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Self-compacting concretes (SCC) – comparison of methods of dosage

Concreto autoadensável (CAA) – comparativo entre métodos de dosagem


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Abstract

The composition of a self-compacting concrete (SCC) should be defined to fulfills a number of requirements, such as self-compactibility, strength and durability. This study aims to compare three methods of dosage for SCC with local materials, so as to determine which one is the most economical and rational, thus assisting the executor in making a decision and enabling economic and technical feasibility for its application. The methods used in the experimental program were: Nan Su et al., which was developed in 2001 [1]; Repette-Melo, which was proposed in 2005 [2]; and Tutikian & Dal Molin, which was developed in 2007 [3]. From the results obtained in the experimental program, it was observed that the method which presented the lowest cost and highest compressive strength at the ages of 7, 28 and 91 days was Tutikian & Dal Molin, while the one which reached the lowest chloride ion penetration, best compactness and highest elasticity modulus was Repette-Melo. In tests carried out in the fresh state, all tested methods yielded mixtures which comply with the self-compactibility levels required by ABNT NBR 15823:2010 [4].

Keywords: self-compacting concrete, methods of dosing, properties in the fresh and hardened state.

Resumo

A composição de um concreto autoadensável (CAA) deve ser definida de forma a satisfazer um conjunto de requisitos, como a autocompactabilidade, resistência e durabilidade. O objetivo deste artigo é comparar três métodos de dosagem para CAA com materiais locais, a fim de determinar o mais econômico e racional, auxiliando a tomada de decisão por parte do executor e proporcionando a viabilidade econômica e técnica para aplicações. Os métodos utilizados no programa experimental foram: o de Nan Su et al., desenvolvido em 2001 [1], o de Repette-Melo, proposto em 2005 [2] e o de Tutikian & Dal Molin, elaborado no ano de 2007 [3]. A partir dos resultados obtidos no programa experimental, observou-se que o método que apresentou os menores custos e maiores resistências à compressão nas idades de 7, 28 e 91 dias foi o de Tutikian & Dal Molin e o que atingiu menor penetração de íons cloretos, melhor compacidade e maior módulo de elasticidade foi o de Repette-Melo. Nos ensaios realizados no estado fresco todos os métodos experimentados obtiveram misturas que se enquadraram na classe de autoadensabilidade requerida pela ABNT NBR 15823:2010 [4].

Palavras-chave: concreto autoadensável. métodos de dosagem. propriedades no estado fresco e endurecido.

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1. Introduction

The development of self-compacting concrete represents a big step towards efficiency and working conditions at construction sites and in the prefabricated buildings industry. Such material enables shorter concreting times, better finish of the concrete surface, as well as better characteristics in the hardened state, thus generating more durable structures (GRUNEWALD, 2004 [5]).

The benefits of SCC go beyond durability and resistance. Its use reduces noise pollution, since it does not call for the use of vibrators, which also contributes to lower electrical energy consumption. The use of SCC also minimizes the risk of accidents caused by an excessive number of people upon the slabs, since it requires less manpower. It also reduces ergonomic problems which affect workers, since the effort made in the launch and finish is smaller. According to Tutikian (2007 [3]), the use of SCC steers construction services towards more industrialized production by reducing manpower cost, increasing quality, durability, confidence in the structure and workers' security.

SCC can be considered the most significant achievement in concrete technology in decades, and it should gradually replace part of the conventional concrete which is currently produced. SCC is a material which boasts a unique combination of performance and uniformity, requirements which cannot be reached through the use of regular conventional construction components (SONEBI 2004 [6]).

Tutikian (2007 [3]) states that the interest SCC has attracted in Brazil is increasing, and it has been used in the prefabricated buildings industry as well as in current special constructions. However, the main studies focus on its mechanical properties, durability and possibility of use with specific types of local materials. Dosage, which is one of the key aspects of this material, has only been studied superficially.

SCC is more widely used in Japan and in Europe. In Brazil, however, a higher level of confidence in the methods of dosage is necessary in order to make SCC more reliable and widespread, thus allowing bigger possibilities for its application anywhere that proves to be economically feasible (TÉCHNE MAGAZINE, 2008 [7]).

Several international and national procedures or recommendations for SCC dosage have been issued as studies have become more consistent. Such methods might differ in criteria for the definition of granular composition, such as the amount of fine materials, the setting of limits for the water/cement ratio, paste volume, amount of superplasticizer admixture, the use of viscosity modifying admixture and separate studies of paste and mortar. Some methods also consist of sequences of calculations, which translate into limit intervals for each material in the mixture.

This study compares three existing methods of dosage for SCC with local materials in order to determine which one is the most economical, sensible and durable, thus assisting the executor in making a decision and providing economical and technical feasibility for practical applications, while also expanding the knowledge about SCC as well as its use. The methods of dosage chosen were the one proposed by Nan Su et al. [1], from 2001, for it is based on equations and empirical calculations; the one by Repette-Melo [2], developed in 2005, for it proposes a sequence of tests from the admixture in the paste to the concrete for the adjustment of the components in the mixture; the one by Tutikian & Dal Molin [3], developed in 2007, for it studies the granular skeleton of concrete before making it self-compacting. The self-compactibility of SCC in the fresh state was compared through tests such as flow, $_{t500mm}$, "L-box" and "V-funnel" based on the limits defined by ABNT NBR 15823:2010 [4]. In the hardened state, the characteristics analyzed were compressive strength at 7, 28 and 91 days, the elasticity modulus at 91 days, propagation velocity of ultrasound waves at 91 days, and chloride ion penetration at 28 days, for all mixtures. This study also determined the cost based on market values of the concrete components.

2. Aims of research

The main aim of this study is to make technical and economical comparisons between the methods of dosage for SCC proposed by Nan Su et al. in 2001 [1], Repette-Melo in 2005 [2], and Tutikian & Dal Molin in 2007 [3], through the use of materials available in the state of Rio Grande do Sul (RS), Brazil.

3. Materials and experimental program

In view of the objectives laid out here, an experimental program was created and developed which defines the tests conducted on the different concretes as well as the materials used in the research. The experimental work was carried out at the Construction Materials Lab (CML) at the Vale do Rio dos Sinos University (UNISINOS).

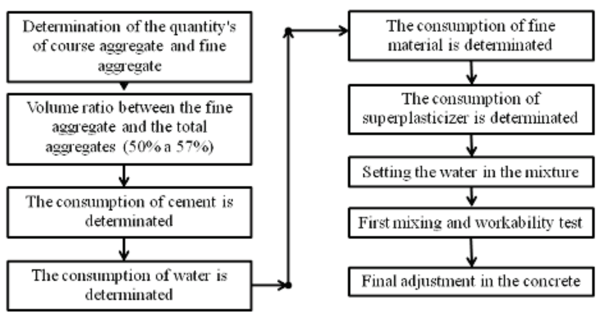
A vertical axis mixer was used in the manufacturing of all concretes, and the placing of materials followed an established order. Firstly, the coarse aggregate was placed, followed by 80% of the water, regular sand, fine sand, cement, admixture and the remainder of the water. In total, 8 mixtures of concrete were measured, with 11 samples measuring 10 cm in diameter and 20 cm in height being manufactured for each one of those mixtures, totaling 88 samples. These samples remained at room temperature for 24 hours, the tops of which protected by sheets of glass. Next, they were removed from their molds and taken to a moist chamber, where they were kept until they reached the relevant ages at which the tests should be performed.

3.1 Showcase of the methods of dosage used

3.1.1 Nan Su et al Method [1]

This method is divided into steps, as shown in Fig. 1. To determine the amount of aggregates, the volume ratio between the fine

Figure 1 – Flowchart of the Nan Su et al., (1) method



aggregate and the aggregate total (S/t) should be verified. According to this method, this ratio should range between 50% and 57%. Given these figures, a 53% S/t ratio was established, and the efficacy of the mixture for self-compactibility on the fresh state tests was analyzed.
The coarse aggregate composition was made up of 60% of 25 mm gravel and 40% of 19 mm gravel to be then employed in Equation 1. This was the arrangement which represented the largest number of voids.

$$W_g = PF*W_{gL}*(1\text{-}S/t) \tag{1}$$

Where:
Wg - amount of coarse aggregate in kg/m³;
WgL - density of coarse aggregate, in loose state in kg/m³ (1528 kg/m³ for the materials studied);
PF - loose state aggregate and compacted state aggregate ratio, in mass (0.941 for the materials studied);
S/t - volume ratio between fine aggregate and aggregate total, which ranges from 50% to 57% (53% adopted).
The result was Wg = 677 kg/m³ of coarse aggregate, being 406.20 kg/m³ for the 25 mm gravel and 270,80 kg/m³ for the 19 mm gravel.
The fine aggregate, i.e., regular sand, was determined through Equation 2.

$$W_s = PF*W_{sL}*S/t \tag{2}$$

Where:
Ws - amount of fine aggregate in kg/m³;
WsL - density of fine aggregate, loose state, in kg/m³ (1470 kg/m³ for the materials studied);
PF - loose state aggregate and compacted state aggregate ratio, in mass (0.902 for the materials studied);
S/t - volume ratio between fine aggregate and aggregate total, which ranges from 50% to 57% (53% adopted).
The result was Ws = 703 kg/m³ of fine aggregate.
After having established the amounts of gravel and regular sand, the amount of cement is determined. So as to obtain the amount of cement per m³, it is first necessary to adopt the required compressive strength in MPa (f'c) at 28 days.
The f'c selected for the calculation was 55 MPa. Therefore the compressive strength of the SCC at 28 days is supposed to be 55 MPa. From Equation 3 the cement consumption for the mixture can then be known.

$$C = \frac{f\ c}{0{,}14} \tag{3}$$

Where:
C - cement consumption in kg/m³;
f'c - required compressive strength in MPa.
Hence the cement consumption was set at 393 kg/m³. After the amount of cement has been determined, the water/cement ratio must be established according to local requirements and aggressive environmental exposure.
In order to establish the amount of water to be added to the mixture, the relevant ABNT NBR 6118:2007 [8] requirements were fulfilled, and the aggressive environmental exposure was defined as III, with a water/cement ratio ≤ 0.50, which was the limit used.
From Equation 4 the amount of water in the mixture is then known.

$$W_{aC} = (a\ /\ c)*C \tag{4}$$

Hence WaC = 196 kg/m³.
The fine material selected for the dosage was fine sand. Since the amounts for all the other SCC components are known, the remaining volume missing to complete 1 m³ belongs to the to the fine material (Vf) which should be found through Equation 5.

$$V_f = 1 - \frac{W_g}{1000*G_g} - \frac{Ws}{1000*G_s} - \frac{C}{1000*G_c} - \frac{W_{aC}}{1000*G_a} - V_{ar} \tag{5}$$

Where:
Gg - coarse aggregate specific mass;
Gs - fine aggregate specific mass;
Gc - cement specific mass;
Ga - water specific mass;
Var - amount of air incorporated into the SCC (in %).
The result obtained, 0.13, is applied in Equation 6 and thus the final result for the amount of fine sand in the mixture is known.

$$W_f = Vf * 1000 * G_{af} \tag{6}$$

Where:
Wf - amount of fines in kg/m³;
Gaf - specific mass for the fine material used in kg/m³;
Vf - volume of fines in the mixture.
Wf = 303 kg/m³ of fine sand in the SCC mixture.
After the amounts of all aggregates are defined and the cement and water consumption is obtained, the percent additive is yet to be determined.
The admixture/binder ratio adopted was 0.70% (amount of solids and liquids in the admixture), which was the value selected as an initial parameter, although such value might be changed depending on the workability tests results.
The amount of water in the superplasticizer was considered as part of the water from the mixture. The quantity of admixture (in kg/m³) used in the mixture was calculated using Equation 7.

$$W_{sp} = n\%*(C) \tag{7}$$

Table 1 – proportions obteined in each determination method

PARAMETER	METHODS							
	Tutikian				Nan Su et al.	Repette-Melo		
1:m	3	4	5	6	4,28	3,50	3,97	4,32
w/c (kg/kg)	0,35	0,47	0,56	0,68	0,50	0,39	0,48	0,56
α (%)	64	62	60	59	67	61	60	59
C (kg/m³)	538	421	350	297	393	490	432	398
TAF (%)	20	20	20	20	18	10	10	10
TG (%)	48	48	48	48	40	50	50	50
Adt (%)	0,62	0,62	0,62	0,62	0,85	0,75	0,75	0,75
R$	313,04	252,53	215,86	188,08	249,25	298,97	267,14	248,49

Where
1:m = Unit trace for each family
a/c = Water / cement ratio (kg/kg)
α = Content of mortar (%)
C = Cement consuption (kg/m³)
TAF = Content of fine sand aggregate in relation of total weight in mass (%)
TG = Content of gravel aggregate in relation of total weight in mass (%)
Adt = Content of additive (%) in relation of cement weight
$ = Total cost to obtein a 1m³ of concrete

n% is the superplasticizer/binder ratio, C is the amount of cement per m³ in the mixture, m% is the amount of solids in the superplasticizer, Wsp is the amount of superplasticizer admixture used, and Wasp is the amount of water in the superplasticizer admixture.
Considering Wsp = 2.75 kg/m³ worth of superplasticizer admixture, the amount of water existing in the admixture is calculated using Equation 8.

$$W_{asp} = (1 - m\%)*W_{sp} \quad (8)$$

The result was Wasp = 1.65 kg/m³ worth of water existing in the admixture.
Considering the amount of water existing in the superplasticizer admixture, the initial water consumption in the mixture became 197.65 kg/m³.
Taking into account all the ratios determined for the SCC composition, the materials were then taken into the lab for dosage, with a unit composition test as the initial step. It is important to observe that the only amounts which may be altered after this step are the water/cement ratio and the amount of admixture/binder ratio.
After mixing the materials using a mixer, workability tests were then carried out in order to verify the self-compactibility of the SCC. Based on the flow test performed, it was verified that the mixture was not fluid enough, presenting a flow result of 450 mm. From that result, superplasticizer admixture was added so as to reach better workability in the mixture, even before other tests were carried out. No water was added to the mixture.
After increasing the amount of admixture in the mixture, new workability tests were conducted, in compliance with ABNT NBR 15823:2010 [4], and it was concluded that the values were within the acceptable limits. The final admixture/binder ratio in the mixture was 0.85.
It should be noted that for this method it was possible to create only one unit composition for the SCC mixture, since this method does not mention how to quantify auxiliary unit compositions for the dosage.
Table 1 shows the unit composition for this method.

3.1.2 Repette-Melo Method [2]

The flowchart for obtaining the SCC mixture by this method of dosage is shown in Fig. 2.
The initial step for making the SCC mixture is the paste composition, by determining the water/cement ratio and the amount of fines added.

Figure 2 – Flowchart of the Repette-Melo (2) method

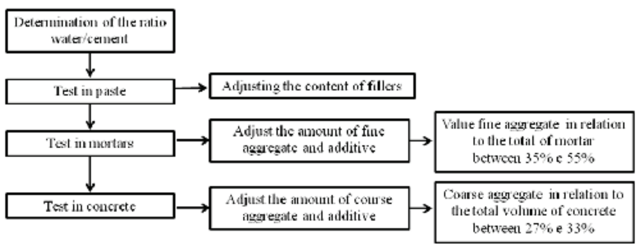
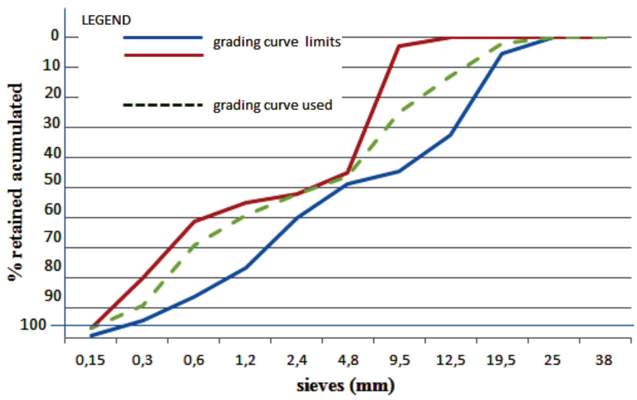


Figure 3 – granulometric curve of the composition of the aggregates used in the Repette-Melo (2) method



In order to determine the water/cement ratio, the starting point established was the compressive strength according to the amount of water and cement used in each unit composition. For the definition of a family of concrete, three values for the water/cement ratio were determined initially: one for the poor unit composition (w/c: 0.56), one for the rich (w/c: 0.39) and one for the intermediate unit composition (w/c: 0.48), based on the previous knowledge about the materials.

The amount of fines is determined for each specified water/cement ratio and it is dosed to replace the cement, in volume. The method establishes that a percentage of filler passing through the 0.075 mm sieve should be used in this stage. Fine sand was used as fine material in order to achieve the SCC mixture. Since fine sand does not have a significant amount of particles smaller than 0.075 mm, it could not be included in the paste composition.

During the next step, the mortar for the mixture is prepared, by defining the amount of fine aggregate in relation to the total volume of mortar and then the basic amount of superplasticizer admixture. The amount of fine aggregate was adjusted only for a water/cement ratio, the intermediate one, with the percentage found being used for the others.

As a basic guideline, the method establishes that the volume of fine aggregate in relation to the total volume of mortar should preferably be not less than 35% and not more than 55%.

A regular sand and fine sand composition was defined as fine aggregate. The choice of percentages for these materials was based on the optimal granulometric curve of the aggregates. From there it was concluded that the amount of fine aggregate which fit best to the limit curve established by the method was the composition made up of 80% of regular sand and 20% of fine sand.

In order to determine the amount of fine aggregate, the mortars were assessed based on the flow test, which was adapted for mortar. According to the test, the ideal amount of fine aggregate in the mortar composition was 50% in relation to the total volume, achieving satisfying test results when the amount of admixture was 0.20% (considering only the amount of solids), since the drainage time was 4 seconds and the flow was 240 mm. According to the method, the ideal amount of admixture is the one which results in a mortar flow diameter between 200 and 280 mm and a draining time in the "V-funnel" between 3.5 and 10 seconds.

The mortar with intermediate amount of water/cement was used in order to determine the amount of coarse aggregate for the preparation of an initial test mixture with 30% of coarse aggregate in relation to the total volume of concrete. The method proposes an amount of coarse aggregate between 27% and 33%, the optimal value being the one which presents satisfying results on the workability tests while reaching a 0.3% percentage of admixture (taking into consideration only the amount of solids). Thus a value of 30% was adopted, which was the midpoint between the proposed limits. Using that percentage, a trial mixture with the intermediate unit composition was created so as to verify the acceptability of the adopted ratio, considering the initial amount of admixture determined during the mortar stage.

A mixture made up of 50% 25 mm gravel and 50% 19 mm gravel was used as coarse aggregate. These percentages were adopted based on the granulometric analyses of the gravel.

Figure 3 shows the granulometric curve of the fine and the coarse aggregate, according to the percentages adopted and the limit curves imposed by the method for determining the granulometric arrangement. As can be seen in Figure 3, the resulting granulometric curve from the mix of aggregates used for the mixture is within the limits recommended by the method. Were it not possible to fit any one of the aggregate compositions into the limit curves, it would be necessary to specify other materials with different granulometric characteristics and which enabled the feasibility of the mixture.

According to the method, the amount of admixture in the mortar represents a good indication of the results which will be achieved in the concrete. Generally speaking, an increase of roughly 0.1% in relation to the optimal amount of mortar is needed. Following the guidelines regarding the amount of admixture, the trial mixture contained initially 0.2% worth of superplasticizer. The flow test showed that the mixture was not fluid enough, which led to a gradual increase in admixture up to the maximum admissible amount, i.e. 0.3% (considering only the amount of solids). In case of unsatisfying results, the amount of coarse aggregate should be altered in relation to the total volume of

Figure 4 – Flowchart of the Tutikian & Dal Molin (3) method

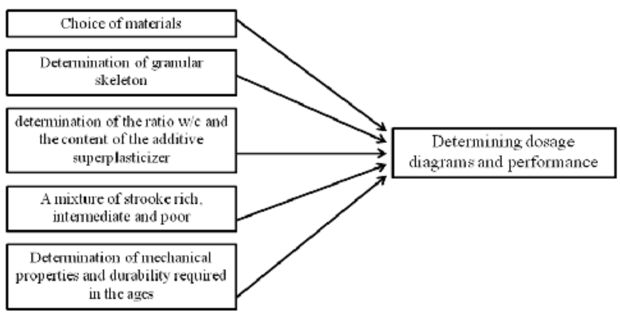


Table 2 – packing test between 25 mm gravel and 19 mm gravel				
25 mm Gravel (%)	19 mm Gravel (%)	Unit massa of mixture (kg/m³)	Compacted bulk density (kg/m³)	Index of voids (%)
100	0	3065,00	1704,35	44,39
90	10	3044,50	1736,23	42,97
80	20	3024,00	1755,36	41,95
70	30	3003,50	1753,04	41,63
60	40	2983,00	1759,42	41,02
50	50	2962,50	1736,23	41,39
40	60	2942,00	1701,45	42,17
30	70	2921,50	1634,78	44,04
20	80	2901,00	1597,10	44,95
10	90	2880,50	1556,52	45,96
0	100	2860,00	1504,35	47,40

concrete while the mixture should be remade with different unit composition components. After the 0.1% increase in admixture, the flow test was performed again and it was verified that with the added superplasticizer the result obtained was in accordance with the established values. The remaining workability tests were then performed, namely T50, "L-box", "V-funnel", so as to verify the compliance of their results with the values given by ABNT NBR 15823:2010 [4].

Once the unit composition test was defined, and through the results obtained, it was possible to calculate the final unit compositions for the SCC. In order to calculate the amount of materials, 1 m³ worth of concrete was used, which was made up of 30% of coarse aggregate and 70% of mortar. The mortar was composed by 35% of fine aggregate while the remaining 65% was composed by water, cement and admixture.

It should be noted that due to the procedures determined by the method of dosage, it is necessary to maintain the same amount of coarse and fine aggregates for all water/cement ratios outlined in the initial step of the mixture procedure. This is relevant when it is recommended that the amount of mortar should be adjusted only for a water/cement ratio (the intermediate one, in the case of the construction of the curve of the family of concrete with three strengths). That implies that the only material which will be altered for each concrete is the cement consumption, which will cause a change in admixture consumption and amount of water. However, from one mixture to another, water will be added and cement and admixture will be reduced, considering for this group a constant amount of 0.35 m³.

The final amount of superplasticizer admixture was 0.3% (only the amount of solids), which is the equivalent of 0.75% if the amount of solids and liquids existing in the admixture is considered. This percentage is set for other unit compositions with the same aggregate/cement ratio in mass, adjusting only the water/cement ratio.

Table 1 shows the unit composition for this method.

3.1.3 Tutikian-Dal Molin Method

The method is presented in schematic form in Fig. 4. The first step taken in order to obtain the mixture was to determine the granular skeleton. The materials were packaged, two by two, starting with the ones with the largest granulometry going all the way down to the ones with the least granulometry. The first package of the compression test was between the 25 mm gravel and the 19 mm gravel, followed by the compacity with regular sand and, lastly, with fine sand.

Table 2 shows the results of packaging the 25 mm gravel with the 19 mm gravel. It was observed that the mixture percentage which provided the smallest number of voids was the one with 60% of 25 mm gravel and 40% 19 mm gravel, with 41.02% of voids. It should be noted that the unit mass of this mixture is not the biggest of all, i.e., the ideal ratio is always the one which results in a smaller number of voids. The compacted unit mass is only an indicator, since it is not sufficient to reach a conclusion.

The second step of the packaging for the SCC mixture was obtaining the compactness between the previous mixture, with 25 mm gravel and 19 mm gravel, and regular sand. Table 3 shows the result of the packaging of the gravel and the regular sand.

Lastly, the last packaging was performed, between the fine sand and and previously packaged aggregates. Table 4 shows the results obtained from the compactness test of those materials.

It was observed that the optimal composition was 80% a mix of 25 mm and 19 mm gravel and regular sand with 20% fine sand, which resulted in 16.61% worth of voids. The test was initiated with substitutions from 10% to 10% and increased in precision to 5% as it neared the ideal final value.

The compactness test values between materials resulted in the following proportions for the SCC mixtures, in mass: 28.80% 25 mm gravel, 19.20% 19 mm gravel, 32% regular sand and 20% fine sand.

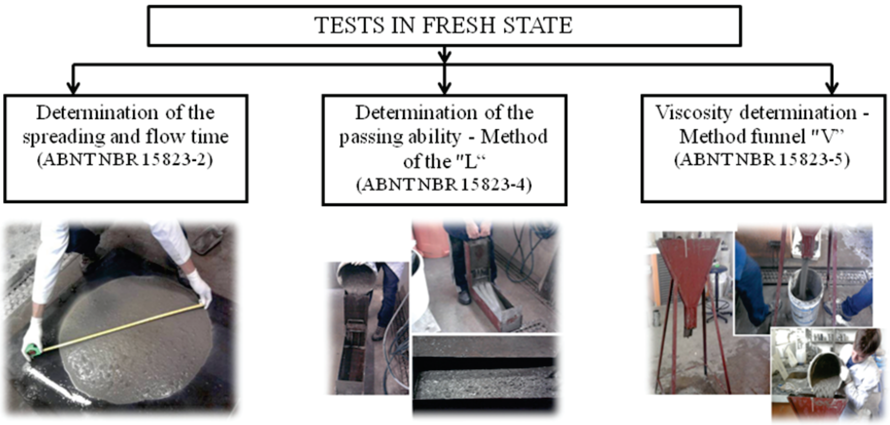
Table 3 – packing test between 25 mm gravel and 19 mm gravel and the regular sand

25 mm and 19 mm Gravel (%)	Regular sand (%)	Unit massa of mixture (kg/m³)	Compacted bulk density (kg/m³)	Index of voids (%)
100	0	2983,00	1759,42	41,02
90	10	2918,70	1846,28	36,74
80	20	2854,40	1951,30	31,64
70	30	2790,10	2062,03	26,09
65	35	2757,95	2092,75	24,12
60	40	2725,80	2125,22	22,03
55	45	2693,65	2091,01	22,37
50	50	2661,50	2078,84	22,39
40	60	2597,20	2014,49	22,44
30	70	2532,90	1959,42	22,64
20	80	2468,60	1892,17	23,35
10	90	2404,30	1745,51	27,40
0	100	2340,00	1628,41	30,41

Table 4 – packing test between 25 mm gravel, 19 mm gravel, the regular sand and fine sand

25 mm, 19 mm gravel and regular sand (%)	Fine sand (%)	Unit massa of mixture (kg/m³)	Compacted bulk density (kg/m³)	Index of voids (%)
100	0	2725,80	2125,22	22,03
90	10	2686,22	2154,78	19,78
85	15	2657,29	2182,61	17,86
80	20	2646,64	2206,96	16,61
75	25	2626,85	2182,61	16,91
70	30	2607,06	2120,58	18,66
65	35	2587,27	2090,43	19,20
60	40	2567,48	2032,75	20,83
55	45	2547,69	1974,49	22,50
50	50	2527,90	1921,74	23,98
40	60	2488,32	1886,96	24,17
30	70	2448,74	1800,00	26,49
20	80	2409,16	1750,72	27,33
10	90	2369,58	1663,77	29,79
0	100	2330,00	1561,74	32,97

Figure 5 – Tests carried out in the fresh state



Following the completion of the compactness test, the next step was to determine the water/cement ratio and the amount of superplasticizer admixture.

From that point on, unit composition I (1:4) was used to prepare the adjustment mixture, so as to confirm the water/cement ratio and, most importantly, determine the amount of superplasticizer admixture experimentally. First an admixture value of 0.50% (considering the amount of solids and liquids in the admixture) was defined, in relation to the cement mass and a water/cement ratio of 0.40. After determining those values, the intermediate mixture was initiated, and from the tests performed in the fresh state, the final ideal amount of superplasticizer admixture and the water/cement ratio were defined.

From the results obtained, the final unit compositions for the SCCs were determined without the need for substitutions. According to the method, the ideal is to create four points so that the behavior equations have a higher coefficient of determination, allowing the curves to be better adjusted. The individual unit compositions are shown in Table 1.

3.2 Tests performed in the fresh state

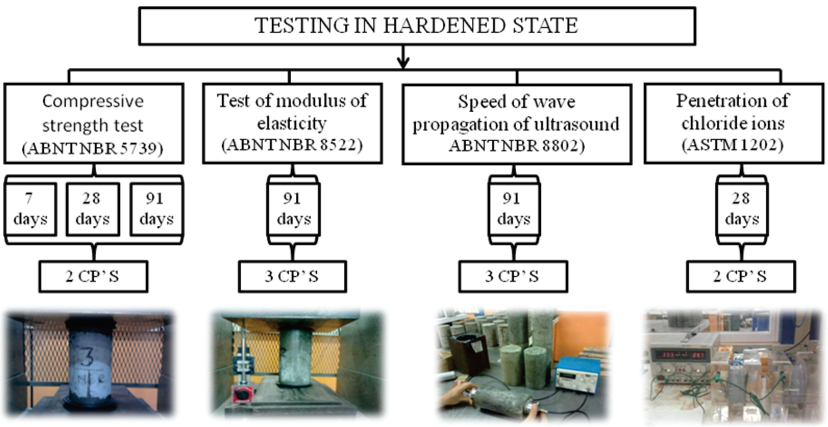
In the fresh state the SCC families were tested in order to assess the flow properties, passing ability, resistance to segregation and apparent plastic viscosity, following the technical specifications defined by ABNT NBR 15823:2010 [4]. The tests included flow tests (SF), draining time (VS), "L-box" (PL) and "V-funnel" (VF). Fig. 5 shows the tests in the fresh state being performed in the lab.

3.3 Tests performed in the hardened state

In order to compare the properties obtained in each SCC family in the hardened state, the concretes were submitted to compressive strength tests at 7, 28 and 91 days, modulus of elasticity at 91 days, propagation velocity of the ultrasound wave at 91 days, and chloride ion penetration at 28 days.

The compressive strength test, performed in compliance with ABNT NBR 5739:2007 [7], was carried out because that is the most commonly used property in research and in real applications, as well as the

Figure 6 – Tests carried out in the hardened state



most recalled by designers and other professionals. The SCC modulus of elasticity test, based on ABNT NBR 8522:2008 [10], was carried out because that is an important characteristic which impacts the removal of the structural pieces from their molds while it is also a reason why some professionals choose not to use SCC, once it may face a significant reduction in its value due to the materials used in its composition.

Table 5 – chemical, fisical and mechanical properties of CP-V-ARI

Chemical properties		Fisical and mechanical properties		
Cement chemical composition	Results (%)			
Silicon dioxide(SiO_2)	18,67	Set time	Begining	02h22min
Aluminum oxide (Al_2O_3)	4,07		End	03h04min
Calcium oxide (CaO)	59,90	Bulk Density	(g/cm^3)	3,13
Iron oxide (Fe_2O_3)	2,56	Compressive strenght (MPa)	1 day	20,5
Magnesium oxide (MgO)	5,31		3 days	33,8
Sulfur oxide (SO_3)	3,02		7 days	40,5
Loss on ignition	3,32		28 days	48,6
Freedom CaO	1,70			
Insoluble residue	0,64			
Equivalent alkali	0,63			

Table 6 – characteristics of the aggregates used in mixtures of SCC

Opening of sieves (mm)	Amount retained acumulated (%)			
	Gravel 25 mm	Gravel 19 mm	Regular sand	Fine sand
# 25	0	0	0	0
# 19	7	0	0	0
# 12,5	35	16	0	0
# 9,5	70	31	0	0
# 6,3	99	86	0	0
# 4,8	100	100	0	0
# 2,4	100	100	15	0
# 1,2	100	100	32	0
# 0,6	100	100	56	3
# 0,3	100	100	97	17
# 0,15	100	100	9	84
# 0,075	100	100	100	99
Depth (< 0,075)	100	100	100	100
Fineness modulus	6,77	6,31	2,11	1,04
Maximum size	25 mm	9,5 mm	4,8 mm	0,6 mm
Bulk density	3,07 kg/dm^3	2,86 kg/dm^3	2,34 kg/dm^3	2,33 kg/dm^3
Unit mass compacted	1,70 kg/dm^3	1,50 kg/dm^3	1,63 kg/dm^3	1,56 kg/dm^3
Unit mass in the released state	1,62 kg/dm^3	1,39 kg/dm^3	1,47 kg/dm^3	1,50 kg/dm^3

ABNT NBR 8802:1994 [11] specifies the execution of the propagation velocity of the ultrasound wave procedure, which was chosen for being a test which relies heavily on the compacity of the mixtures, identifying the packaging among all components. The chloride ion penetration test was chosen for being a representative for durability, regardless of its application. This test was adapted from the ASTM 1202:2007 [12] norm. Fig. 6 shows the tests performed in the hardened state.

3.4 Materials used

For the execution of the experimental work, the materials selected were ones found in the state of Rio Grande do Sul (RS), which are economical and already used by the construction services for other purposes.
In order to determine the characteristics of the aggregates used in the experimental work, the procedures adopted were in accordance with the following standards: the specific mass tests of the fine aggregates (regular sand and fine sand) were performed according to ABNT NBR NM 52:2009 [13], while the specific mass tests for the coarse aggregates followed ABNT NBR NM 53:2009 [14]. The unit mass tests were performed following ABNT NBR NM 45:2006 [15], and the granulometric composition analyses were made according to the ABNT NBR NM 248:2003 [16] procedures.

3.4.1 Cement

The cement used was CPV-ARI (Portland cement with high initial resistance). It was chosen because it is the most widely used in the prefabricated building industry, which is one of the areas where SCC can be employed with the most benefits. Table 5 shows its chemical, physical and mechanical properties.

3.4.2 Aggregates

Two basalt gravel compositions were used as coarse aggregate. Regular river sand was used as fine aggregate, and a non-pozzolanic material was used as fine material, namely fine sand. This aggregate is also used by some local companies, especially concreting service providers for conventional concrete (CC) composition and it may be stored outside in stalls which are relatively easy to be built, without the need for great resources such in the acquisition of a silo, for instance. All aggregates are commercially available in the South of Brazil. Table 6 shows the characteristics of the aggregates.

3.4.3 Superplastizer Additive

In order to dose the SCCs, a third generation superplasticizer admixture was used, one based on a chain of modified polycarboxylic ether which acts as a dispersant for the cementitious material, enabling superplastification and great water reduction, making the concrete more workable without change in the setting time. The characteristics are shown in Table 7.

3.4.4 Water

Water from the public water supply was used in the manufacturing of the concretes, according to ABNT NBR 15900:2009 [17].

4. Results and Discussions

Table 1 shows the unit compositions obtained from the duties imposed by each method of dosage performed in the experimental program.
The unit values to calculate the total SCC costs, shown in Table 1, were quoted by suppliers in June 2011, when the basic unit cost in Rio Grande do Sul (CUB - RS) for single-family homes was R$ 868.99 while the dollar rate was R$ 1.73. The price found for the ARI-RS cement was 0.44 R$/Kg. The sands cost 0.013 R$/Kg, the

Table 7 – characteristics of superplastizer additive

Technical datas	
Function:	Superplastizer additive of third generation for concrete
Chemical base:	Polycarboxylic ether
Aspect:	Liquid
	White cloudy
Seciundary action	Water reducer
Total water solubility	
It does nor contein calcium chloride, intentionally added, or chloride-based ingredients.	

Test	Specification	Unit
Appearance	White cloudy liquid	Visual
pH	5 – 7	-
Density	1,067 – 1,107	g/cm³
Solids	38,0 – 42,0	%
Viscosity	< 150	cps

basalt gravel cost 0.022 R$/Kg, and the superplasticizer admixture used cost 14.50 R$/Kg.

4.1 Fresh state tests results

Table 8 shows the results for the tests performed to assess the SCC behavior in the fresh state.
Considering the results obtained in the fresh state, it was possible to conclude that the values achieved in the procedures carried out to assess SCC self-compactibility, as shown in Table 8, were satisfying, for they fit the standards outlined by ABNT NBR 15823:2010 [4]. In each family executed, it was verified that the SCC unit composition which provided the most cohesion, fluidity and viscosity was the one which presented the highest cement consumption, a larger amount of mortar and consequently a smaller gravel consumption per m³, which allows the concrete more freedom to flow.

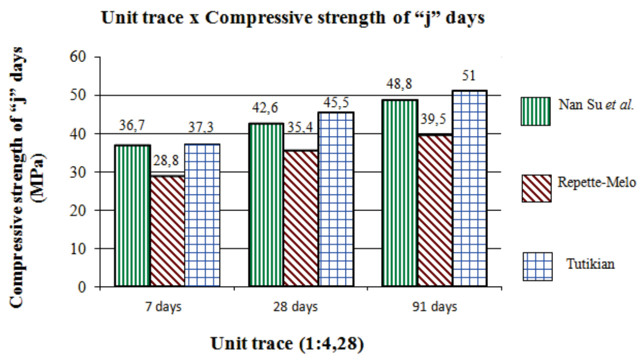
Table 8 – results of the fresh properties

Method	Trace (1:m)	Spread		T_{500mm}		"L-Box"		"V-Funnel"	
		Result (mm)	Class NBR 15823	Result (s)	Class NBR 15823	Result (h2/h1)	Class NBR 15823	Result (s)	Class NBR 15823
Nan Su et al.	1:4,28	710	SF2	2	VS1	0,90	PJ1	9	VF2
Repette-Melo	1:3,50	690	SF2	2	VS1	0,90	PJ1	7	VF1
	1:3,97	660	SF2	2	VS1	0,90	PJ1	6	VF1
	1:4,32	610	SF1	1	VS1	0,80	PJ1	5	VF1
Tutikian	1:3	710	SF2	2	VS1	0,90	PJ1	7	VF1
	1:4	690	SF2	2	VS1	0,85	PJ1	6	VF1
	1:5	640	SF1	1	VS1	0,85	PJ1	5	VF1
	1:6	590	SF1	1	VS1	0,80	PJ1	5	VF1

Table 9 – values for the comparisons between the three methods of the experimental program

COMPARISONS BETWEEN METHODS Nan Su et al., Repette-Melo e Tutikian & Dal Molin			
Property	Reference	Comparison	Values of reference
Compressive strength at 7,28 and 91 days	Unit trace	Compressive strength at 7, 28 and 91 days for the same unit traces	4,28
Cost	Compressive strength at 7 days	Cost of the mixtures for the same range of compressive strength at 7 days	36,7 MPa
Cost	Compressive strength at 28 days	Cost of the mixtures for the same range of compressive strength at 28 days	42,6 MPa
Cost	Compressive strength at 91 days	Cost of the mixtures for the same range of compressive strength at 91 days	48,8 MPa
Modulus of elasticity	Compressive strength at 91 days	Modulus of elasticity for the same range of compressive strength at 91 days	48,8 MPa
Ultrasound	Compressive strength at 91 days	Ultrasound for the same range of compressive strength at 91 days	48,8 MPa
Chloride ions penetration	Compressive strength at 91 days	Chloride ions penetration for the same range of compressive strength at 91 days	48,8 MPa

Figure 7 – Compressive strength of "j" days for the same unit trace 1:4,28



4.2 Hardened state concrete properties comparisons

Firstly, the compressive strengths found at 7, 28 and 91 days will be compared for the same individual unit compositions and after the mixtures costs, as well as the modulus of elasticity, the propagation velocity of the ultrasound wave, and the chloride ion penetration, for the same compressive strength range.
In the Nan Su et al. method, it was not possible to execute the behavior equation and the dosage diagram, since only one unit composition was determined through it. Hence, so that the comparisons could be made, the base values resulting from this method of dosage were used. For the other two experiments, Repette-Mello, 2005 [2], and Tutikian & Dal Molin, 2007 [3], the same individual unit composition and compressive strength in the behavior equations will be sought, and they will be determined according to the characteristic properties of those methods.
It should be noted that this comparison is valid, since the results found by Nan Su et al., 2001 [1], are within the data limits established in the hardened state properties achieved in the Repette-Melo, 2005 [2], and Tutikian & Dal Molin, 2007 [3].
Table 9 shows the values established for the comparisons, in the hardened state, between the three dosage experiments. The age of 91 days will be the standard for the comparisons involving the modulus of elasticity, propagation velocity of the ultrasound wave, and chloride ion penetration.

4.2.1 Compressive strengths to 7, 28 and 91 days for the same unit stroke

For this comparison, an individual unit composition (1:m) was set. Through the behavior equations, the compressive strength at 7, 28 and 91 days was searched, as shown in Fig. 7, and it was possible to analyze which experiment reached the highest compressive strength for the same individual unit composition (1:4.28).
Observing Fig. 7, it can be concluded that the Tutikian & Dal Molin method, 2007 [3], presented a compressive strength at 7 days 1% higher than that presented by Nan Su et al., 2001 [1], and 29.5% higher than that presented by Repette-Melo, 2005 [2]. It should also be noted that, at 28 days, the Tutikian & Dal Molin method, 2007 [3], again achieved a higher compressive strength than the other two methods. Its value was 6.8% higher than the one obtained by Nan Su et al., 2001 [1], and 28.5% higher than that of Repette-Melo, 2005 [2]. Lastly, it was verified that the Tutikian & Dal Molin method, 2007 [3], was also superior regarding compressive strength for the same individual unit composition, compared to the two other methods. At 91 days the result found was 4.5% higher than that of Nan Su et al., 2001 [1], and 29.1% higher than that of Repette-Melo, 2005 [2].

4.2.2 Cost of mixtures for the same compressive strength range at 7, 28 and 91 days

The cost comparisons, having the compressive strength set at 7 days, for all the methods, are shown in Fig. 8.
Based on the data presented in Fig. 8, it is observed that the Tutikian & Dal Molin method, 2007 [3], presented, for the same compressive strength range at 7 days, a cost which was 4.50% lower than that obtained by Nan Su et al., 2001 [1], and 14.5% lower than that obtained by Repette-Melo, 2005 [2].
For the same compressive strength range at 28 days, the Tutikian & Dal Molin method, 2007 [3], presented an estimated result which is 7.6% lower than that found by Nan Su et al., 2001 [1], and 14.9% lower than the result found by Repette-Melo, 2005 [2].
Finally, it was observed that for the compressive strength at 91 days the Tutikian & Dal Molin method, 2007 [3], once again obtained a value 6.1% lower than that by Nan Su et al., 2001 [1], and 14.4% lower than the value obtained by Repette-Melo, 2005 [2].
This behavior is probably owed to a better packaging of the materials promoted by the method of dosage and the lower admixture consumption in relation to the amount of cement used in the admixture. Better aggregate granulometric packaging enables the mixture to boast fewer voids, thus obtaining a more homogeneous structure.
In the concretes dosed by the Tutikian & Dal Molin method, the amount of superplasticizer admixture used was about 27% lower than that used by Nan Su et al., 2001 [1], and approximately 17.3% lower than that used by Repette-Melo, 2005 [2], thus favoring a cost comparison.

Figure 8 – cost comparison for the same range of compressive strength of "j" days

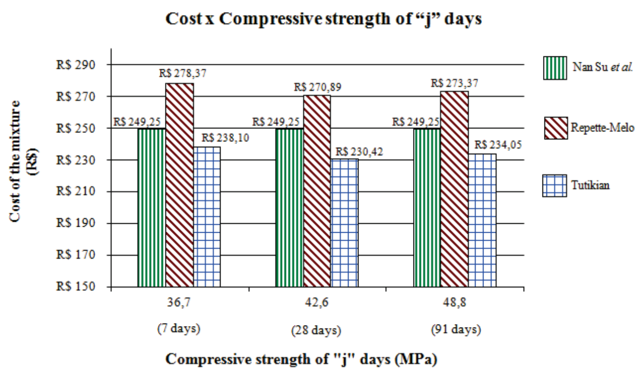
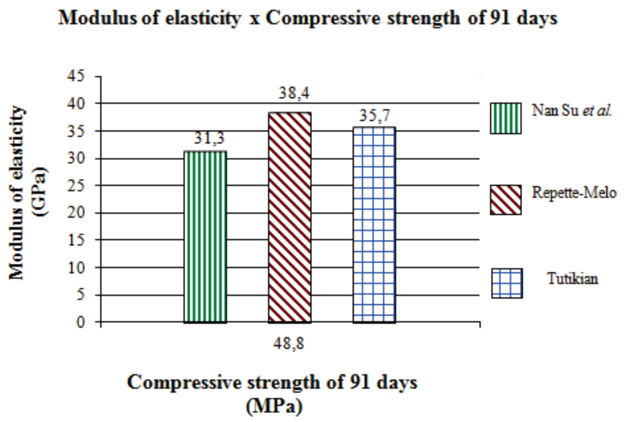


Figure 9 – modulus of elasticity comparison for the same range of compressive strength of 91 days for all methods



4.2.3 Modulus of elasticity for the same compressive strength range at 91 days

The performance analysis done in all methods, which relates the modulus of elasticity for the same compressive strength range at 91 days is shown in Fig. 9.
According to the data presented in Fig. 9, it is observed that the Repette-Melo method, 2005 [2], presented a larger modulus of elasticity, for a strength of 48.8 MPa at 91 days, which is 7.6% higher than what was obtained by Tutikian & Dal Molin, 2007 [3], and 22.7% higher than what was found by Nan Su et al., 2001 [1].
The higher results achieved by Repette-Melo, 2005 [2], for this property are probably due to the larger amount of coarse aggregate obtained in the mixture composition and the smaller amount of mortar promoted by the method of dosage.
When the amounts of mortar obtained by all methods are compared, setting a compressive strength of 48.8 MPa at 28 days, which was achieved by Nan Su et al., 2001 [1], it is possible to demonstrate that the experiment conducted by the Repette-Melo method, 2005 [2], the mixture presented an amount of mortar of 59.9%, while Tutikian & Dal Molin, 2007 [3], achieved 60.6% and Nan Su et al., 2001 [1] presented 67.4%.
It should be noted that in the Repette-Melo method, 2005 [2], the amount of coarse aggregate used was 50% in relation to the aggregate total, in mass, compared to 48% used by Tutikian & Dal Molin, 2007 [3], and 40% used by Nan Su et al., 2001 [1].

4.2.4 Propagation of velocity of the ultrasound wave for the same compressive strength range at 91 days

The propagation velocity of the ultrasound wave measurements were taken using the same samples from the modulus of elasticity test, therefore the same compressive strength ranges for the comparison were defined, as well as the test age, at 91 days.
Fig. 10 shows the comparisons made for all methods of dosage, relating the ultrasound wave velocity for the same strength range at 91 days.
As can be seen in Fig. 10, the method which presented the best results was Repette-Melo, 2005 [2]. It is important to highlight that the difference between the results found by Repette-Melo, 2005 [2] and those found by Tutikian & Dal Molin, 2007 [3], is small, namely 0.4%, while the results found by Nan Su et al., 2001 [1] were 8.3% higher.
The difference between the values found by those two methods to assess this property is too small, therefore it can be said that Tutikian & Dal Molin, 2007 [3], and Repette-Melo method, 2005 [2], reached similar values for the propagation velocity of the ultrasound wave.

4.2.5 Chloride ions penetration for the same compressive strength range at 91 days

Lastly, Fig. 11 shows the values obtained by all concretes regarding chloride ion penetration.

Figure 10 – ultrasound wave speed comparison for the same range of compressive strength of 91 days for all methods

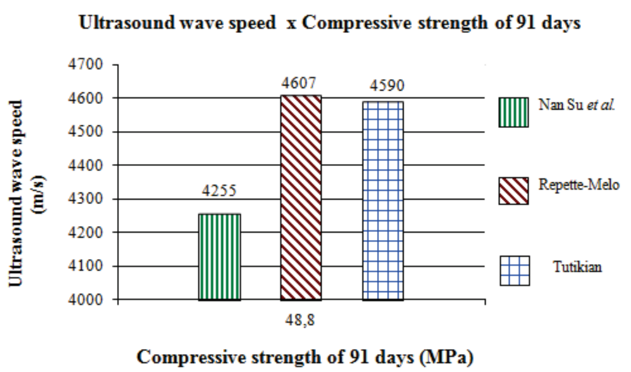
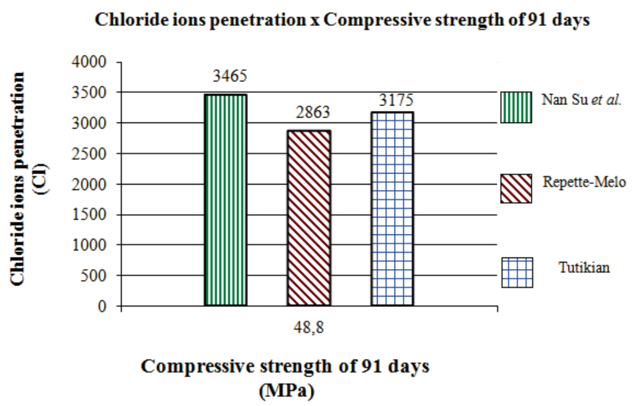


Figure 11 – chloride ions penetration comparison for the same range of compressive strength of 91 days for all methods



This test was performed at 28 days, and, in order to keep a coherent comparison between the performance diagram properties, the same compressive strength ranges selected for the other categories were maintained.

Based on the data shown in Fig. 11, it can be concluded that the Repette-Melo method, 2005 [2], presented a chloride ion penetration 9.8% lower than did Tutikian & Dal Molin, 2007 [3] and 17.4% lower than did Nan Su et al., 2001 [1].

The amount of water in relation to the cement consumption in the mixture is an important factor which impacts concrete porosity, which in turn has a direct impact on chloride ion penetration. Thus it should be noted that the Repette-Melo method, 2005 [2], provided a water/cement ratio of 0.46, against 0.51 in Tutikian & Dal Molin, 2007 [3] and 0.50 in Nan Su et al., 2001 [1]. Those results were achieved by setting the compressive strength at 91 days at 48.8 MPa, which is the value defined by the experiments done by the Nan Su et al. method, 2001 [1]. That value was adapted to match the behavior equations identified Tutikian & Dal Molin, 2007 [3] and Repette-Melo, 2005 [2].

4.3 Non quantitative aspects reported in the executation of the methods of dosage

Among the non quantitative aspects observed during the procedures for obtaining SCC through the methods performed during the experimental program, it was observed that in the procedures defined by Nan Su et al., 2001 [1] the calculation of cement consumption depends solely on the required compressive strength. During the experimental work, in order to determine the proportion of cement in the SCC mixture, it was established that the compressive strength at 28 days, according to the formula, would be 55 MPa, which resulted in an amount of cement corresponding to the adopted strength. However, it can be verified that this process did not work properly, since the result for compressive strength at 28 days for this method was 44.8 MPa, which is 18.5% less than the value defined in the proposed empirical formula. It is known that there are several types of cement, aggregates, binders and admixtures which impact the final strength, and, in case it is intended to establish a universal equation to calculate cement consumption, all the aforementioned variables must be included.

In order to define the amount of admixture, which is an important factor in cost composition for the SCC mixtures, the Repette-Melo method, 2005 [2], determines an establishment of the proportions to be used, firstly during the paste stage, then during the mortar stage and finally in the concrete. These early studies, in order to obtain the best performance from the admixture in the mixture, ended up creating a slower and more troublesome procedure for the dosage of concrete. It was verified, through other methods, that such experiments have little effect on the amount of admixture. In Tutikian & Dal Molin, 2007 [3], for instance, which does not make use of such processes in order to achieve the superplasticizer consumption, a percentage 21% smaller of material in the mixture was obtained, in contrast to what was found by Repette-Melo, 2005 [2]. Thus it can be said that the ideal and optimal content of the admixture depends on the interaction of all elements in the unit composition, i.e., cement, sand, gravel, and that is only possible in the concrete stage.

The Repette-Melo method, 2005 [2], in order to determine the coarse aggregate, proposes that the values used should range from 27% to 33% in relation to the total volume of concrete. That is a rather empirical procedure, since the worker in charge of the dosage will have seven alternatives for the choice of amount of coarse aggregate in the mixture. That engenders doubt during the choice, as happened to Nan Su et al., where an intermediate percentage was selected.

5. Final Considerations

In this study, three methods of dosage for the manufacturing of SSC were compared technically and economically, using the same materials. In view of the proposed goals, after the lab work, it can be concluded that:

- From this study, it was verified that, in order to dose SCC with aggregates found in the South of Brazil, the method which presented the smallest cost and higher compressive strengths at the ages of 7, 28 and 91 days was Tutikian & Dal Molin, 2007 [3], while the one which reached the highest chloride ion penetration and highest compacity and modulus of elasticity was Repette-Melo, 2005 [2]. During tests performed in the fresh state, all methods tried obtained mixtures which fit in the required self-compactibility class;
- However, it should be noted that during the comparisons made between Repette-Melo, 2005 [2] and Tutikian & Dal Molin, 2007 [3], the characteristics which involve the propagation velocity of the ultrasound achieved very similar results, i.e., the results may be considered identical due to the number of samples analyzed;
- Regarding workability verification, it is observed that the values achieved for each method of dosage tried could be adjusted, as long as the proportion of superplasticizer admixture is increased. That was not done in this study, since the amount was set to achieve the values of the established self-compactibility class.

These considerations are only valid for the concretes dosed in this study, with materials from the South of Brazil, determined according to the presented proportions. It should be noted that the mechanical properties may suffer alterations if other materials are used, or higher or lower amounts of admixture are used, for instance. The criteria and compared aspects suggested may be useful instruments in selecting, among various methods with potentially the same answers, the one which best fits reality or specific needs for applications.

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