A SIMPLE AND RATIONAL METHODOLOGY FOR THE FORMULATION OF SELF-COMPACTING CONCRETE MIXES

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Abstract

The increasing use of Self-Compacting Concrete (SCC) in the construction industry should be assured by the development of mix designs adequates to improve their fresh/hardened state properties and its economy. This paper presents a methodology for the formulation of SCC that achieves some of these developmental goals without reliance on extensive laboratory testing and batch trials. Applications, results in fresh and hardened state, and discussion of the SCC obtained are presented. The proposed method can provide lower costs when compared to a currant SCC mix design method and the literature used for comparison.

Keywords: Self-compacting concrete; Mix design; Proportioning.

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INTRODUCTION

Over the last 25 years, self-compacting concrete (SCC) has witnessed a huge development, which is due, mainly, to its intrinsic advantages (De Schutter et al, 2008). This development took place initially, in chemistry incorporated into concrete (Okamura, 1997), and later was extended into the rest of its constitutive materials, using all sort of natural aggregates, mineral residues or recycled aggregates (Najim and Hall, 2010; Topcu et al, 2010; Wang Choj et al, 2006; Cuenca et al, 2013), incorporation of other components (light aggregates, different types of fibers, PCM, etc.) (Hunger et al, 2009; Jalal et al, 2013; Azeredo and Dinis, 2013), advancing on the influence of the chemical and mineral admixtures.

Later on, research advanced in diverse fields, such as durability (De Schutter and Audenaert, 2007), test methods (U-box, L-box, V-funnel, J-ring, etc.) (BIBM et al, 2005; JSCE 1999; ACI 2007), and it transitioned, most recently, to the modeling of different behaviors in the fresh and hardened states, with multiple statistical treatment methodologies (Pepe et al, 2013; Almeida Filho et al, 2010; Sebaibi et al, 2010).

Also recently, several methods for mix design have been proposed (Agullo et al, 1999; Su et al, 2001; Saak et al, 2001; Xie et al, 2002; Su and Miao, 2003; Aguilar and Barrera, 2003; Patel et al, 2004; Alyamac, 2009; Ferrara et al, 2007; Shen et al, 2009; Sebaibi et al, 2013) without any clear unanimity about which is the most suitable, which is in part a reflex of many conditionals such as different economic and social conditions in different countries, the means available, environmental politics, access to different concrete components, and so on. As a result, rather than making ad-hoc planning for each case, it is more important to enhance a fundamental understanding that enables the design of self-compacting concrete with a scientific methodology, taking into account, not only the components, but also the fabrication means and application resources.

A natural characteristic of SCC, because it has a larger amount of fine aggregates, is that its mechanical properties tend to be higher than those of normal concrete. From this point of view, the literatura on the topic, in referred journals as well as in international conference communications (e.g., the International Congresses on Self Compacting Concrete, which take place in Chicago) situates its mean value of resistance between 50 and 60 MPa (Vilanova 2009), which limits some applications in which low or medium resistances are required. In practice, SCC, at least in Spain (Rodriguez Viacava et al. 2012, 2014), is used more often in prefabricated elements than in in situ construction, which is a limiting factor. The construction methods of the two cases are usually different.

From this point of view, much work is emerging in terms of design and application of SCC with low and medium resistances (25–35 MPa) (Sonebi 2004; Roncero et al. 2008; Bermejo et al. 2010; Rodriguez Viacava et al. 2012) taking advantage of different types of local materials and/or wastes, trying to enhance its application field with reasonable costs.

The aim of this paper is to propose a rational procedure for SCC mix proportioning through an optimization process using simple experimental techniques with locally available materials, oriented to concretes with low or medium mechanical properties, which is necessary in order to extend the utilization of SCC.

The method is applied to different case studies; results obtained from concrete in the fresh and hardened state are presented and discussed. In order to analyze the cost of the proposed method, a comparative analysis with the method proposed by American Concrete Institute (ACI) 237R-07 (ACI 2007) is developed (using the same materials). Moreover, laboratory mixtures of SCC, which were obtained with the mix-proportioning method here proposed, were compared with selected data from the literature (again, data using similar materials, and also dealing with similar compressive strength ranges).

PROPOSED METHOD

Fundaments and Phases

In order to achieve self-compactability, the method takes into consideration not only high deformability and resistance to segregation, but also the packing density of the aggregates, in order to obtain the minimum content of voids and a uniform concrete strength. That is, first it deals with the physical part of the dosage (granular skeleton) and subsequently on the chemical part (additives)

The proposed method assumes that SCC can be obtained by optimizing the composition of the paste and the granular skeleton (as is common practice), each of them individually, as well as by optimizing the paste content in the concrete. The model suggests that the viscosity and flow resistance of the paste govern the fluidity and cohesion of the concrete, and the filling capacity without blocking is ensured by the paste content in the concrete which is in turn associated with the granular skeleton structure.

A schematic description of the proposed mix design is presented in Figure 1. The Method is developed in three stages. The first stage is related to the concrete optimization of phases, which involves the paste and the granular skeleton; this optimization allows adaptability of the method to the use of local waste and aggregates. The second stage is related to the calculation of the amount of materials needed in order to produce a cubic meter of concrete. The produced concrete mixes allow, on a third stage, the adjustments of parameters (paste volume, air entrainment and water/powder ratio) to ensure the SCC requirements.

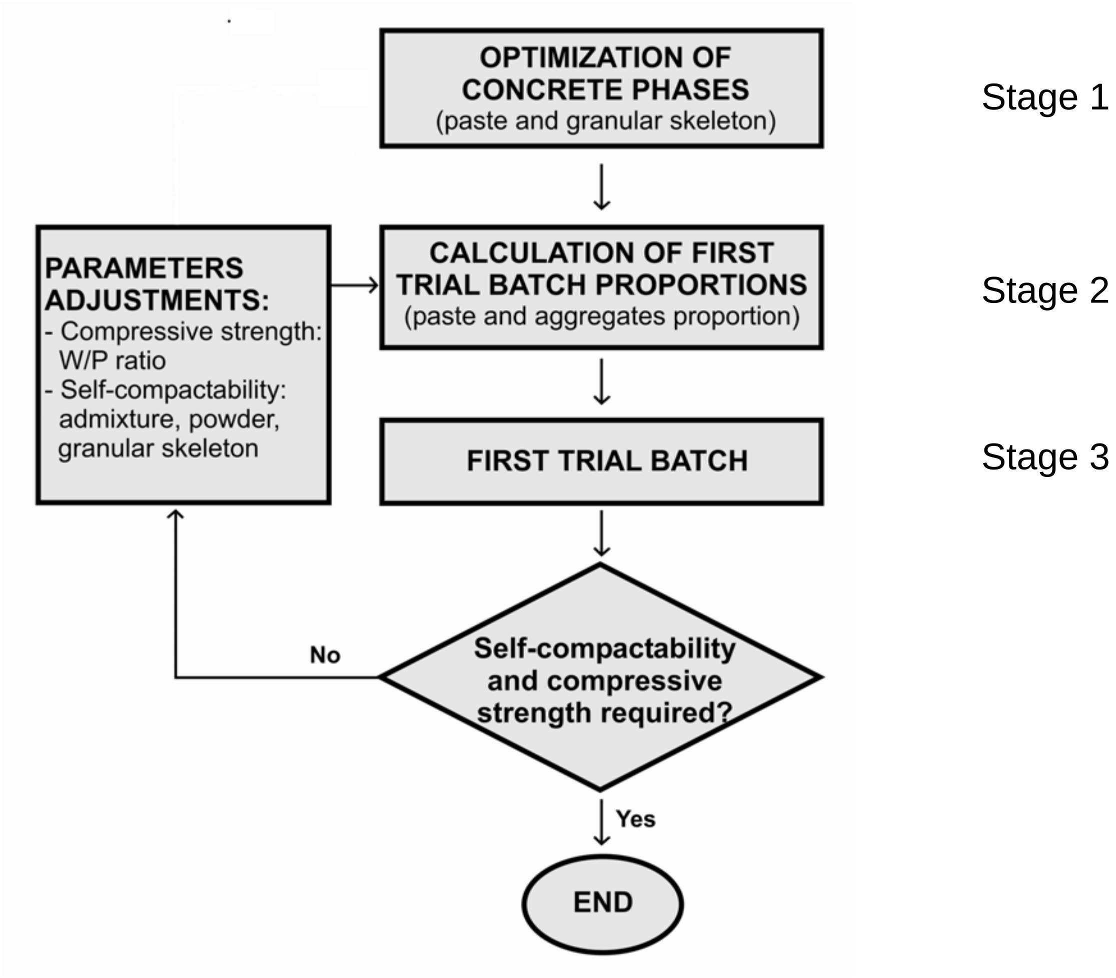


Figure 1. Schematic structure of proposed mix design method

The methodology that is here introduced for the design of SCC considers the concrete as a two-phase material consisting of paste and aggregates. The paste-aggregate model, two-phases, has also been utilized by other researchers for SCC (Su et al. Saak et al. 2001; Gomes et al. 2002). The design method assume that the paste composition does not intervene in the determination of the optimum proportion between the aggregate mix (de Larrard 1999;

Gomes et al. 2002; Torrales Carbonari 1996; Sedran et al. 1996), which permits a independence of both phases; and that, on the other hand leads to that a optimum paste volume associated to the aggregate skeleton should guarantee the deformability of the concrete without blockage (Gomes et al. 2002; Torrales Carbonari 1996).

The method presented is based on previous work for obtaining SCC (Rodriguez de Sensale 2006) and experience accumulated during its application in the realization of construction works at different scales (office buildings, homes, airport, dam repair, etc ...) made from 2006 to date in Uruguay. Additional description of the optimization approach and the procedure are presented in the following sections. A detail sequence of the proposed mix design is presented in Figure 2.

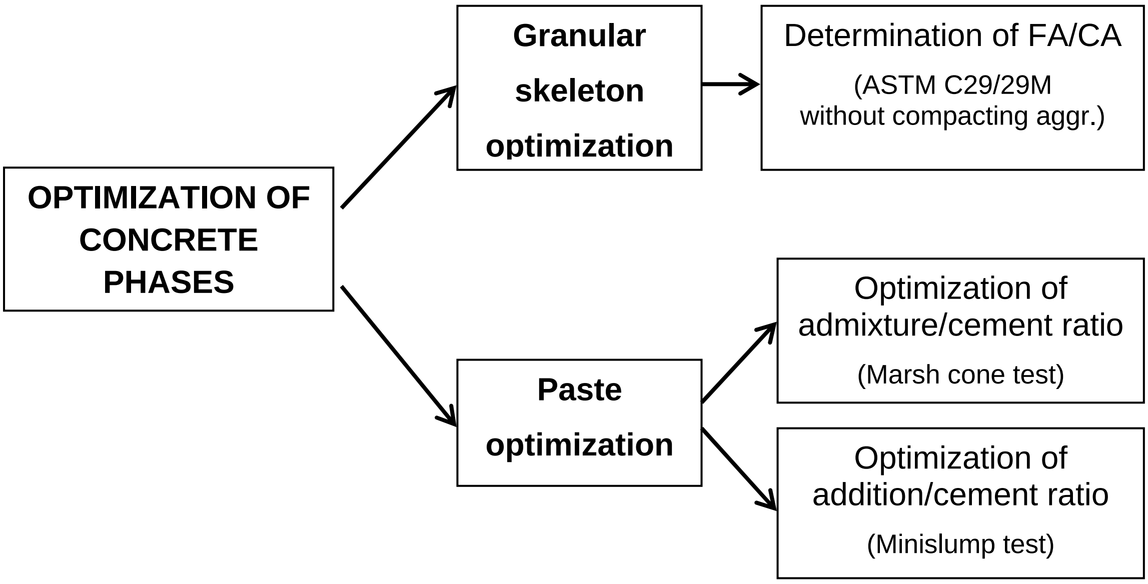


Figure 2. Stage 1: Optimization of concrete phases

The experimental tests are done with all the materials that will be used in the concrete, in order to obtain the maximum fluidity, which improves the self-compactability and the segregation resistance. To achieve this, the method is “custom made” and it guarantees the obtention of SCC through few laboratory trials. The used tests are conventional, simple and cheap, and could be performed in any laboratory. The used equipment is very simple and inexpensive.

Granular Skeleton Optimization

The granular skeleton is defined as the mixture of all aggregates present in concrete. The packing density of the aggregate mix is the basic of several mix-design procedures, with the objective to define an aggregate skeleton that is more compact and with the lowest void content; this can be attained by adjusting the percentage of dry fine and coarse compacted aggregate (Petersson et al. 1996; Torrales Carbonari 1996). This simple idea is based in the hipothesis that a packing density between fine aggregate and coarse aggregate (FA/CA) with the minimun content of voids will lead to a possible reduction of the cement paste volume, porosity and shrinkage (Klein et al 2013), which corresponds to concretes with better performance on workability and durability (Torrales Carbonari 1996; Sedran et al 1996; Gomes et al 2002; Rodriguez de Sensale 2006; Klein et al 2013).

Self-compacting concrete does not require compaction. A high paste volume is necessary to fill the voids between the aggregates and to guarantee the properties of segregation resistance, filling and passing ability. In this sense, an experimental proceeding based on the ASTM C29/29M-09 standard (ASTM, 2009) is used; both without compacting the aggregates. The fine-coarse aggregate ratio is obtained by mixing several combinations of dry aggregates and calculating the void content for each of them. The optimum is the ratio with the minimum void content; the volume of the void content can be used to initially estimate the paste volume (next sub-section).

The procedure is simple for practical application; in this regard, no mathematical model is used, and it takes into account the shape, texture and the grain size of the aggregates and considers the feature that no SCC compaction is required.

Paste Optimization

Paste is defined as the concrete fraction consisting of powder, air, water and admixture. Powder is the mixture of cement and additions (whether inert, pozzolanic or latent hydraulic). The use of cement as the only fine material leads to a high percentage of paste; which, implies higher SCC production costs in addition to the negative consequences for its behavior when hardened. The definition of the paste composition involves the determination of the admixture/cement and the addition/cement ratios in order to assure high segregation resistance and maximum flowability. Both properties of the paste are insured by using the superplasticizer saturation and additions. The dosage of each of these two materials is determined by simple test methods (which was one of the goals on this method). A previous step consists of defining the water/powder ratio between 0.32 and 0.45, as recommended by ACI (2007) by considering that the increase in both the fineness and the shape coefficient of the aggregate can lead to a SCC production with less powder (Aguilar and Barrera 2003), or according to equations where the water/powder ration is determined by considering the required compresive strength (e.g. Nikbin et al, 2014; Hemalatha et al, 2015).

The definition of the admixture/cement ratio implies the determination of the compatibility between cement and admixture and the optimal dosing of the admixture, which is important to avoid negative effects (delay setting, loss of air entrainment, effects of physical and chemical segregation, and alterations on flow and hardening properties) when making concrete. The Marsh Cone Test (Agullo et al 1999; Aitcin 1998; Nunes et al 2013) allows both determinations, and, in case of compatibility between admixture and cement, it enables to obtain the so-called saturation point, defined as the dose of admixture from which an increase of its amount does not causes a significant increase in fluidity, considering this value as the maximum content of admixture to be incorporated in concrete. Performing the Marsh Cone Test begins with the water/power (w/p) ratio previously chosen, and then we followed the method used at the University of Sherbrooke (Aitcin, 1998).

The definition of the addition/cement ratio is necessary to assure good flowability and segregation resistance; because of that the content of powder should not be too low. Also, the use of too much cement increases costs as well as the drying shrinkage of SCC; reasons for which fillers or additions are used. The Miniature Slump Test proposed by Kantro (1980) is used to optimize the addition/cement ratio in order to obtain the maximum flowability. The results obtained from the Marsh Cone Test are taken as starting point, and then different percentages of cement replacement by addition are used till obtaining the mixture of larger diameter.

Calculation of the First Trial Batch Proportion

The amounts of materials are calculated to 1m^3 of concrete, according to the following sequence of ten steps (Figure 3) :

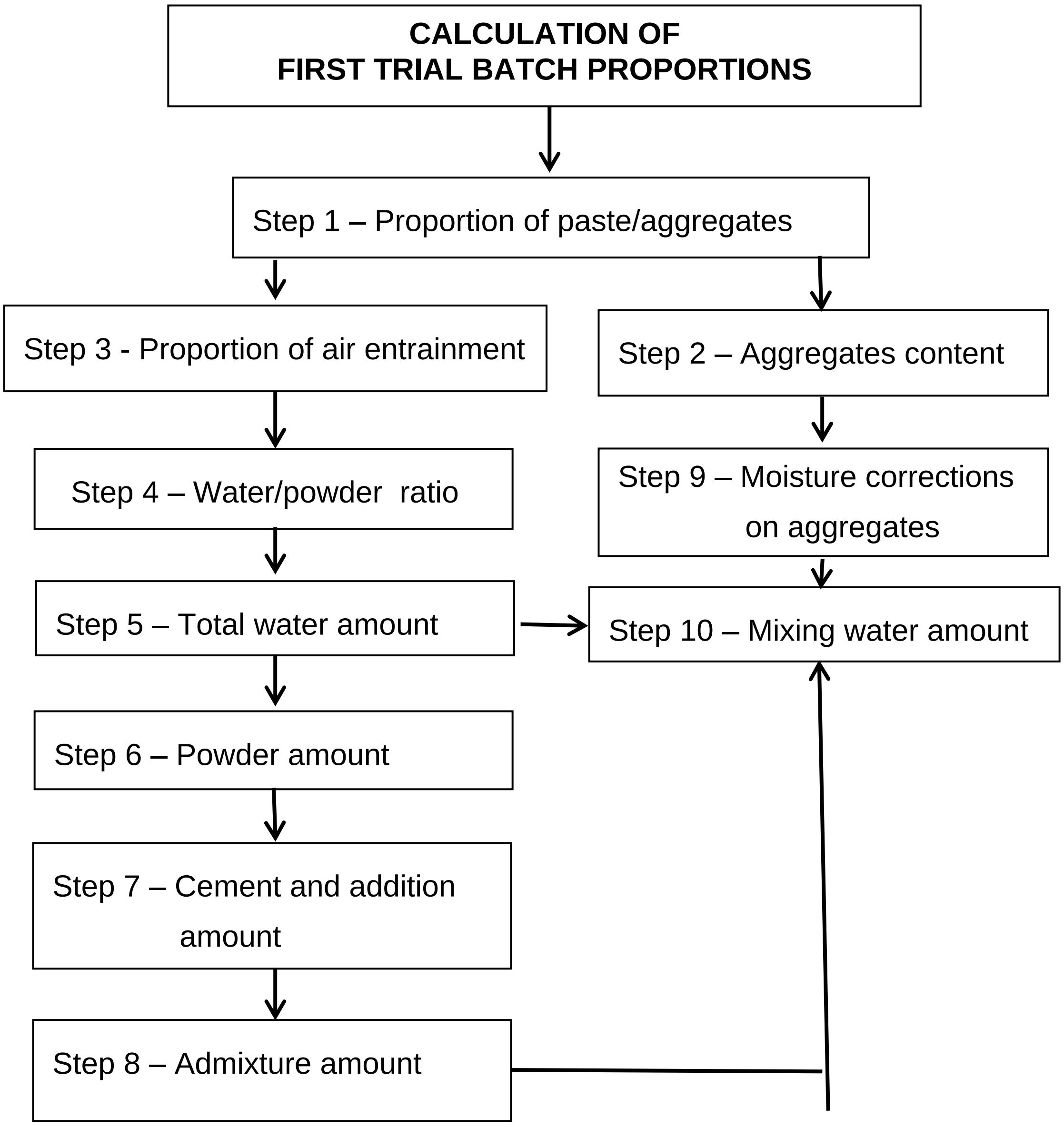


Figure 3. Stage 2. Calculation of first trial batch proportions

1. Proportion of Paste/Aggregates: the amount of paste (P) and aggregates (A) is set so that P + A = 1m^3 of concrete. To define the amount of paste, a range should be set with a lower limit that will depend on the available materials and can be assumed up to 34% as used by Sedran et al.(1996) and Sedran & de Larrard (1999), and with an upper limit of 42% for economic reasons.

2. Aggregate content: considering the total aggregate volume defined in step 1 and the optimal fine/coarse aggregate ratio (see Granular Skeleton Optimization section), the fine and coarse aggregates are estimated using its specific gravity values.
3. Set Proportion of Air Entrainment: the percentage of entrained air that is trapped in the paste should be as low as possible since admixtures incorporate air over time; therefore it is recommended not to exceed 2%.
4. Set Water/powder ratio (w/p): is defined as specified in Paste Optimization section considering the mixture of cement and additions as powder.
5. Total Water Amount (Wtot): The entrainment air is subtracted from the paste volume, and the total water amount (W_{tot}) is calculated from the remaining volume. In accordance with the European Guidelines for SCC (BIB 2005) the total water amount for SCC is in the range of 150 l/m^3 to 210 l/m^3. Due to the total water amount depends on the aggregates, the water/ powder ratio used and the conformity criteria for the properties in fresh state established, usually is necessary to use more than 210 l/m^3. In this respect, in the scientific literature can be found HAC made with higher total water amounts as indicated above (Cuneyt, 2007; Felekoglu and Sarikahya, 2007; Hemalatha et al, 2015; Hunger et al, 2009; Sahmaran and Yaman, 2007; Siddique et al, 2012; Rodriguez de Sensale, 2006; Roziere et al, 2007; Sonebi, 2004; Vilanova, 2009;). If there is no prior experience with SCC mixtures, it is suggested to start with the equation 1

$$W_{tot} = A.\ln\left(\frac{w}{p}\right) + B \qquad \text{(Eq. 1)}$$

where w/p is the water/powder ratio obtained from step 4. The values of A and B are presented in Figure 4 for different contents of paste. This equation is based on the results of experimental laboratory SCC mixtures performed with 5 different paste contents (34, 36, 38, 40 and 42%), 6 water/powder ratios in the range of 0.32 to 0.42 , different types of coarse aggregates (red gravel, named G, and black crushed stone, named P) with maximum aggregate sizes from 9 to 25 mm (G 25, P20, G19, G 12.5, P 12.5, G 9), and considering 3 repetitions of each of these mixture.

6. Powder Amount (p): is defined using the data obtained from step 4 and 5

$$p = W_{tot}/(w/p) \qquad \text{(Eq. 2)}$$

7. Cement and addition amount: are determined considering the optimal percentages obtained in the Minislump Test (see Paste Optimization section).
8. Admixture Amount: Is calculated according to the optimal percentage obtained in the Marsh Cone Test (see Paste Optimization section), taking into account the percentage of solids containing in the admixture. If the Marsh Cone Test is not performed, it is recommended to start using 1% of superplasticizer by weight of cementitious material.
9. Moisture Corrections on Aggregates: Determine the water present in aggregates (Wagg) and correct the quantity of aggregates.
10. Mixing Water Amount (Wmix): is calculated according to equation 3.

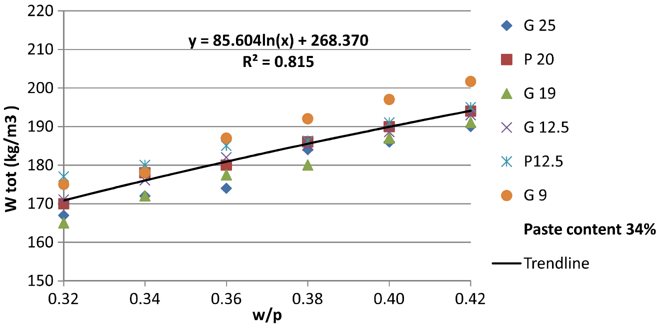
$$W_{mix} = W_{tot} - W_{agg} - W_{ad} \qquad \text{(Eq. 3)}$$

where W_{mix} is the mixing water; W_{tot} is the total water amount (Step 4); W_{agg} is the water present in aggregates (Step 9); W_{ad} is the water present in the admixture solution.

A contrast of the quantity of mixing water could be obtained, depending on the application, according to Klein et al (2012) and Klein et al. (2013).

$$W_{tot} = A.\ln\left(\frac{w}{p}\right) + B$$

Paste content (%)	A	B
34	85.604	268.37
36	89.856	283.19
38	94.108	298.01
40	98.360	312.83
42	102.612	327.65



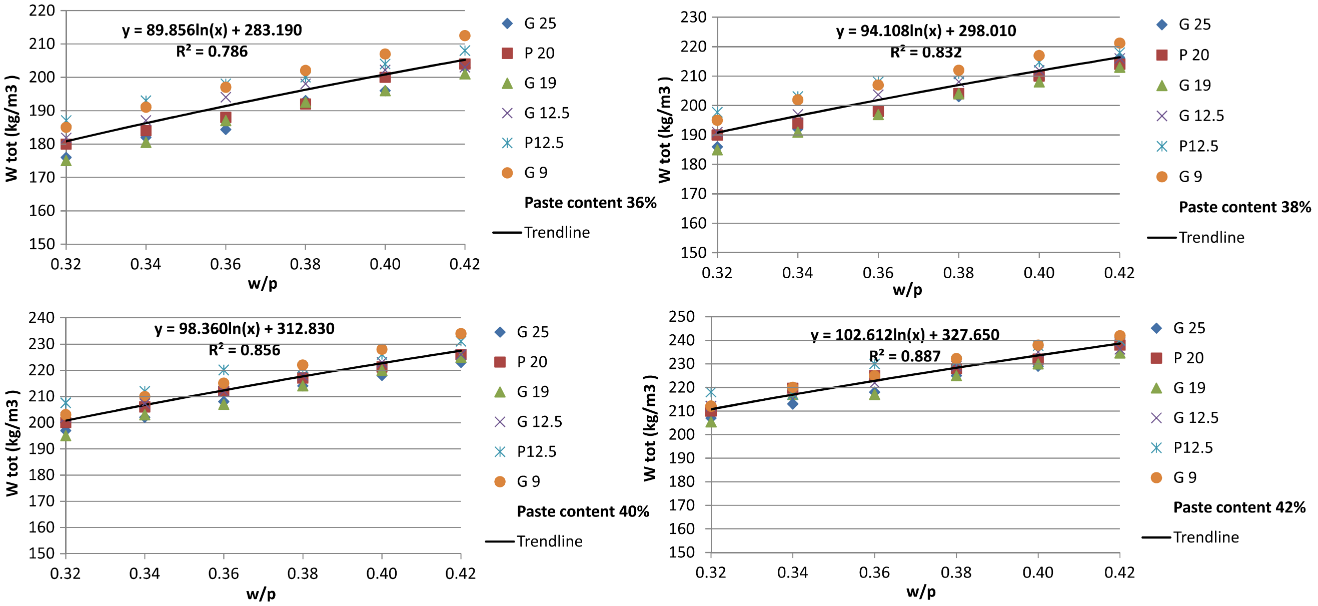


Figure 4. Values of A and B for different contents of paste

First Trial Batch

The sequence showing the stage is presented in Figure 5. The first trial batch was evaluated in the fresh state according to the procedures established by BIB (2005): slump-flow test, L-box, resistance to segregation and Funnel V. The requirements of the European Guidelines for SCC are presented in Table 1; in adittion to this the air content of mixtures (ASTM C231 (ASTM,2014), was also determined.

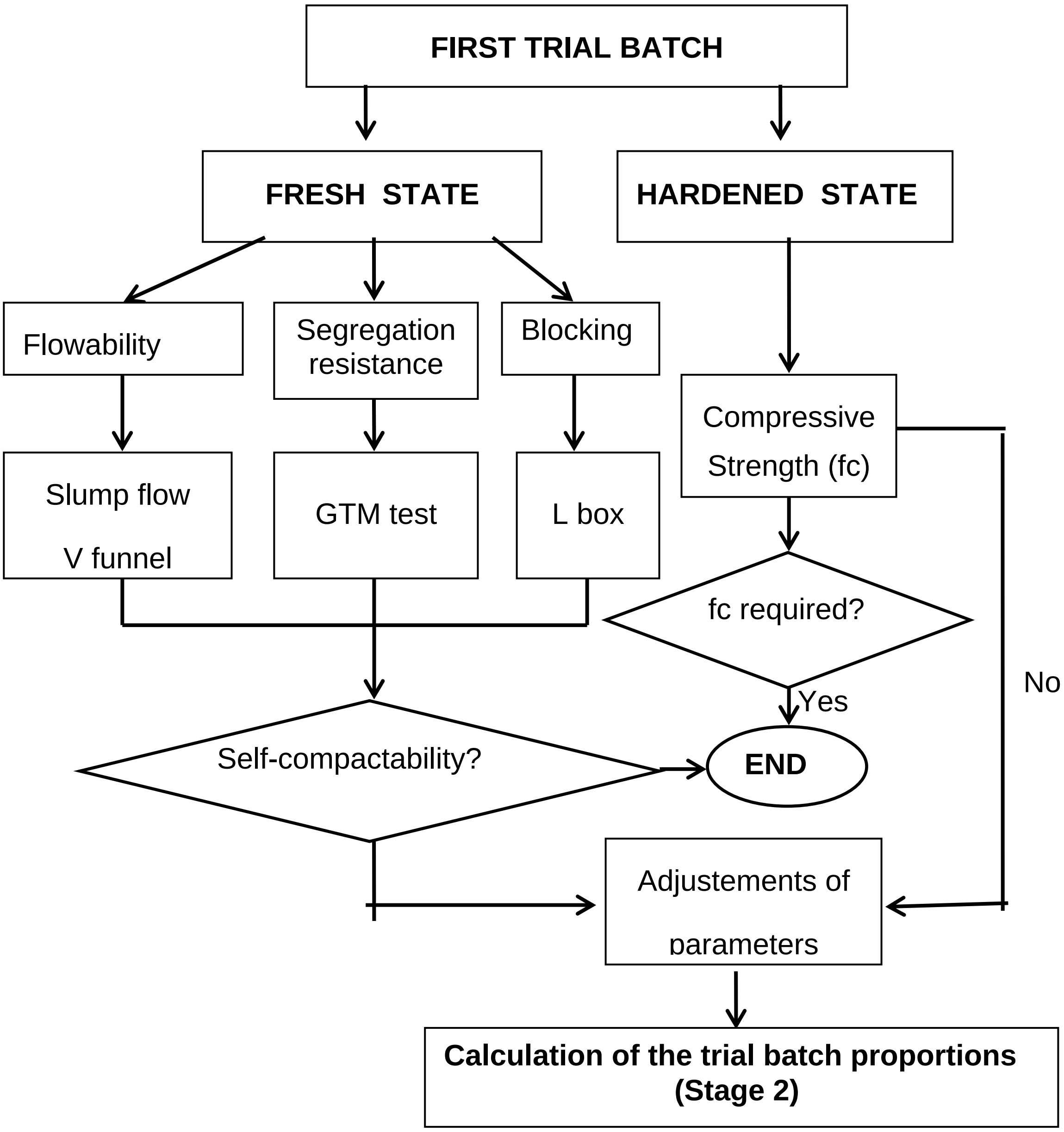


Figure 5. Satage 3: Fisrt trial batch

Table 1. Conformity Crtiteria for properties in Fresh State of SCC

Test	Conformity criteria
Slump-flow	52 ≤ diameter (cm) ≤ 90
V-funnel	7s < *T1* <27 s
L-box	*H2/H1*≥ 0,75
Sieve segregation resistance	Segregation resistance < 23%

According to the results on fresh state, parameter adjustments should be made. When a mixture does not satisfy the desired criteria of self-compactability, adjustments in the admixture, powder, and granular skeleton should be made.

When the mixture satisfies the desired criteria of self-compactability, the compressive strength is evaluated and depending on it results, adjustments should be made on w/p ratio or the addition content and type (Hemalatha et al. 2015; Siddique et al. 2012,). Related to the use of additions, it should be consider whether it is necessary to lower compressive strength. A filler can be used to decreasethe strength and a pozzolan can be used to increase it.

In addition, the ideal sequence of materials placement in the mixer and the mixing times required should be studied to achieve self-compacting mixtures. Different researchers (Emborg 2000) agree that the procedure followed in mixing times, sequence of materials placement and mixing equipment, are aspects that strongly affect the final quality of the material. For the first trial batch, all dry materials placed initially and then the water added together with the additive is the ideal sequence, according Emborg (2000) and Rodriguez de Sensale (2006).

APPLICATIONS, RESULTS AND DISCUSSION

In order to fully understand the procedure for proportioning SCC mixtures presented previously, the method was applied in different case studies with and without additions; some particular aspects are pointed out. The fresh state was studied according to first trial batch section. In hardened state, the compressive strength at the age of 28 days was evaluated on concrete cylindrical specimens of 10x20 cm (ASTM C39/C39M-10). Also cylindrical specimens of 15x30cm were molded for the evaluation of air permeability (SN 505 262/1, 2003) using the Torrent Permeability Test (Torrent and Frenzen 1995; Torrent 1999; Ebensperger and Torrent 2010) and electrical resistivity with the Wenner four-points method (Whiting and Nagi 2003). In both cases, the specimens were kept in moist chamber until the age of 28 days.

Materials

Normal portland cement (I 42.5) was used for the application. Cement kiln dust (CKD), inert filler local obtained as residue of a cement industry located in Uruguay, was used for partial replacement of cement in mass. The CKD used meet the requirements for filler stablished in the Standard UNE-EN 12620:2002 (UNE-EN 2002) and is an inactive mineral addition (Rodriguez de Sensale, 2006; Rodriguez Viacava et al, 2012 and 2014;). Tables 2 and 3 show the characteristics of the cement and additions used.

Parameters		**Values**	**Parameters**	**Values**
Characteristics			**Chemical composition (%)**	
Retained on 74µm Sieve (%)		0.8	SiO_2	21.18
Retained on 44µm Sieve (%)		6.4	Al_2O_3	4.27
Specific surface, Blaine (cm^2/g)		3219	Fe_2O_3	2.74
Water for Normal Consistency (%)		30.3	CaO	60.54
Initial setting time (min)		195	MgO	3.70
			SO_3	2.93
			K_2O	1.71
			Na_2O	0.00
Compressive strength (MPa)	2 days	28.4	CL^-	0.15
	7 days	39.4	Loss on ignition	2.42
	28 days	48.7	Insoluble residue	1.42

Table 2. Characteristics of Portland Cement

Parameters	Values
Characteristics	
Passing sieve 63 µm	98.70%
Activity Index	72%
Density	2.75 kg/m^3
Chemical properties	
Silicon dioxide (SiO_2)	12.90%
Aluminium oxide (Al_2O_3)	4.08%
Ferric oxide (Fe_2O_3)	1.68%
Calcium oxide (CaO)	40.61%
Magnesium oxide (MgO)	2.22%
Sulphur oxide (SO_3)	0.30%
Potassium oxide (K_2O)	2.36%
Sodium oxide (Na_2O)	0.01%
Chloride content (Cl^-)	0.20%
Loss on ignition	34 ±1%
Insoluble residue	18.3±0.5%

Table 3. Characteristics of Cement Kiln Dust

A polymer-based ultra high range superplasticizer (SP) with density of 1.10 kg/l was used as chemical admixture.

The aggregates used were obtained from local sources. Natural sand with a maximum nominal size of 4.75mm, fineness modulus of 2.92 and specific gravity of 2.55, was used as fine aggregate. Three different crushed granites were used as coarse aggregate, two red gravel (named g and G) and one black crushed stone (p) with a maximum aggregate size (MAS) of 12.5 mm, 19 mm and 12.5 mm, respectively and specific gravities of 2.28, 2.25 and 2.35. Figure 6 shows the granulometric curves of the aggregates used.

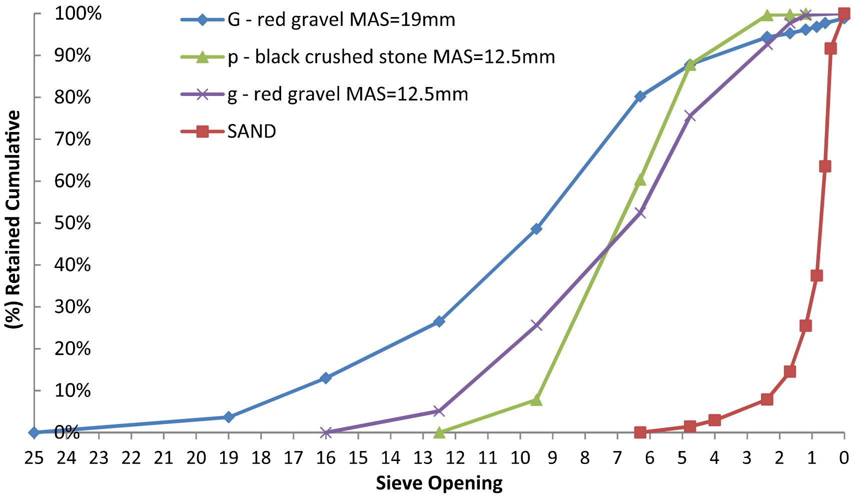


Figura 6. Granulometric curves of aggregates

Experimental determination of fine to coarse aggregate ratio

Figure 7 shows the results obtained using the ASTM C29/C29M (ASTM, 2009) without compaction for different employed aggregates. The optimum obtained fine to coarse aggregate ratio was approximately 50/50 in mass for two of the three coarse aggregates used (g and p). In the present paper, a single value was adopted for all case studies (50/50), indicated with a dashed red line, considering that in practice it can be modified according to the casting place system (Agullo et al. 1999).

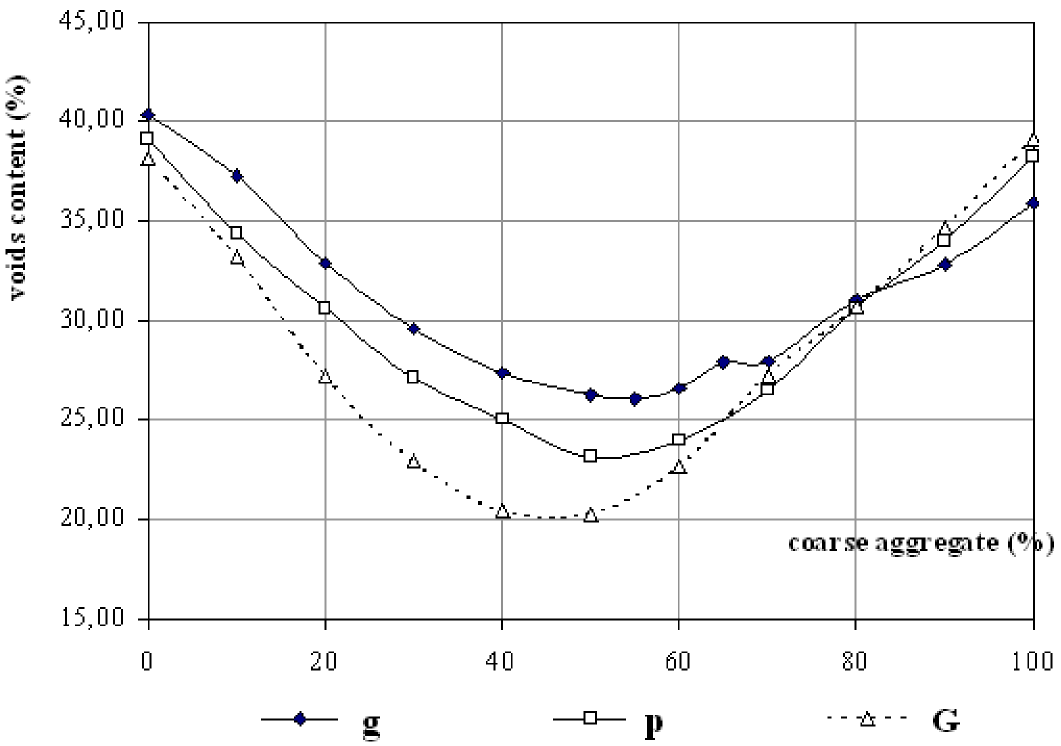


Figure 7. Percentage of voids for all granular skeletons [data from ASTM C29/C29M-09 (without compacting)]

Experimental tests in paste

To determine the optimum proportion of the admixture, the fluidity of different binding pastes were measured by using the Marsh Cone Test (Aitcin 1998). Once the optimum percentage of superplasticizer is obtained, the optimum addition content is acquired by using the mini-slump test (Kantro 1980); results are presented in Table 4. Considering as a selection criterion to achieve the greatest diameter (given by the T_{115} value), if it is taken as a main requirement the filling capacity of SCC, better results will be obtained with 20% replacement of cement by addition.

Table 4. Mixtures, Marsh Cones, and Minislump results

Mixture	Cement (%)	Addition (%)	Water/ powder	Optimum SP (%)	Diameter (mm)	T_{115} (s)
1	100	0	0.377	0.30	136.5	1.47
2	95	5	0.377	0.29	146.0	1.78
3	90	10	0.377	0.27	149.4	1.81
4	85	15	0.377	0.30	153.0	1.91
5	80	20	0.377	0.35	154.5	1.28
6	75	25	0.377	0.40	154.0	1.27
7	70	30	0.377	0.45	153.3	1.26

Calculation, results and discussion of the mix proportions for the first trial batch

Table 5 shows, as example, the amounts calculated by applying the method, with different contents of paste (42, 40 and 38%) and addition of 20% of CKD as substitution of cement (optimum percentage obtained with the mini-slump test); in the case of 42% paste content different types of aggregates were used; and in the case of 38% paste content a mixture without addition was also studied. Air entrainment was considered at 0%, anticipating the incorporation of air bubbles by the chemical admixture used. The chemical admixture is expressed as a percentage of the cement weight (on anhydrous solid basis) and as the amount of superplasticizer which is the optimum as defined in "Paste Optimization" section.

Mixtures containing 40% and 42% paste content without addition, contain a large amount of Portland cement, therefore the only mixtures analyzed were those containing addition. Mixtures with 38% paste content have lower amounts of cement, because of this mixtures with and without addition were studied to observe differences.

For the first trial batch presented in Table 5, all dry materials were placed initially and then water was added together with the additive, according to Emborg (2000). All concrete mixes were homogeneous. After mixing, fresh concrete was evaluated and the measured results are presented in Table 6. All the mixtures were SCC, according to the requirements specified by the European Guidelines for Self-Compacting Concrete (BIBM et al. 2005).

Table 5. Mix proportions for First Trial Batch

Mix	w/p	w/c	Paste content (%)	PC (kg/m^3)	Addition (kg/m^3)	Powder (kg/m^3)	Wtot (kg/m^3)	Coarse Agg.		Fine Agg. (kg/m^3)	SP (%)	
								Type	(kg/m^3)		(%)	(kg/m^3)
1	0.36	0.45	42	498.96	124.74	623.7	222	g	700.35	700.35	0.35	4.99
2	0.34	0.43	42	511.56	127.89	639.45	217	p	710.50	710.50	0.35	5.12
3	0.34	0.43	42	511.56	127.89	639.45	217	G	696.00	696.00	0.35	5.12
4	0.36	0.45	40	471.11	117.77	588.88	212	g	724.50	724.50	0.35	4.71
5	0.34	0.43	40	486.36	121.59	607.95	207	g	724.50	724.50	0.35	4.86
6	0.40	0.40	38	529.20	0.00	529.2	212	g	748.65	748.65	0.30	4.54
7	0.34	0.43	38	462.42	109.6	572.02	197	g	748.65	748.65	0.35	4.62

Table 6. Results Obtained for First Trial Batch in Fresh State

Mix	w/p	Paste content (%)	Slump flow		V-funnel	L-box	Segreg. Resist. (%)	Air content v/v (%)
			T50 (s)	Diam. (cm)	T1 (s)	H2/H1		
1	0.36	42	1.21	74.75	4.57	1	3.11	2.30
2	0.34	42	2.03	75.50	3.64	1	13.45	1.10
3	0.34	42	2.18	66.00	3.45	1	11.87	2.80
4	0.36	40	2.90	64.00	7.34	0,83	13.33	2.80
5	0.36	40	2.75	70.30	5.48	1	11.28	2.30
6	0.34	40	2.75	80.30	4.62	1	1.49	2.20

7	0.40	38	2.18	71.50	3.89	1	17.62	1.75
8	0.34	38	2.53	73.25	5.20	1	1.89	3.10

The diameter values obtained from the slump-flow test are included in the categories SF2, suitable for many normal applications (e.g. walls, columns) according to BIBM et al. (2005).

The results for the V-funnel show that all the mixtures belong to the low viscosity category (VF1).

The values of H2/H1 obtained with the L-box test (with 3 rebars) met the values indicated by (BIBM et al. 2005) so that SCC can flow without segregation or blocking in presence of steel bars.

The values of segregation resistance shows that all mixtures belongs to SR2 category defined by (BIB 2005), in all cases reflect the low rate of mortar passage through the sieve. The air content values obtained in the studied mixtures are close to the values found in different literature sources (ACI 2007; Felekoglu et al. 2007; Persson 2001).

Table 7 shows the results in hardened state for compressive strength at the age of 28 days, air permeability and electrical resistivity. As can be seen, the mixtures showed compressive strength between 30–65 MPa.

Table 7. Results Obtained for First Trial Batch in Hardened State

Mix	w/p	Paste content (%)	Compressive strenght (MPa)	Air permeability Kt $(10^{-16}\ m^2)$	Electrical resistivity ρ (kς.cm)
1	0.36	42	63.3	0.003	7
2	0.34	42	51.8	0.031	8
3	0.34	42	58.3	0.005	6
4	0.36	40	48.7	0.005	11.1
5	0.36	40	42.9	0.005	8
6	0.34	40	57.1	0.007	8
7	0.40	38	32.6	0.562	11
8	0.34	38	36.8	0.006	8

Table 8. Mix Proportions

Mix	w/p	Paste content (%)	PC (kg/m^3)	Addition (kg/m^3)	Powder (kg/m^3)	Wtot (kg/m^3)	w/c	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	SP (%)	
										(%)	(kg/m^3)
4	0.36	40	588.88	0	588.88	212	0.36	724.50	724.50	0.30	5.89
5	0.36	40	471.11	117.77	588.88	212	0.45	724.50	724.50	0.35	4.71
ACI[a]	0.36	40	500	0	500	201	0.40	923	615	1	9.29

[a] Data obtained using ACI (2007)

Table 9. Results in Fresh and Hardenerd States

Mix	Slump flow diameter (cm)	V funnel T1 (s)	L-box H2/H1	Segreg. Resist. (%)	Air content v/v (%)	Compr strenght (MPa)	Air permabiity Kt $(10^{-16}\ m^2)$	Electrical Resistance ρ (kς.cm)
4	64.00	7.34	0.83	13.33	2.80	48.7	0.005	11.1
5	70.30	5.48	1.00	11.28	2.30	42.9	0.005	8.0
ACI[a]	75.00	6.13	0.94	13.20	0.50	41.86	0.005	15.0

[a] Data obtained using ACI (2007)

In relation to compressive strength, is noted that, in mixtures with the same aggregate identified as "g" and filler, higher paste content is correlated with higher compressive strengths. On the other hand, for a paste content of 42% with different coarse aggregate and the same MAS ("g" and "p"), we can see that the mixture with "g" has higher compressive strength values than mixing with "p", which is due to laminar shape having "p" as already observed previously for "P". For different MAS ("g" and "G") mixing with "g" enables higher compressive strength, which is also logical as present lower MAS.

In relation to air permeability of the concrete cover, as seen in Figure 8 all mixtures show Good quality, except for mix “7” (38% of paste and without filler) that shows Normal quality. Therefore the results obtained are consistent with the compressive strength results.

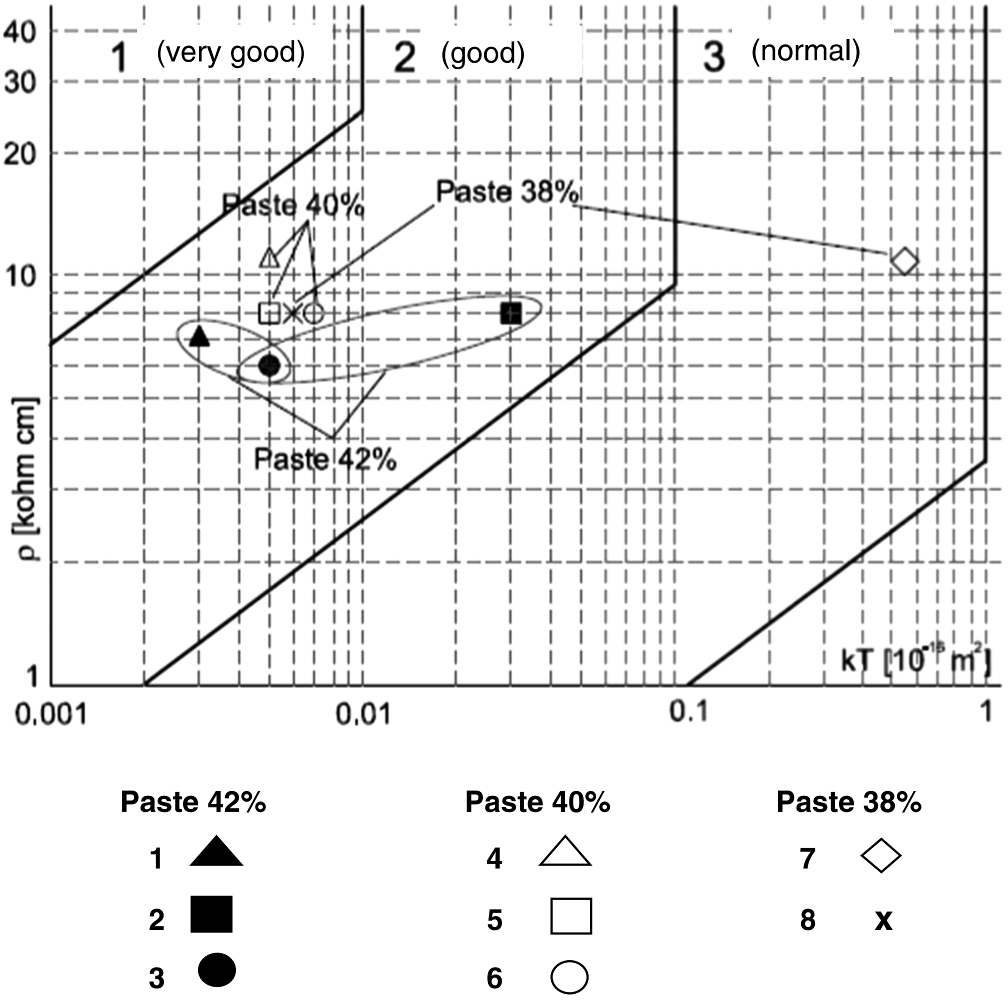


Fig. 8. Quality of concrete cover obtained with Torrent air permeability test method and electrical resistivity

COST ANALYSIS OF THE PROPOSED METHODOLOGY TO DESIGN SCC MIXES

In order to analyze costs of the proposed method on the production of SCC, first a comparative analysis with the method proposed on ACI (2007) was made with the same local materials used in this paper. To perform the comparison, from table 5 was selected the examples named as 4 and 5, without and with 20% addition, and from the ACI (2007) was selected a mix with 40% paste content and a water/powder ratio of 0.36. Table 8 present the mix proportion and the results obtained in fresh and hardened state. In the fresh state verification, the mixture obtained with the ACI method required adjustments; the table 8 shows the adjusted values.

The mix proportion with the proposed method (named 4 and 5) presents higher powder content and total water than the ACI mixture, but minor superplasticizer and aggregates content, this represents cost savings as can be seen below. The two methods yielded mixtures with similar characteristics in fresh and hardened state. The three mixtures are in the same range of compressive strength (40-50 MPa) and similar air permeability (Good quality).

In order to obtain a cost analysis of the described method for design SCC mixes, the authors also have reviewed published information on a variety of laboratory mixtures of SCC. Selected data from the review (Reinhardt and Stegmaier 2006; Felekoglu 2007; Yazici 2008; Cuneyt 2007) are presented in Table 9, where the examples have similar compressive strength and type of Portland Cement (type I 42.5) as the mixtures showed in Table 5.

Figures 9 and 10 present the cost comparison for the mixtures in tables 5, 8 and 9, per cubic meter and per compressive strength obtained, respectively, in wihch mixtures are named for their appointment in the corresponding table followed by compressive strength in MPa provided in parentheses. The unit values to calculate the total SCC costs were provided by suppliers in January 2014 on Uruguay. The price for the cement was U\$ 0.28/kg; the coarse aggregate cost was U\$ 0.03/kg (U\$45/m^3), the sand cost was U\$ 0.011/kg (U\$12.5/m^3), the superplasticizer cost was U\$ 8.40/kg. The addition used, CKD, is a residue of cement industries employed by the factories of concrete in Uruguay and brings no additional cost to producers, for this reason can be effectively employed in SCC applications on Uruguay and used in the examples studies. For CKD is assumed the international price minimum of the limestone filler, which is U\$ 0.025/kg (U\$60/m^3) and the maximum U\$ 0.042/kg (U\$100/m^3).

In each compressive strength range is noted that the results obtained with the proposed method gives the lowest cost. This behavior is probably due to a better optimization and packaging of the materials promoted by the mix-proportioning method.

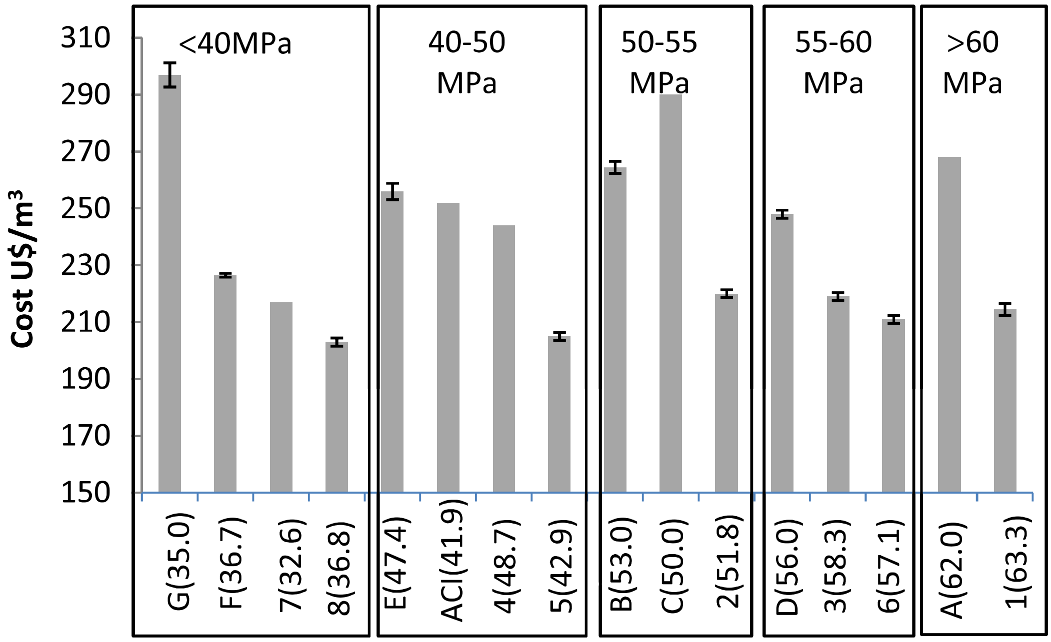


Fig. 9. Cost comparison for SCC mixtures of Tables 5, 8, and 10 per cubic meter

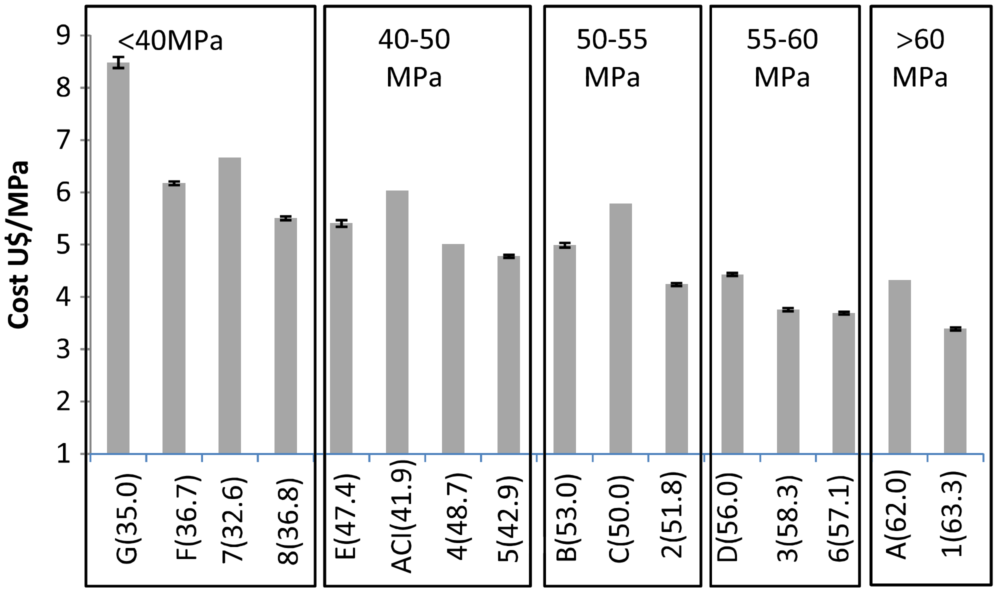


Fig. 10. Cost comparison for SCC mixtures of Tables 5, 8, and 10 per compressive strength obtained

^{a}Yazici (2008). ^{b}Felekoğlu (2007). ^{c}Reinhardt and Stegmaier (2006). ^{d}Cuneyt (2007).

Table 10. Mix proportions and Results for selected SCC Mixtures

CONCLUSIONS

From the methodology presented and the results achieved it is possible to draw the following conclusions:

- The paper proposes a rational methodology to design SCC through an optimization process, considering the concrete as a two-phase materials (paste and aggregates). Experimental tests are done with all the materials that will be used in the concrete, in order to obtain maximum fluidity and segregation resistance.

Ref.	PC (kg/m^3)	Addition (kg/m^3)	Powder (kg/m^3)	Wtot (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	SP (kg/m^3)	Slump Flow Diameter (cm)	Compr. Strength (MPa)
A^a	600	0	600	165	780	880	7.98	71.00	62
B^a	420	180	600	165	746	847	13.02	78.50	53
C^b	600	0	600	190	837	754	10.50	79.0	50
D^c	500	129	629	185	819	705	8.50	78.00	56
E^a	470	241	711	180	877	567	10.00	77.00	47.4
F^d	500	100	600	290	761	912	6.00	75.00	36.68
G^a	300	300	600	165	723	825	20.50	80.00	35

- The procedure for SCC mix design is developed in three simple stages presented in the paper. The optimization of phases use simple experimental techniques adapted for local waste and aggregates. The calculation of the first trial batch proportions, is based on the optimization results and equations. Finally the first trial batch is evaluated and parameter adjustements are provided.

- The tests used in the proposed method are conventional, simple and cheap, and could be performed in any laboratory. The method is quite easy for practical implementation
- Regarding fresh state verification, it is observed that the values achieved in a first trial batch presented in the examples needed no adjustments, due to the optimization of the paste and aggregates.
- The range of compressive strength obtained with the examples presented applying the proposed method was of the order of 30 to 65 MPa.
- In relation to air permeability the results obtained are consistent with the compressive strength.
- The optimization of the paste and granular skeleton allows adaptability of the method to the use of waste and local aggregates, respectively.
- Concerning the cost of SCC, the proposed method appears to give lower costs in relation to the literature examples used for comparison.

The increasing use of SCC in the construction industry should be guaranteed by the development of mix designs adequates to improve their properties in fresh and hardened state and its economy. The proposed approach achieves some of these developmental goals without reliance on extensive laboratory testing and trials batch. Reasons for the good performance of the propose methodology are the better optimization and packaging of the materials.

REFERENCES

ACI (American Concrete Institute). (2007). "Self- consolidating concrete." ACI 237R–07, Farmington Hills, MI.

Aguilar, C., and Barrera, H. (2003). “Influence of fines on self compacting concrete properties.” Rev. Ing. Constr., 8(1), 40–46 (in Spanish).

Agullo, L., Toralles-Carbonari, B., Gettu, R., and Aguado, A. (1999). “Fluidity of cement pastes with mineral admixtures and superplasticizer. A study based on the Marsh cone test.” Mater. Struct., 32(7), 479–485.

Aitcin, P. C. (1998). High-performance concrete, E&FN Spon, London.

Almeida Filho, F. M., Barragan, B. E., Casas, J. R., and El Debs, A. L. H. C. (2010). “Hardened properties of self-compacting concrete: A statistical approach.” Constr. Build. Mater., 24(9), 1608–1615.

Alyamaç, K. E., and Ince, R. (2009). “A preliminary concrete mix design for SCC with marble powders.” Constr. Build.Mater., 23(3), 1201–1210.

ASTM. (2009). “Standard test method for bulk density (unit weight) and voids in aggregates.” C29/C29M-09, West Conshohoken, PA.

ASTM. (2014). “Standard test method for air content of freshly mixed concrete by the pressure method.” C231-14, West Conshohoken, PA.

Azeredo, G., and Diniz, M. (2013). “Self-compacting concrete obtained by the use of kaolin wastes.” Constr. Build. Mater., 38, 515–523.

Bermejo, E. B., Moragues, A., Galvez, J. C., and Fernandez Canovas, M. (2010). “Permeability and pore size distribution in medium strength self-compacting concrete.” Mater. Constr., 60(299), 37–51.

BIBM (European Precast Concrete Organisation), CEMBUREAU (European Cement Association), ERMCO (European Ready-mix Concrete Organisation), EFCA (European Federation of Concrete Admixture Associations), and EFNARC (European Federation of Specialist Construction Chemicals and Concrete Systems). (2005). “The

European guidelines for self-compacting concrete." ⟨http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf⟩ (Jul. 2, 2015).

Cuenca, J., Rodríguez, J., Martín-Morales, M., Sánchez-Roldán, Z., and Zamorano, M. (2013). "Effects of olive residue biomass fly ash as filler in self-compacting concrete." Constr. Build. Mater., 40(1), 702–709.

Cuneyt, A. (2007). "Self-compactability of high volume hybrid fiber reinforced concrete." Constr. Build. Mater., 21(6), 1149–1154.

De Larrard, F. (1999). Concrete mixture proportioning—A scientific approach, E&FN Spon, London.

De Schutter, G., and Audenaert, K. (2007). "Durability of self-compacting concrete." RILEM Rep. 38, RILEM Publications S.A.R.L., Bagneux, France.

De Schutter, G., Gibbs, J., Domone, P., and Bartos, P. J. M. (2008). Self-compacting concrete, Whittles, Dunbeath, Scotland, U.K.

Ebensperger, L., and Torrent, R. (2010). "Concrete air permeability 'in situ' test: Status quo." Rev. Ing. Constr., 25(3), 371–382.

Emborg, M. (2000). "Mixing and transport." Brite Euram, Final Rep. Of Task 8.1, Self-Compacting Concrete, Sweden, 1–65.

Felekoğlu, B. (2007). "Utilisation of high volumes of limestone quarry wastes in concrete industry (self-compacting concrete case)." Resour. Conser. Recycl., 51(4), 770–791.

Felekoğlu, B., and Sarikahya, H. (2007). "Effect of chemical structure of polycarboxylate-based superplasticizers on workability retention of self-compacting concrete." Constr. Build. Mater., 22(9), 1972–1980.

Felekoğlu, B., Türkel, S., and Baradan, B. (2007). "Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete." Build. Environ., 42(4), 1795–1802

Ferrara, L., Park, Y. D., and Shah, S. P. (2007). "A method for mix-design of fiber-reinforced self-compacting concrete." Cem. Concr. Res., 37(6), 957–971.

Gomes, P., Gettu, R., and Agull ´o, L. (2002). "Diseño de hormigones autocompactables de alta resistencia." Procedimiento para su dosificación y métodos de caracterización, Cem.-Hormigón, 30–42 (in Spanish).

Hemalatha, T., Ramaswamy, A., and Chandra Kishen, J. M. (2015). "Simplified mixture design for production of self-consolidating concrete." ACI Mater. J., 112(2), 277–286.

Hunger, M., Entrop, A. G., Mandilaras, I., Brouwers, H. J. H., and Founti, M. (2009). "The behavior of self-compacting concrete containing micro-encapsulated phase change materials." Cem. Concr. Compos.,31(10), 731–743.

Jalal, M., Ramezanianpour, A. A., and Pool, M. K. (2013). "Split tensile strength of binary blended self compacting concrete containing low volume fly ash and TiO2 nanoparticles." Compos. Part B: Eng., 55, 324–337.

JSCE (Japanese Society of Civil Engineering). (1999). "Recommendation for self-compacting concrete." ⟨http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter01/recommendations.htm⟩ (Jul. 2, 2015).

Kantro, D. L. (1980). "Influence of water-reducing admixtures on properties of cement paste—A miniature slump test." Cem. Concr. Aggregates, 2(2), 95–102.

Klein, N. (2012). "El rol fisico del agua en mezclas de cemento portland." Ph.D. thesis, Universidad Politécnica de Catalunya, Barcelona, Spain (in Spanish).

Klein, N., Bachmann, J., Aguado, A., and Toralles-Carbonari, B. (2013). "Evaluation of the wettability of mortar component granular materials through contact angle measurements." Cem. Concr. Res., 42(12), 1611–1620.

Najim, K. B., and Hall, M. R. (2010). “A review of the fresh/hardened properties and applications for plain-(PRC) and self-compacting rubberised concrete (SCRC).” Constr. Build. Mater., 24(11), 2043–2051.

Nikbin, I. M., et al. (2014). “A comprehensive investigation into the effects of water to cement ratio and powder content on mechanical properties of self-compacting concrete.” Constr. Build. Mater., 57(1), 69–80.

Nunes, S., Milheiro-Oliveira, P., Sousa Coitinho, J., and Figueiras, J. (2013). “Robust SCC mixes through mix design.” J. Mater. Civ. Eng., 10.1061/(ASCE)MT.1943-5533.0000592, 183–193.

Okamura, H. (1997). “Self compacting concrete.” Concr. Int., 9(7), 50–54.

Patel, R., Hossain, K. M. A., Shehata, M., Bouzoubaa, N., and Lachemi, M. (2004). “Development of statistical models for mixture design of highvolume fly-ash self-consolidating concrete.” ACI Mater. J., 101(4), 294–302.

Pepe, M., Mazaheripour, H., Barros, J., Sena-Cruz, J., and Martinelli, E. (2013). “Numerical calibration of bond law for GFRP bars embedded in steel fibre-reinforced self-compacting concrete.” Compos. Part B: Eng., 50(July), 403–412.

Persson, B. (2001). “A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete.” Cem. Concr. Res., 31(2), 193–198.

Petersson, O., Billberg, P., and Van, B. K. (1996). “A model for selfcompacting concrete.” Proc., RILEM Int. Conf. on Production Methods and Workability of Fresh Concrete, Paisley, E&FN Spon, London, 484–492.

Reinhardt, H., and Stegmaier, M. (2006). “Influence of heat curing on the pore structure and compressive strength of self-compacting concrete (SCC).” Cem. Concr. Res., 36(5), 879–885.

Rodriguez de Sensale, G. (2006). “Self-compacting concrete.” Final Project Rep. PDT S/C/OP/19/01, Agencia Nacional de Investigación e Innovación (ANII), Montevideo, Uruguay.

Rodriguez Viacava, I., Aguado, A., and Rodriguez de Sensale, G. (2012). “Self-compacting concrete of medium characteristic strength.” Constr. Build. Mater., 30, 776–782.

Rodriguez Viacava, I., Cavalaro, S. H. P., Rodríguez-de-Sensale, G., and Aguado, A. (2014). “Hormigones autocompactantes de resistencias medias.” Cem.-Hormig´on, 28–36.

Roncero, J., Corradi, M., Khurana, R. S., Magarotto, R., and Moro, S. (2008). “Smart dynamic concrete: New approach for the ready-mixed industry.” 3rd North American Conf. on the Design and Use of Self- Consolidating Concrete, Vol. 2, Surendra P. Shah, ed., Center for Advanced Cement-Based Materials (ACBM), Red Hook, NY, 602–607.

Roziere, E., Granger, S., Turcry, P. Y., and Loukili, A. (2007). “Influence of paste volume on shrinkage cracking and fracture properties of selfcompacting concrete.” Cem. Concr. Compos., 29(8), 626–636.

Saak, A., Jennings, H., and Shah, S. (2001). “New methodology for designing self-compacting concrete.” ACI Mater. J., 98(6), 429–439.

Sahmaran, M., and Yaman, O. (2007). “Hybrid fiber reinforced selfcompacting concrete with a high volume coarse fly ash.” Constr. Build. Mater., 21(1), 150–156.

Sebaibi, N., Benzerzour, M., Sebaibi, Y., and Abriak, N. E. (2013).“Composition of self-compacting concrete (SCC) using the compressible packing model, the Chinese method and the European standard.” Constr. Build. Mater., 43, 382–388.

Sedran, T., and De Larrard, F. (1999). “Optimization of self-compacting concrete thanks to packing model.” Proc., 1st Int. RILEM Symp. On SCC, Stockholm, RILEM, Paris, 321–332.

Sedran, T., De Larrard, F., Hourst, F., and Containe, C. (1996). “Mix design of self-compacting concrete.” Production methods and workability of concrete, P. J.M. Bartos, D. L. Marrs, and D. Cleand, eds., E&FN Spon, London, 439–450.

Shen, J., Yurtdas, I., Diagana, C., and Li, A. (2009). “Mix design method of SCC for pre-cast industry.” Can. J. Civ. Eng., 36(9), 1459–1469.

SIA. (2003). “Construction en béton-specifications complémentaires, Annexe E: On site air permeability, according to the Torrent method.” SIA 262/1:2003, Zurich, Switzerland, 30–31.

Siddique, R., Aggarwal, P., and Aggarwal, Y. (2012). “Influence of water/powder ratio on strength properties of self-compacting concrete containing coal fly ash and bottom ash.” Constr. Build. Mater., 29, 73–81.

Sonebi, M. (2004). “Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans.” Cem. Concr. Res., 34(7), 1199–1208.

Su, N., Kung-Chung, H., and His-Wen, C. (2001). “A simple mix design method for self-compacting concrete.” Cem. Concr. Res., 31(12), 1799–1807.

Su, N., and Miao, B. (2003). “A new method for the mix design of médium strength flowing concrete with low cement content.” Cem. Concr.Compos., 25(2), 215–222.

Topcu, I. B., Bilir, T., and Uygunoğlu, T. (2009). “Effect of waste marble dust content as filler on properties of self-compacting concrete.” Constr. Build. Mater., 23(11), 1947–1953.

Torrales Carbonari, B. (1996). “Estudio paramétrico de variables y componentes relativos a la dosificación y producción de hormigones de altas prestaciones.” Ph.D. thesis, Universidad Politécnica de Catalunya, Barcelona, Spain (in Spanish).

Torrent, R. (1999). “Un método rápido y no destructivo para medir la permeabilidad del hormigón.” Materiales de construcción, 49(254), 51–56.

Torrent, R., and Frenzer, G. (1995). “A method for rapid determination of the coefficient of permeability of the covercrete.” Proc., Int. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE), Berlin, 985–992.

UNE-EN. (2002). “Aridos para hormig´on.” UNE-EN 12620,Madrid, España.

Vilanova, A. (2009). “Influencia de la dosificaci´on y empleo de diferentes tipos de cemento y adiciones en las propiedades mecánicas del hormigón autocompactante.” Ph.D. thesis, Universidad Politécnica de Madrid, Madrid, Spain (in Spanish).

Wang Choj, Y., Jic Kim, I., Cheol Shin, H., and Young Moon, H. (2006). “An experimental research on the fluidity and mechanical properties of high-strength lightweight self-compacting concrete.” Cem. Concr. Res., 36(9), 1595–1602.

Whiting, D., and Nagi, A. (2003). “Electrical resistivity of concrete—A literature review.” Portland Cement Association, Skokie, IL.

Xie, Y., Liu, B., Yin, J., and Zhou, S. (2002). “Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash.” Cem. Concr. Res., 32(3), 477–480.

Yazici, H. (2008). “The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze-thaw resistance of selfcompacting concrete.” Constr. Build. Mater., 22(4), 456–462