,4,8 kg/m^3.

By observing with the "Domone" modification the powder materials quantity is reduced by 55 kg/m^3 having as consequence an increase of 90 kg/m^3 of the fine aggregates component. Although in the BRr and BVr concretes the volumes of powder materials are inferior to those of BR and BV, the dosage of superplasticizer (measured as a percentage of the total mass of powder material calculated for the concrete) is greater, in order to compensate for the increase of fine aggregates, ensuring the required rheology and workability characteristics for the concrete.

By reducing the powder volumes in the mix (paste reduction) and in other hand increasing the contents of fine aggregates, contributes for a reduction in the spread (deformation capacity). To increase the deformability of the mix keeping the same water/powder ratios an increase to the superplasticizer dosages is required.

In the fresh concretes, all of them presented a homogeneous aspect with a uniform distribution of the aggregates and no indices of segregation occurrence where observed. By observation of table 4, in general, states that all the concretes had the necessary requirements to be considered as fresh self-compacting concretes, as all the concretes passed the "General Method" criteria for the v-funnel test, slump flow test and U-Box test. BR and BRr did not achieve the minimum requirements in the L-Box test, even though no aggregate blockage was observed while flowing through the reinforcement steels. The low values of PA parameter in BR concrete are explained by the fact that this test was done only 50 minutes after the concrete mix. In BRr concrete the PA parameter values are slightly below 0,8 which can still be considered acceptable. In the tests it is possible to observe that the concretes with fly ash had a better performance in the fresh state tests and by this it is possible to state can state that the fly ash contribute to improve SCC fresh state characteristics.

Table 4 SCC fresh and hardened state test results.

Concrete designation		**BR**	**BV**	**BRr**	**BVr**	A.criteria
Fresh state characteristics						
Slump flow test	S [mm]	680	698	663	665	600-700
	T_{500} [s]	2,50	1,54	2,75	2,67	2-5
V-funnel test – T_{funnel} [s]		15,12	18,72	19,97	18,82	10-20
U-box test – H_u		352,5	356,0	-	354,0	≥ 300
L-box test	T_{200} [s]	-	1,52	2,03	1,41	-
	T_{400} [s]	-	3,97	-	-	-
	PA	0,72	0,86	0,78	0,80	≥ 0,80
Hardened state characteristics – 7 days						
Ultrasonic pulse velocity tests – v_m [m/s]		4900	4802	4884	4777	-
Compressive strength [MPa]		73,2	66,9	68,4	59,8	-

As expected BR and BV concretes that have in them a greater volume of powder material and less volume of fine aggregate, have more deformation capacity , which originates greater spread diameters in the slump flow tests than those of BRr and BVr, this fact is explained because they have less inter particle friction.

Results also show that for greater spreads T_{500} times get smaller, which means that for greater deformation abilities (fluidity) originates lesser viscosity (cohesion) with greater flow abilities. The risk of segregation occurrence diminishes with the increase of viscosity (cohesion). In a SCC it is desirable to have simultaneously both high deformation capacity and viscosity, as no segregation was observed in any of the concretes, concluding that these characteristics were achieved with success.

The T_{funnel} was relatively high in all mixes, show in that all concretes have a high viscosity. Some authors state that the T_{funnel} time should be smaller than 15 second, this way ensuring that the mix haves the desired deformability and viscosity, but since all the tested mixes presented high deformation capabilities this is not seen as an issue.

In the U-Box test all concretes had very satisfactory results, by achieving H_u > 300 mm, observing that the concrete is almost at the same level in both compartments. This test was not able to be performed for BRr concrete due to technical problems, but it was also expected to achieve Hu≥ 300 mm, supported by the fact that it reached passing criteria in the other tests, mainly the L-Box test that is considered as more restrictive.

In the hardened state all concretes presented a good superficial finishing, with a surface that was homogenous, with out air voids, flat and showing no imperfections.

For all concretes in the hardened state, characteristics, where only tested at 7 days due to time limitations. All concretes showed high resistance values, above 60 MPa. This is explained by the fact of the mixes containing high quantities of powders and another explanation for this resistance is the fact of its self compacting property, which makes it independent from the external compaction, since it has a uniform compaction this, enhances its resistance.

The concretes where the powder material is composed only by cement are the ones that present greater resistance, because the use of fly ash originates lower resistances in the early ages. As expected powder reductions give origin to a resistance reduction.

After the compressive strength tests, a uniform distribution of the aggregates among with the paste was observed, presenting no indices of segregation as for the ultrasonic pulse velocity they had the same behavior pattern as the compression strength.

In this work a mortar characteristics study was also conducted for the fresh and hardened states, due to the fact that the tests are easier and faster to conduct than those with concrete and on another hand test mortar production less costly and requires less means.

Table 5, presents a compilation of the characteristics for the fresh and hardened states of the mortars that gave origin to the concretes.

Table 5 Obtained results for SCC mortars, for an optimal quantity Sp

Mortar designation		**AR**	**AV**	**ARr**	**AVr**
Fresh state characteristics					
Optimal superplasticizer dosage [%]		2,4	2,0	3,0	2,3
Flow test	D_{med} [mm]	269,3	260,5	271,0	270,0
	G_m	6,3	5,8	6,3	6,3
Density [g/cm^3]		2,28	2,21	2,28	2,21
Hardened state characteristics – 7 days					
Ultrasonic pulse velocity tests– v_m [m/s]		4407	4217	4517	4413
Bending strength [MPa]		10,39	10,09	13,38	9,03
Compressive strength [MPa]		86,0	71,7	87,5	70,2

In the mortars that have the powder material composed only by cement, the density value is 2,28 g/cm^3, and in the mortars with fly ash addition this value is only 2,21 g/cm^3, this is explained by the fact that the fly ash's density is lower than the cement's.

Comparing with concretes, mortars present greater resistances to compression due to a confinement effect on the mortar samples, because of their reduced dimensions. It is observable that resistance and ultrasonic pulse velocity have the same behavior patters as in concrete, except for mortar ARr for which in all tests done it presented value slightly above expected. To this we can state, that since mortars are produced in smaller quantities (1.5 liters), they are more susceptible to errors due to temperature, humidity and weightings.

8. Conclusion

In concrete production we can verify the applicability of the "General Method" is verified, and also Domone's proposed modification, sustained on the fact that concretes that met all the requirements needed to obtain self compactability were obtained. All concretes presented simultaneously high deformation capacity and an adequate viscosity, having also good filling and passage capacity, as well for resistance to segregation.

It was observed that in the concretes with addition of fly ash presented improved fluidity and deformability, being these the one with the best results in the fresh state, by this concluding that fly ash is a good addition to SCCs, as by adding them to the mix, concretes need less superplasticizer to achieve the desired rheological and self-compactation characteristics.

It was observed that concretes with less powder need a bigger dosage of superplasticizer to achieve the desired rheological and self-compactation characteristic values.

It is possible to point out the high compression strength values obtained (values between 60 and 70 MPa), fact that is justified by the large quantities of powders, the low water/powder ratios used, by the compaction due to the self compacting properties of the concrete and its correct grading of aggregate composition.

It was observed that the compression strength is bigger in the concretes with more powder and it is smaller for the ones that have fly ash addition, because fly ash addition originates inferior resistances in young age concretes. The same pattern was observed in ultrasonic pulse velocity behavior.

After the compressive strength tests, an even distribution of the aggregates and the paste was observed and no segregation had occurred, reinforcing that the concrete met all the required requirements to be considered a self-compacting concrete.

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