Viability of Two New Mixture Design Methodologies for Self-Consolidating Concrete

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Viability of Two New Mixture Design Methodologies for Self-Consolidating Concrete

by Pedro Silva, Jorge de Brito, and João Costa

This paper presents the results from an experimental study of the technical viability of two mixture designs for self-consolidating concrete (SCC) proposed by two Portuguese researchers in a previous work. The objective was to find the best method to provide the required characteristics of SCC in fresh and hardened states without having to experiment with a large number of mixtures.

Five SCC mixtures, each with a volume of 25 L (6.61 gal.) were prepared using a forced mixer with a vertical axis for each of three compressive strength targets: 40, 55, and 70 MPa (5.80, 7.98, and 10.15 ksi). The mixtures' fresh state properties of fluidity, segregation resistance ability, and bleeding and blockage tendency, and their hardened state property of compressive strength were compared. For this study, the following tests were performed: slump-flow, V-funnel, L-box, box, and compressive strength. The results of this study made it possible to identify the most influential factors in the design of the SCC mixtures.

Keywords: concrete rheology; mixture design methods; self-consolidating concrete.

INTRODUCTION

This paper presents part of the work submitted in the master's dissertation of the first author (Silva 2007). A great deal of work has been published since then on mixture design methods, properties, applications, advantages and drawbacks, and other aspects. The approach to self-consolidating concrete (SCC) mixture design has been more complex than that for conventional concrete (Aaron et al. 2001).

Most work on this topic clearly shows the material's potential and many examples are cited to prove this (Collepardi et al. 2004). Three SCC mixture design methods must be emphasized because of their widespread acceptance:

- The method proposed by Okamura et al. in 1993 (Domone 2000; Okamura et al. 2000);
- The method proposed by the Japanese Society of Civil Engineers (JSCE) in 1998 (Domone 2000; Nawa et al. 1999); and
- The method proposed by the Swedish Cement and Concrete Research Institute (CBI) in 1999 (Domone 2000; Petersson et al. 1996).

The first two are more widely used, partly because they are quite straightforward. The third is notable for its importance but is less easy to apply (Nepomuceno 2005).

These methods are used all over the world by companies with SCC production capacity, but they have been implemented independently. Each firm has worked independently to study and find out how to achieve the required performance. There is no general consensus on how to obtain mixtures that will perform as required for the particular needs of each job, using locally available materials. Currently, each firm relies on its own know-how derived from the experience and skills of its technical staff (Collepardi 2003).

The aforementioned three methods have formed the basis for a number of studies designed to optimize mixtures so that SCC mixtures can be designed to meet specific performance requirements in the fresh and hardened states. Sedran and de Larrard (1996), Gomes (2002), BIBM et al. (2005), Alencar and Helene (2008), and Shen et al. (2009) have published work on this aspect.

There is still room, however, for a more efficient calibration of the parameters that will give a target compressive strength and self-compactibility by optimizing the quantities of the mixture components.

With these needs in mind, some research has been carried out in Portugal by Ferreira (2001) and Nepomuceno (2005). The two mixture design methods are based on the Okamura et al. (Domone 2000; Okamura et al. 2000) and JSCE (Domone 2000; Nawa et al. 1999) methods. The first method also used the Faury method (Faury 1958) with respect to using a reference curve for SCC and the adaptation of the parameters currently used in the reference curves method. This was based on the principle that the optimal particle-size distribution of aggregate of a certain concrete as a function of parameters, such as the target workability and the type of aggregate, is given by a reference curve established experimentally by researchers. The second method introduces new parameters in relation to the methods proposed by Okamura et al. (Domone 2000; Okamura et al. 2000) and JSCE (Domone 2000; Nawa et al. 1999), which are better suited to controlling the SCC's compressive strength.

The experimental mixtures used in this study were prepared according to both the Okamura et al. and JSCE methods. This study focused on the production of concrete with target compressive strengths of 40, 55, and 70 MPa (5.80, 7.98, and 10.15 ksi) and the evaluation of consistency and mechanical behavior. The results were then compared.

RESEARCH SIGNIFICANCE

This study analyzes the viability of two innovative SCC mixture design methods. These methods seek to establish a procedure to obtain satisfactory mixtures—that is, appropriate compositions for each situation so as to achieve different performance levels in terms of target compressive strength and self-compactibility. They do so by introducing new parameters into the calculation and considering some parameters as variables that have until now been taken as constants.

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MIXTURE DESIGN METHODS

One major difference between the two methods concerns the possibility of a mortar study before preparing the concrete mixtures. However, in the Nepomuceno (2005) method, this is always performed and its results (mineral additions, water, and high-range water-reducing admixture content) are essential to the next stage; Ferreira's (2001) work led him to consider the aforementioned parameters as constant, so he dispensed with the mortar study.

Method proposed by Ferreira (2001)

Ferreira (2001) proposed a reference curve for SCC and customized the parameters currently used in the Faury reference curve method (Faury 1958).

Ferreira's (2001) proposal is briefly described in the following, specifically emphasizing the main differences from the conventional Faury (1958) method. The main changes concerned the quantification of the binder and a reformulation of the equation that governs the reference curve by adapting it to the criteria defined by Okamura et al. (Domone 2000; Okamura et al. 2000) and JSCE (Domone 2000; Nawa et al. 1999).

Compacity prediction—The assumptions usually considered are valid—that is, it is assumed that a unit volume of concrete is made of two parts: a solid part, the sum of the absolute volume of all solid components (called compacity σ), and another part consisting of liquid and air, called the voids index I. This index is determined by the well-known Faury expression (Faury 1958)

$$I = \frac{K}{\sqrt[5]{D_{max}}} + \frac{K'}{\frac{R}{D_{max}} - 0.75} \quad (1)$$

where K is the numerical coefficient (obtained experimentally by Faury (1958)), depending on the concrete's consistency, the compaction energy, the nature of the aggregates, and the use of admixtures; K' is the parameter (obtained experimentally by Faury (1958)) function of compaction; D_{max} is the maximum aggregate size, in mm; and R is the average radius of the mold.

Binder content—The determination of the binder content in a conventional concrete is related to the target mechanical strength and durability. The Feret expression (Eq. (2)) is normally used to obtain the binder content.

$$f_{c,j} = k_{i,j} \cdot \gamma^2 \quad (2)$$

where $f_{c,j}$ is the concrete compressive strength, in MPa, j days after mixing; $k_{i,j}$ is the parameter (obtained experimentally by Feret) determined as a function of the characteristics and age of the binder; and γ is the compacity of the paste volume analytically determined as

$$\gamma = \frac{\upsilon}{\upsilon + I} \quad (3)$$

where υ is the absolute volume of the binder; and for I, refer to Eq. (1). As long as very high strengths are not required, the defining parameter with respect to binder content in SCC is the need to guarantee self-compactibility.

As proven by Ferreira (2001) through his experimental work, Feret's equation in its original form is unsuitable for SCC, so an adjustment of the type $f_{c,j} = k_{i,j} \cdot \gamma^n$ was made and a value of n equal to 3 was selected as the most suitable for SCC. The binder content is thus obtained with the following Feret-type equation

$$f_{c,j} = k_{i,j} \cdot \gamma^3 \quad (4)$$

For portland cement Type I CEM 42.5R (every cement type mentioned in this paper follows European Standard EN197-1: 2000) and 30% fly ash of the type used in the reference work (Ferreira 2001), a value of $k_{i,j} = 604.67$ is admissible at 28 days. Rearranging Eq. (3), the binder's absolute volume is given by

$$\upsilon = \frac{\gamma \cdot I}{1 - \gamma} \quad (5)$$

where

$$\gamma = \sqrt[3]{\frac{f_{c,j}}{k_{i,j}}} \quad (6)$$

with $k_{i,j} = 604.67$ (in the conditions described).

Admixture content—There are many admixtures available in the market and the manufacturer's instructions for its content must be followed. The compatibility of a particular admixture with the type of cement and filler material used should be predetermined.

Ferreira (2001) concluded that SCC could be obtained with an admixture content between 0.5 and 2% by volume, testing mortars using carboxylate high-range water-reducing admixtures.

Reference curve—The solid part of concrete (σ) can be divided into three major fractions (Ferreira 2001):

- Coarse aggregate (between D_{max} and 4.76 mm [0.187 in.]);
- Medium and fine aggregate (between 4.76 and 0.074 mm [0.187 and 0.003 in.]); and
- Material less than 0.074 mm (0.003 in.) (mostly cement and mineral additions).

In the criteria presented by Okamura et al. (Domone 2000; Okamura et al. 2000) and JSCE (Domone 2000; Nawa et al. 1999) for SCC, a coarse aggregate fraction of 50% for all the aggregates is considered acceptable. Ferreira (2001) uses these criteria, and because this volume depends on the coarse aggregate content planned for each mixture, he adapts the Faury reference curve to these new points:

- The first point is maintained and corresponds to D_{max};
- The inflection point of the curve (second point) for SCC is now constant at D = 4.76 mm (0.187 in.) instead of $D_{max}/2$ for conventional concrete; and
- The last point is the frontier between the medium and fine aggregate fraction and the cement and mineral additions fraction.

Knowing the abscissas, the ordinates of the points of the reference curve (p') for SCC can be determined as

$$p'(4.76) = 50 + G \tag{7}$$

$$p'(0.074) = \frac{F \cdot 100}{100 - p_{c+s}} \tag{8}$$

where G is the parameter, depending on the maximum aggregate size (refer to Eq. (12) and (13)); F is the function of the very-fine materials content (cement and mineral addition) in the mixture (refer to Eq. (11)); p_{c+s} is the percentage in volume of the cement and mineral additions ($c + s$) in relation to the solid part ($\sigma = 1 - I$), given by

$$p_{c+s} = \frac{c+s}{1-I} \cdot 100 \tag{9}$$

As with Faury's (1958) reference curve for conventional concrete, the one adapted for SCC takes into consideration the aggregates and the cement and mineral additions (the fraction less than 0.074 mm [0.003 in.]). Therefore, the curve had to be adapted by removing the cement and mineral additions from the SCC reference curve by using the following expression (Ferreira 2001)

$$p'(d) = \left(p(d) - p_{c+s}\right)\frac{100}{100 - p_{c+s}} \tag{10}$$

where $p'(d)$ is the percentage volume of all the aggregates that pass through the d mm sieve; $p(d)$ is the percentage volume of all the aggregates, cement, and mineral additions that pass through the d mm sieve; and for p_{c+s}, refer to Eq. (8).

The coordinates of the points of the curves referred to are presented in the Appendix* in Table A.1.

Parameter F depends on the cement and mineral addition content in the mixture. Ferreira (2001) establishes the relationship between the cement plus mineral addition and parameter F for the maximum aggregate sizes used (12.7 and 19.1 mm [0.5 and 0.75 in.]) (refer to Fig. A.1 in the Appendix).

Parameter F therefore increases as the cement and mineral addition content decreases. In other words, higher values of F imply an increase in the use of fine aggregates and a decrease in the cement and mineral addition content.

* The Appendix is available at **www.concrete.org** in PDF format as an addendum to the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

From Fig. A.1, it can also be concluded that the maximum aggregate size has no influence on parameter F because the two curves are practically coincident.

Using a linear regression between the percentile content of cement and mineral additions and parameter F, the following equation is established (Ferreira 2001)

$$F = -1.1104 \cdot p_{c+s} + 20.924 \text{ (with } R^2 = 1) \tag{11}$$

where F is the function of the very-fine materials' content (cement and mineral addition) in the mixture; and for p_{c+s}, refer to Eq. (8).

Ferreira's (2001) experiments showed that parameter G must be estimated by taking into account the maximum aggregate size, the paste volume in the mixture, and the level of self-compactibility envisaged. This can be evaluated by the slump-flow and L-box tests. The paste content is equal to the binder volume (calibrated by parameter F) plus the voids index I.

Ferreira (2001) proposes two expressions where the dependent variable is parameter G and the independent variables are D_{max}, F, I, and the value of D_{final} or H_2/H_1, which are given by the slump-flow and L-box tests, respectively

$$\begin{aligned} G &= -7.952 - 0.146 D_{max} \\ &+ 1.279F + 454.923I - 0.137 D_{final} \end{aligned} \tag{12}$$

$$\begin{aligned} G &= -211.923 + 0.301 D_{max} \\ &+ 0.581F + 875I + 0.142(H_1/H_2) \end{aligned} \tag{13}$$

where for D_{max}, refer to Eq. (1); F is the parameter determined through Eq. (11); I is the voids index in m^3/m^3; D_{final} is the slump-flow test result, in mm; and H_2/H_1 is the L-box test result, as percent.

Mixing water—The mixing water content a is derived by deducting the volume of voids and admixture from the volume of the liquid fraction (voids index I)

$$a = I - V_v - adj \tag{14}$$

where V_v is the voids volume; and adj is the volume of the admixture solution. This is accurately determined using an aerometer (air content meter) for concrete, although at the design stage, the figures in the ACI 613 standard (ACI Committee 613 1954), which relate voids volume to maximum aggregate size, can be used.

Method proposed by Nepomuceno (2005)

Nepomuceno (2005) proposed a new method to design SCC mixtures based on the experimental work described in his PhD thesis. It establishes two new parameters that are more appropriate for compressive strength control.

The author divides the study of SCC composition into four main stages:

1. The definition of the basic essential data;
2. The definition of the basic options for the materials;
3. The study of mortar mixtures; and
4. The study of concrete mixtures.

The basic essential data are the elements needed to define the target fresh and hardened state properties that the SCC must achieve.

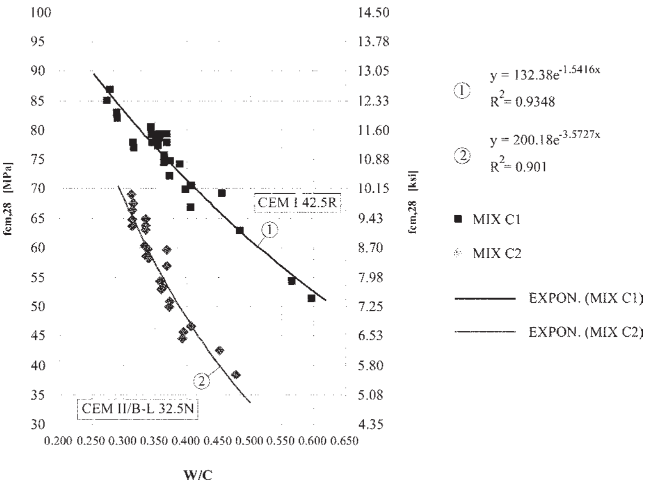

Fig. 1—Relationship between $f_{cm,28}$ *(compressive strength at 28 days) and* w/c *in mass (Nepomuceno 2005).*

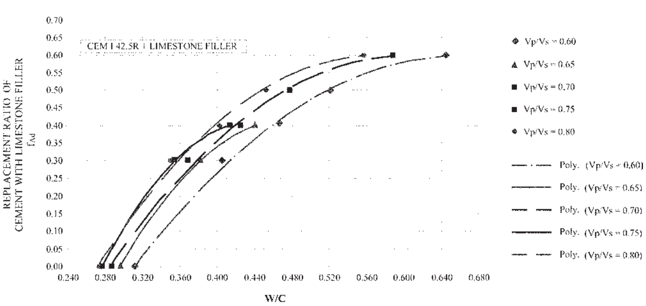

Fig. 2—Relationship between f_{ad} *(replacement ratio of cement with mineral additions) and* w/c *for mortars with CEM I 42.5R and limestone filler (Nepomuceno 2005).*

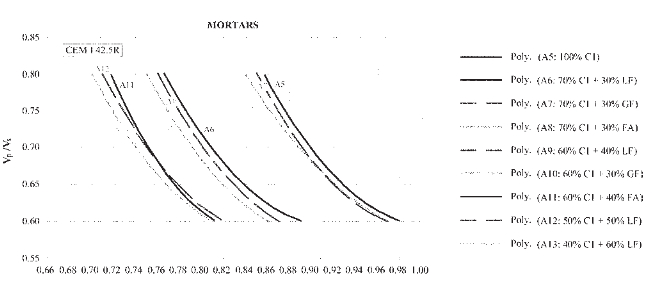

Fig. 3—Relationship between V_p/V_s *and* V_w/V_p *for mortars with Type* C_1 *cement: CEM I 42.5R (LF is limestone filler; GF is granite filler; and FA is fly ash) (Nepomuceno 2005).*

This proposal is based on a set of correlations valid for materials selected as a function of criteria that include their quality for SCC production and their availability in the area where the study was performed (Covilhã in eastern Portugal).

Silva (2007) made a preliminary study of two sands and two gravels to be used in the two stages of the research (mortars and concretes). Several mixtures using different proportions were made to maximize the compacity, and therefore the loose bulk density, at each stage.

Mortar study: definition of water-cement ratio (w/c) *by mass*—The target *w/c* depends on the compressive strength desired at 28 days and the type of cement used. Nepomuceno (2005) proposed the graph in Fig. 1 for the cements used in his work, where C_1 is CEM I 42.5R and C_2 is CEM II/B-L32.5N.

Mortar study: choice of volumetric ratio value (V_p/V_s)—The range of V_p/V_s values (volume ratio between the total powder content, cement and mineral additions, and fine aggregates in the mixture) should be from 0.60 to 0.80, preferably from 0.65 to 0.80. As a starting point for his design, Nepomuceno (2005) chose an average value between 0.70 and 0.75.

Mortar study: determination of replacement ratio of cement with mineral additions—To calculate the replacement ratio of cement with mineral additions (f_{Ad}), several pre-established values were used: the *w/c* in mass, the volumetric ratio V_p/V_s, and the correlations proposed by Nepomuceno (2005) for this purpose (refer to Fig. 2).

Once the *w/c* (depending on the established compressive strength) and the V_p/V_s have been chosen, the replacement ratio of cement with mineral additions is calculated. Figure 2 shows various alternatives for the replacement ratio of cement with mineral additions, depending on V_p/V_s to achieve a given compressive strength through the *w/c*. The relationships shown have been devised to obtain a rheological self-consolidating behavior according to initial specifications.

Nepomuceno (2005) used several mineral additions but only the correlations involving limestone filler are presented herein because that was the only one used in this study.

Mortar study: determination of (V_w/V_p) *and* ($S_p/p_{\%}$) *ratios*—The V_w/V_p value (volume ratio between the water and fine material content in the mixture) and $S_p/p_{\%}$ value (percentile ratio in mass between the high-range water-reducing admixture and fine material content in the mixture) that produce the target rheological properties are estimated using the correlations established by Nepomuceno (2005) (Nepomuceno and Oliveira 2008). They depend directly on the parameter V_p/V_s and the very-fine materials that lead to the established reference curves.

The concept is exemplified in Fig. 3 and 4 for the C_1 cement, and the rheological characteristics are quantified by the slump-flow and V-funnel tests for mortars—that is, the rheological parameters are calibrated through the relative flow area G_m and the relative flow speed R_m. The relationships shown have been devised to obtain a rheological self-consolidating behavior according to initial specifications.

Mortar design—Once all these parameters are known, the volumes of all components are determined. Knowledge of the bulk density of the components and the unit content of each fine material enables their weight proportion per unit volume to be determined.

Experimental mixtures and evaluation of rheological parameters—Once the parameter V_p/V_s is set and the parameters V_w/V_p and $S_p/p_{\%}$ are estimated, the next stage is to prepare experimental mixtures of mortar where the rheological characteristics G_m and R_m must be evaluated. Room must be left to adjust the amount of water and high-range water-reducing admixture, thereby changing the V_w/V_p and $S_p/p_{\%}$ parameters until they achieve the intended target for SCC, of G_m between 5.3 and 5.9 and R_m between 1.14 and 1.30 s^{-1} (Nepomuceno and Oliveira 2008).

After these corrections, one has to check whether the *w/c* remains the same. If the *w/c* has changed, one has to go back to the calculation stage, correct the value of V_p/V_s, and repeat the procedure described previously. The time spent to achieve the rheological target values maintaining the preset *w/c* depends heavily on the experience of whomever is running the tests (Nepomuceno and Oliveira 2008).

Concrete study: definition of voids volume V_v *and ratio* V_m/V_g—For analytical purposes, the voids volume is assumed to be constant at approximately V_v = 0.03 m^3 (0.098 ft^3). If aerometer measurements make it possible to conclude that this assumption is wrong, the real value can be used to repeat the design.

The V_m/V_g ratio (volume ratio between the mortar and coarse aggregate content) depends directly on the level of self-compactibility targeted and can be evaluated by several tests, two of which are:

- The L-box test, yielding the parameter H_2/H_1; and
- The box test, yielding the parameter H (Ouchi 1998; Takada 2000).

Nepomuceno (2005) recommends using only the L-box test to evaluate self-compactibility to reduce the number of tests performed.

The self-compactibility degree is therefore inferred from the parameter H_2/H_1 measured by the L-box test and from the relationship between V_p/V_s and V_m/V_g represented by MN ($MN = (V_p/V_s) \times (V_m/V_g)$).

Each combination of V_p/V_s and V_m/V_g is represented by a mixture number MN, which is the product of two parameters and expresses, to some extent, the "solid skeleton of the mixture."

Figure A.2 represents the relationship between MN and H_2/H_1 when D_m is between 630 and 670 mm (24.8 and 26.4 in.). Assuming $H_2/H_1 \geq 0.80$ and $D_m \geq 630$ mm (24.8 in.), the parameter MN should be 1.70 or higher. In the end, this means that $(V_p/V_s) \times (V_m/V_g) = 1.70$—that is, $V_m/V_g \geq 1.70/(V_p/V_s)$.

Concrete design—The procedure for designing the concrete mixtures is similar to that for mortars. First, taking into account the preceding points, the volume content of each component is defined. Knowing their bulk densities and also the unit content of the aggregate, the corresponding weight content per unit volume can be determined.

EXPERIMENTAL PROGRAM

Materials used

The materials used in this study were selected as a function of the design methods under analysis and according to availability in the Lisbon region. The following materials were therefore used: two types of cement complying with EN 197-1: 2000 (calcareous portland cement II/B-L 32.5N with a specific gravity [SG] of 3.05 and a normal portland cement I-42.5R with SG 3.15); two mineral additions, fly ash with SG 2.30 and limestone filler with SG 2.70; two limestone-based coarse aggregates, Gravel 1 with SG 2.69, D_{max} 9.52 and Gravel 2 with SG 2.70, D_{max} 19.10; two siliceous sands, one coarse with SG 2.56, D_{max} 6.35 and fineness modulus of 3.39, and one fine with SG 2.61, D_{max} 1.19 and fineness modulus of 1.64; and a third-generation concrete high-range water-reducing admixture/strong water-reducer admixture per European Norm EN 934-2: 2001, a modified polycarboxylic high-range water-reducing admixture in liquid form with a density of 1.05.

Regarding the choice of aggregates, both methods have the same requirements for the production of SCC (such as D_{max}, the reference curve or the optimal mixture); however, any type of aggregate typically used for conventional concrete can be used.

The two methods differ in their approach to the selection of cement, addition, and high-range water-reducing admixture. Ferreira (2001) limits his method to just one type of

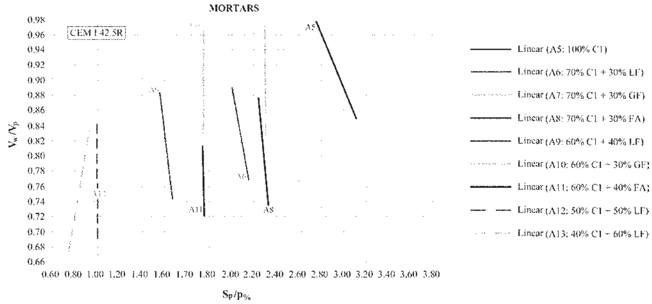

Fig. 4—Relationship between V_w/V_p *and* $S_p/p_{\%}$ *for mortars with Type* C_1 *cement: CEM I 42.5R (LF is limestone filler; GF is granite filler; and FA is fly ash) (Nepomuceno 2005).*

cement, addition, and high-range water-reducing admixture and shows no correlation with other materials, and this leads to the study being repeated for each set of materials. Nepomuceno (2005) uses two types of cement, four types of addition, and a modified polycarboxylic high-range water-reducing admixture and makes it relatively easy to introduce new materials. Nepomuceno established behavior patterns for the mortar phase, which is essential for the behavior of the SCC in the fresh state. This enables new materials—especially cement—to be introduced without the need to reproduce the original study. In other words, the Nepomuceno method can be implemented using other materials, provided that the relevant appropriate correlations similar to those developed by the authors are determined. For example, the introduction of a new type of cement would only require the establishment of new correlations between f_{cm28} and the w/c, because it was found that the behavior of the mortar, as identified by the trend of the average correlations between $V_p/V_s = f(w/c)$, $V_w/V_p = f(V_p/V_s)$, and $S_p/p_{\%} = f(V_w/V_p)$, is independent of the type of cement or addition used (Nepomuceno 2005).

Preliminary study

The methods were applied using different procedures for selecting components and designing the mixture content. These procedures were derived from the experimental work. Because the main objective of this study is to check the viability of the methods, some decisions had to be made concerning their correct use. In the Ferreira (2001) method, Type I 42.5R cement and fly ash as a mineral addition are used. Nepomuceno's (2005) method allows a choice of either II/B-L32.5N or I 42.5R cements and fly ash, granite filler, or limestone filler as mineral additions. These differences were unavoidable given the original premises of the study, which were to only use the methods in the circumstances that were actually tested in the original research. They may affect the applicability and technical performance of the methods, however, and they are reflected in the results obtained.

Therefore, in the mixtures where the Ferreira method was tested, cement of Type I 42.5R and fly ash were used, following the author's recommendations to optimize the results. For the Nepomuceno method, Type II/B-L32.5N cement was chosen for the compressive strength targets of 40 and 55 MPa (5.80 and 7.98 ksi), Type I 42.5R cement was used for the target value of 70 MPa (10.15 ksi), and limestone filler was chosen as the mineral addition, again according to the author's recommendations for optimization purposes.

Table 1—Mixture compositions of methods under analysis (Silva 2007)

		40 MPa (5.80 ksi)				55 MPa (7.98 ksi)				70 MPa (10.15 ksi)			
		FM		NM		FM		NM		FM		NM	
Composition		m^3/m^3	kg/m^3	m^3/m^3	kg/m^3	m^3/m^3	kg/m^3	m^3/m^3	kg/m^3	m^3/m^3	kg/m^3	m^3/m^3	kg/m^3
Cement II/B-L 32.5N (C)		—	—	0.109	331.3	—	—	0.150	454.8	—	—	—	—
Cement I-42.5R (C)		0.095	301.1	—	—	0.111	362.4	—	—	0.130	421.6	0.128	403.5
Fly ash (FA)		0.055	129.1	—	—	0.070	155.3	—	—	0.080	180.7	—	—
Limestone filler (LF)		—	—	0.109	296.4	—	—	0.064	174.4	—	—	0.085	232.3
High-range water-reducing admixture (*adj*)		0.006	6.5	0.010	10.0	0.007	7.8	0.008	8.2	0.009	9.0	0.008	8.9
Water (A)		0.195	195.0	0.148	148.0	0.194	194.0	0.160	160.3	0.193	193.0	0.160	160.1
Fine aggregate	Fine sand	0.157	410.3	0.093	243.8	0.108	281.0	0.092	239.1	0.080	207.8	0.091	238.8
	Coarse sand	0.132	338.0	0.218	558.0	0.144	367.5	0.214	547.1	0.148	378.5	0.213	546.5
Coarse aggregate	Gravel 1	0.138	371.4	0.170	455.8	0.132	353.3	0.170	455.8	0.128	343.6	0.170	455.8
	Gravel 2	0.201	543.2	0.113	305.6	0.215	581.4	0.113	305.6	0.213	575.8	0.113	305.6
Air		0.020	—	0.030	—	0.020	—	0.030	—	0.020	—	0.030	—
Bulk density, kg		2294.6		2348.8		2302.7		2345.1		2309.9		2351.5	
Total aggregate		0.629	1662.9	0.594	1563.1	0.598	1583.2	0.588	1547.5	0.569	1505.6	0.588	1546.7
Fine aggregate		0.289	748.3	0.311	801.8	0.251	648.5	0.305	786.2	0.228	586.3	0.305	785.4
Coarse aggregate		0.340	914.6	0.283	761.3	0.347	934.7	0.283	761.3	0.341	919.3	0.283	761.3
Very-fine material		0.150	430.2	0.218	627.7	0.181	517.7	0.214	629.2	0.210	602.28	0.213	635.8
Binding paste		0.371	631.7	0.406	785.7	0.402	719.5	0.412	797.6	0.431	804.3	0.412	804.8
Mortar		0.660	1380.0	0.717	1587.5	0.653	1368.0	0.717	1583.8	0.659	1390.6	0.717	1590.2
Solid part		0.779	2093.1	0.812	2190.8	0.779	2100.9	0.802	2176.7	0.779	2107.9	0.801	2182.5
Liquid part		0.221	201.5	0.188	158.0	0.221	201.8	0.198	168.5	0.221	202.0	0.199	169.0

Notes: FM is Ferreira method; NM is Nepomuceno method; 1 $lb/ft^3 \cong 16.03\ kg/m^3$.

RESULTS AND DISCUSSION

Introduction

Experiments were performed to evaluate the viability of two SCC design methods, one described by Ferreira (2001) and the other by Nepomuceno (2005). There were three main stages:

- The use of the design methods to determine the mixture proportions;
- Mortar study (only for the Nepomuceno method, as stated in the chapter "Mix Design Methodologies under Study"); and
- Concrete study.

This section fully compares the results, which are then correlated with the content of the various components of the mixtures, with the values obtained by the researchers who proposed the SCC design methods in the first place and available reference values.

The analysis of the results focuses on the ability of the two methods to fulfill the concrete target characteristics: fresh state (rheologic behavior) and hardened state (mechanical strength), and the differences detected.

The next points present the comparison of the most important volumetric ratios in terms of concrete design and the final test results for the fresh and hardened states.

Mixture compositions—The mixture compositions for each compressive strength target determined according to the two methods are presented in Table 1.

For the two lower targets of 40 and 55 MPa (5.80 and 7.98 ksi), the total powders' (cement and mineral additions) content is clearly lower in the Ferreira method mixtures because Type I 42.5R cement was used instead of the Type II/BL32.5N cement in the Nepomuceno method. For the higher target of 70 MPa (10.15 ksi), the values are balanced in the two methods.

The different approach of the methods is clearly reflected in the type and content of the mineral additions used. A constant replacement of cement by a mineral addition ratio of 30% is proposed for the Ferreira method, whereas Nepomuceno's method has a ratio of between 20 and 50%.

The Ferreira method is always less demanding in terms of the high-range water-reducing admixture, and the trend is the opposite for the water content. In this method, the high-range water-reducing adxmiture content depends solely on the variation of the binder content; in Nepomuceno's method, it depends on a combination of parameters such as the fine materials and water content and the type and content of the mineral additions. The use of limestone filler in higher proportions allows significantly lower water content in the Nepomuceno method without compromising the SCC's rheological behavior.

The differences in approach are evident in terms of mixture composition as the compressive strength target becomes more demanding. The Ferreira method is more conventional in its effect on the components' content, in particular the aggregate volume, by decreasing the fine aggregate content in favor of the coarse aggregate (except for the highest target compressive strength) and leading to a smaller overall aggregate content. It also increases the paste volume, but this is

Table 2—Average fresh state results (Silva 2007)

Compressive strength target	Slump-flow test				V-funnel test		L-box test				Box test	
	T_{50}, seconds		D_m, mm (in.)		T, seconds		T_{40}, seconds		H_2/H_1, %		H, mm (in.)	
	FM	NM	FM	NM	FM	NM	FM	NM	FM	NM	FM	NM
40 MPa (5.80 ksi)	3.41	3.94	675 (26.57)	698 (27.48)	9.26	13.87	3.98	4.04	82	86	327 (12.87)	327 (12.87)
55 MPa (7.98 ksi)	3.53	6.19	642 (28.28)	673 (26.50)	11.39	13.59	4.08	3.80	81	83	329 (12.95)	333 (13.11)
70 MPa (10.15 ksi)	3.19	4.64	644 (25.35)	668 (26.30)	9.91	14.10	2.68	3.52	82	85	329 (12.95)	336 (13.23)

Notes: FM is Ferreira method; NM is Nepomuceno method; T_{50} is time that flowing sample takes to reach diameter of 500 mm (19.69 in.); D_m is diameter of spread; T is flow time; T_{40} is time that flowing sample takes to reach length of 400 mm (15.75 in.); H_2/H_1 is ratio between height of concrete at end of horizontal section of apparatus and height of concrete remaining in vertical section; H is height concrete reaches after flowing through reinforcing bars of apparatus.

not reflected in the mortar content because of the drop in fine aggregate content. For the same mechanical strength in the Nepomuceno method, the overall content of coarse aggregate, which is always lower than in the other method, is less affected and the mortar is progressively enriched with fine aggregate and paste volume.

The changes in the mortar content are associated with the way the aggregate content is controlled in the mixture and these influence the fresh state concrete behavior. The results of the workability test presented in the following fully demonstrate this point.

Using the determined mortar content and the corresponding volumetric ratios, it is possible to compare these results with the reference values. A set of values recommended by SCC-related reference bodies and authors was selected: Okamura et al. (2000) (Domone 2000), JSCE (Domone 2000); (Nawa et al. 1999), and the technical committees 174-SCC (RILEM TC 174 2001) and EPG SCC (BIBM et al. 2005) (the European guidelines for SCC).

Table A.2 gives the reference values and the values achieved using each design method for each mechanical strength target. Some differences in the parameters are considered more relevant by the various authors and this is essentially because of the individual mixture design methods proposed. However, when two or more authors agree on the parameters chosen, the numerical differences between them are of no consequence.

Table A.2 shows some parameters that fall outside the recommended reference ranges; thus:

- In terms of fine aggregate, the Ferreira method values for the higher strength targets are slightly lower than recommended; for the coarse aggregate, Ferreira's values are always slightly above those recommended, whereas Nepomuceno's values are always slightly below (even though the difference is smaller), which indicates the different approaches of the two methods;
- In terms of cement and mineral addition content, in the Nepomuceno method, the intended rheological behavior is achieved through the mortar, thus leading to values above those recommended; and
- In terms of the fine aggregate/paste volume ratio, the differences from the reference values can be considered negligible.

Generally, even though the discrepancies can be considered unimportant in both cases, the Nepomuceno method offers slightly better compliance with the recommended parameters' range.

Fresh state results—The average values from the various tests are given in Table 2. Here it is important to note the differences in paste content and the specific approach of each method.

It must be noted that the values are for mixtures where slight adjustments were made to the water and high-range water-reducing admixture content to obtain a predetermined rheological behavior. These corrections are minimal in absolute volume terms: approximately 0.02% for water (less than 5 L/m^3 [0.40 gal./ft^3]), and 0.06% for high-range water-reducing admixtures (less than 0.4 L/m^3 [0.03 gal./ft^3]).

Slump-flow test—The final flow time (not evaluated herein) depends mostly on the value of the diameter of the spread (D_m). The time the flowing sample takes to reach a diameter of 500 mm (19.69 in.) (T_{50}) allows for a better evaluation of the SCC in terms of viscosity and is easier to determine (Nagamoto and Ozawa 1999). A visual observation gives immediate indications as to the SCC's homogeneity and its resistance to segregation and bleeding.

The average values for the slump-flow test are given in Table 2. Essentially, they allow for the evaluation of the deformation rate and the diameter of the spread of the SCC. The results for T_{50} and D_m obtained with the Nepomuceno method are higher on average than those for the Ferreira method.

It is also concluded that the results obtained do not significantly deviate from the reference values and are within the targets envisaged—that is, D_m between 630 and 700 mm (24.80 and 27.56 in.) in Nepomuceno's recommendations and between 600 and 720 mm (23.62 and 28.35 in.) in Ferreira's.

The Ferreira method leads to average values of approximately 2 seconds for T_{50} and 650 mm (25.59 in.) for D_m. In comparison, the Nepomuceno method leads to average values of approximately 3.5 seconds for T_{50} and average D_m values that depend mostly on the replacement ratio of cement by mineral additions. This clearly affects the fluidity and consistency of the mixture, albeit within the target values.

Therefore, the values obtained in this study are consistent with those given by the authors of the design methods.

The mixtures produced by the Nepomuceno method exhibited a good distribution of the coarse aggregate and the absence of segregation and bleeding. Coarse aggregate can even be found at the borders of the spread diameter.

In the mixtures produced by the Ferreira method, a greater tendency for the coarse aggregate to remain at the center is observed as well as a slight trend for the paste to separate from the rest of the aggregate at the borders of the spread diameter. No case showed a tendency to bleed.

These results are coherent with the mixture content in both methods. The higher coarse aggregate content in the Ferreira method leads to a greater tendency to segregation. The higher content of very-fine materials and binding paste (that is, higher mortar content) in the Nepomuceno method leads to better mixture cohesion—that is, higher values of T_{50}, also, even though the average D_m values are acceptable.

V-funnel test—The average values in Table 2 allow for the ability of SCC to pass through small openings to be evaluated. A joint analysis of these results with those from the flowing table test is also interesting.

However, the interpretation of the V-funnel test results requires consideration of some general points. This test depends on two main factors:

1. Content and maximum size of the coarse aggregate; and
2. Flowability of concrete (mortar content).

The results of this test show that greater viscosity leads to a longer flow time. In other words, an SCC should have a reasonable spread diameter on the slump table (650 to 700 mm [25.59 to 27.56 in.]) but also an acceptable flow time (over 10 seconds). This correlation can be disrupted when a lower viscosity is associated with greater fluidity. This is essentially explained by the interaction between coarse aggregates. When their content is high, this can cause some jamming of the V-funnel and thus a higher flow time that is not linked to self-compactibility but to an excess of coarse material (Nagamoto and Ozawa 1999).

Table 2 shows that almost all the average values for both design methods are within the reference values' range (flowing time between 10 and 20 seconds). Note that the values given by the Ferreira method are close to the lower limit, whereas the ones obtained by the Nepomuceno method are clearly higher and close to the average values that the author obtained in his original study (between 11 and 16 seconds). Ferreira did not use this test in his original study.

The results from this test show good correlation with the components' content (for example, mortar) for both design methods. Once again, the higher mortar content and replacement ratio of cement with mineral additions in Nepomuceno's method are clearly reflected in the higher average results of the test.

Also noteworthy is the fact that the higher content of coarse aggregate in the Ferreira method was not enough to cause a blockage at the orifice of the V-funnel, which would have affected the results. Visual observation also yielded the following conclusions: the coarse aggregate was visible at the top of the mold (before the lid was opened), which shows a uniform distribution, and there was no bleeding. Furthermore, after the test was performed, the concrete looked like a uniformly distributed mass.

The joint analysis of both tests (slump-flow and V-funnel) shows that concrete produced according to the Ferreira method displays less viscosity and behaves more as a fluid mass and not strictly as an SCC. The concrete produced according to Nepomuceno's method is clearly more viscous, although without losing the ability to self-consolidate and fill every empty space, as observed in the results of the L-box and box tests.

L-box and box tests—A simple analysis of the values presented in Table 2 reveals the mixtures' filling ability and resistance to blockage and segregation. Visual observation of the samples also allows their stability to be checked.

The average H_2/H_1 (ratio between the height of the concrete at the end of the horizontal section of the apparatus and the height of the concrete remaining in the vertical section) and H values (the height the concrete reaches after falling through the obstacle element of the apparatus) are well balanced for both methods (target values > 80% and > 322 mm [12.7 in.], respectively), with a slight increase of H_2/H_1 in the Nepomuceno method.

The reference values proposed by the authors for the L-box test show some difference: H_2/H_1 > 80% (Nepomuceno) and H_2/H_1 > 60% (Ferreira). Ferreira justifies his value with some real cases where mixtures with H_2/H_1 of appoximately 60% have presented no problems in in-place application, depending on the reinforcement ratio. The results obtained in this study all fall within these recommendations, even though the authors considered 60% a low figure for the workability required of an SCC and 80% was chosen as the target.

The global results from this study, with H_2/H_1 between 81 and 82% for the Ferreira method and 83 and 86% for the Nepomuceno method, are closer to those reported by Nepomuceno in his research (H_2/H_1 between 80 and 90%), but they differ from those obtained by Ferreira (H_2/H_1 between 67 and 83%).

In the L-box test, segregation is less noticeable than in the aforementioned tests, even though a slight tendency toward jamming at the reinforcing bars was observed in the mixtures produced according to Ferreira. This makes it difficult to correlate these results with those obtained in the slump-flow and V-funnel tests.

These results highlight the influence of the higher coarse aggregate and lower paste volume of the Ferreira method's mixtures. This has two clear consequences in relation to the Nepomuceno mixtures, even though all of them provide acceptable H_2/H_1 results:

- A tendency for blocking to occur; and
- Slightly lower T_{40} values (the time that the flowing sample takes to reach a length of 400 mm [15.75 in.]).

In other words, and as reported by Ferreira (2001), self-compactibility with coarse aggregate content higher than 0.30 m^3/m^3 (0.30 ft^3/ft^3) is possible only for a very-fine materials' content higher than 0.19 m^3/m^3 (0.19 ft^3/ft^3). As a matter of fact, the only mixture produced by Ferreira in his study and reproduced in this study that strictly behaved like an SCC was the one for the target of 70 MPa (10.15 ksi), whose very-fine materials content was equal to 0.21 m^3/m^3 (0.21 ft^3/ft^3).

Both methods complied with the reference values in the box test (H > 322 mm [12.68 in.]), and no bleeding was observed. The tendency to segregate seen in the mixtures produced by the Ferreira method in the previous tests was not observed in the box test. This is because the shape of the equipment makes it difficult to observe signs of segregation if they are not evident in a concrete sample (Khayat 1999).

Compressive strength results—Table 3 presents the average results of the compressive strength test at 7 and 28 days. As expected, compressive strength increases with time and the targeted compressive strength. The actual values obtained compare well with the targets for both design methods and show some uniformity. For targets of 40 and 55 MPa (5.80 and 7.98 ksi), the values obtained by the Ferreira method are slightly higher than those for the Nepomuceno method, whereas for a target of 70 MPa (10.15 ksi), there is virtually no difference. With just one exception, every figure for the two methods is slightly below the targets and the differences are approximately uniform for all target levels.

The results of the Nepomuceno method mixtures show an increase in compressive strength associated with the higher cement content for a given coarse aggregate content. This cement content increases because the replacement ratio (cement with mineral additions) is progressively lowered as the compressive strength target increases.

Table 3—Average values of compressive strength test (Silva 2007)

Compressive strength target	Compressive strength test							
	Average at 7 days, MPa (ksi)		Average at 28 days, MPa (ksi)				Hardening coefficient at 7 days	
	FM	NM	FM	σ_{FM}	NM	σ_{NM}	FM	NM
40 MPa (5.80 ksi)	31.16 (4.52)	29.74 (4.31)	41.67 (6.04)	1.39 (0.20)	38.84 (5.63)	1.69 (0.25)	0.75	0.77
55 MPa (7.98 ksi)	39.66 (5.75)	41.41 (6.00)	54.35 (7.88)	1.02 (0.15)	52.24 (7.57)	0.83 (0.12)	0.73	0.79
70 MPa (10.15 ksi)	53.34 (7.73)	57.08 (8.28)	66.36 (9.62)	0.73 (0.11)	67.24 (9.75)	1.30 (0.19)	0.80	0.85

Notes: FM is Ferreira method; NM is Nepomuceno method; σ is standard deviation.

The compressive strength of the Ferreira method mixtures improves by proportionally increasing the binder (cement plus mineral addition) content, keeping the replacement ratio constant, and reducing the fine aggregate content in favor of the coarse aggregate content.

Therefore, despite the small differences found, the two methods can reach the targeted mechanical performance. Thus, the mortar content, always lower in the Ferreira method, only affects the fresh state, as mentioned previously. The same can be said for the different cement types used in the 40 and 55 MPa (5.80 and 7.98 ksi) targets: Type I 42.5R cement in the Ferreira method and Type II/B-L32.5N cement in the Nepomuceno method—Type I 42.5R cement was used in both methods for the 70 MPa (10.15 ksi) target.

It can therefore be stated that the hardened properties of SCC essentially depend on the composition of the mixture and the coarse aggregate it contains. In Nepomuceno's mixtures, the coarse aggregate content is constant and the influence on the compressive strength is due to the mortar. For Ferreira's mixtures, this influence is more evenly distributed between the mortar matrix and the coarse aggregate content.

In the Nepomuceno method, the mortars' properties are suitably tuned in the first stage, and when it comes to concrete production, the mortar matrix (water + admixture + cement + mineral additions + fine aggregates) is properly optimized to obtain the SCC's required properties. The procedures are different in the Ferreira method and the matrix components are made to depend on the total aggregate content and other factors, with some loss of efficiency of the matrix optimization.

Notwithstanding the differences between the design methods, the aggregates' contribution to concrete mechanical strength—and in particular that of the coarse aggregate—cannot be ignored. In the Nepomuceno method, however, the mortar matrix makes a meaningful contribution to the compressive strength. Accordingly, for the lower targets of 40 and 55 MPa (5.80 and 7.98 ksi), Ferreira's mixtures' values are slightly higher than Nepomuceno's because the compressive strength is mostly governed by the quality of the mortar matrix, which is approximately constant for the Ferreira method but improves with the strength target for the Nepomuceno method, and not that of the coarse aggregate. For the target of 70 MPa (10.15 ksi), the coarse aggregate, which is the same material in all the mixtures, is the conditioning factor in the concrete's compressive strength, and the quality of Nepomuceno's mixtures is better. Thus, the two methods produce mixtures of roughly the same compressive strength.

The fact that different coarse aggregates were used in the original experimental work and in this study may also explain the small difference found between the real compressive strength values and the targets. This influence is expected to be greater in the Ferreira method than in Nepomuceno's because the quality and content of the coarse aggregate used by Ferreira is the main contribution to the compressive strength. Nepomuceno used crushed granite rock from Fundão in eastern Portugal, duly corrected for shape and yielding a small percentage of long, flat particles. Ferreira used crushed limestone from the Pombal region in western Portugal, also with acceptable properties for concrete production. This study used crushed limestone from the Pêro Pinheiro region near Pombal. The reason for these choices was always to use locally available materials for which the only criterion was the maximum aggregate size. That option adversely affected the quality of the coarse aggregate in this study. It was found to be significantly altered from a geological point of view and exhibited water absorption levels and Los Angeles wear test results outside those strictly recommended (water absorption: Gravel 1 = 5.00% and Gravel 2 = 4.00%; Los Angeles wear: Gravel 1 = 34.30% and Gravel 2 = 33.20%). This meant that results in this study differed from those of the Ferreira and Nepomuceno studies—namely, a small decrease in expected compressive strength.

No other mechanical properties of SCC in the hardened state were analyzed in this study. Nevertheless, special attention should be paid to shrinkage phenomena, given the self-consolidation demands of SCC production consequences for paste content (higher) and coarse aggregate content (lower) compared with conventional concrete. On the basis of the higher coarse aggregate content of mixtures produced using the Ferreira method, the shrinkage of such mixtures is expected to be lower than that of mixtures produced using the Nepomuceno method.

CONCLUSIONS

The differences in the design approach of these methods led to concrete mixtures that can, in most cases, be classified as SCC but which diverge in terms of fresh state behavior. This immediately suggests the possibility of distinct applications of the mixtures produced using these methods. In relation to this, it can be stated that the SCCs produced using the Nepomuceno method are better in terms of self-compactibility than those produced using the Ferreira method. This is because in the fresh state, Ferreira's mixtures behave more like a fluid concrete than a real SCC, and this tendency is altered only when the very-fine materials content is higher than 0.19 m^3/m^3 (0.19 ft^3/ft^3)—that is, for very high compressive strength (approximately 70 MPa [10.15 ksi]). The analysis of the fresh state results presented in Table 2 and the parameters presented in Table A.2 makes it possible to say that the 40 MPa (5.80 ksi) concrete will hardly be considered an SCC, the 55 MPa (7.98 ksi) concrete will almost be an SCC, and the 70 MPa (10.15 ksi) concrete has all the characteristics of an SCC.

From a practical point of view, however, the Ferreira method is simpler and makes the influence of changes in component content on concrete behavior easier to understand. These advantages would be lost if the changes required to obtain real SCCs for compressive strengths lower than 70 MPa (10.15 ksi) were to be introduced into the method—that is, optimization of the high-range water-reducing admixture and mineral addition content at the preliminary mortar stage.

The Nepomuceno method could be improved if the V_p/V_s ratio described in the beginning of this paper were adjusted to a behavior target. In this study, the V_p/V_s ratio was considered to be constant and equal to 70%.

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APPENDIX

Table A.1 - Coordinates of the reference curves for SCC, adapted from Ferreira (2001)

Diameter x (mm; in)	Percentage of material passed (in volume)	
	y (curve with cement)	y (curve without cement)
D_{max}	100	100
4.76 (0.187 in)	$p(4.76) = (50+G) + \left(1 - \frac{p_{c+s}}{100}\right) + p_{c+s}$	$p'(4.76) = 50 + G$
0.074 (0.003 in)	$p(0.074) = p_{c+s} + F$	$p'(0.074) = \frac{F \cdot 100}{100 - p_{c+s}}$

Table A.2 - Reference parameters: comparison of the mixes (Silva 2007)

Mix parameters		RILEM	EPG SCC	JSCE	OKAMURA	**40 MPa** (5.80 ksi)		**55 MPa** (7.98 ksi)		**70 MPa** (10.15 ksi)	
						FM	NM	FM	NM	FM	NM
Fine aggregate	$[m^3/m^3]$	---	0.28 - 0.32	---	---	0.289	0.311	0.251	0.305	0.228	0.305
	$[kg/m^3]$ $[lb/ft^3]$	710 - 900 44.3 - 56.2	770 - 882 48.1 - 55.1	---	---	748.3 46.7	801.8 50.0	648.5 40.5	786.2 49.1	586.3 36.6	785.4 49.0
Coarse aggregate	$[m^3/m^3]$	0.30 - 0.34	0.27 - 0.36	0.28 - 0.30	---	0.340	0.283	0.347	0.283	0.341	0.283
	$[kg/m^3]$ $[lb/ft^3]$	750 - 920 46.8 - 57.4	750 - 1000 46.8 - 62.4	---	---	914.6 57.1	761.3 47.5	934.8 58.3	761.3 47.5	919.3 57.4	761.3 47.5
Very fine material	$[m^3/m^3]$	---	---	0.160 - 0.190	---	0.150	0.218	0.181	0.214	0.210	0.213
	$[kg/m^3]$ $[lb/ft^3]$	450 - 600 28.1 - 37.4	380 - 600 23.7 - 37.4	---	---	430.2 26.8	627.7 39.2	517.7 32.3	629.2 39.3	602.3 37.6	635.8 39.7
Water content	$[m^3/m^3]$	0.150 - 0.200	0.150 - 0.210	0.155 - 0.175	---	0.195	0.148	0.194	0.160	0.193	0.160
Binding paste	$[m^3/m^3]$	0.340 - 0.400	0.300 - 0.380	---	---	0.371	0.406	0.402	0.412	0.431	0.412
Water/very fine material ratio in mass		---	---	0.280 - 0.370	---	0.450	0.236	0.370	0.255	0.320	0.252
Water/very fine material ratio in volume		0.80 - 1.20	0.85 - 1.10	---	0.90 - 1.00	1.30	0.68	1.07	0.75	0.92	0.75
Fine aggregate/paste ratio in volume		0.40 - 0.50	---	---	0.40	0.440	0.43	0.38	0.43	0.35	0.43
Coarse aggregate/total aggregate ratio in volume		---	---	---	0.50	0.540	0.48	0.58	0.48	0.60	0.48

FM-Ferreira method; NM-Nepomuceno method.

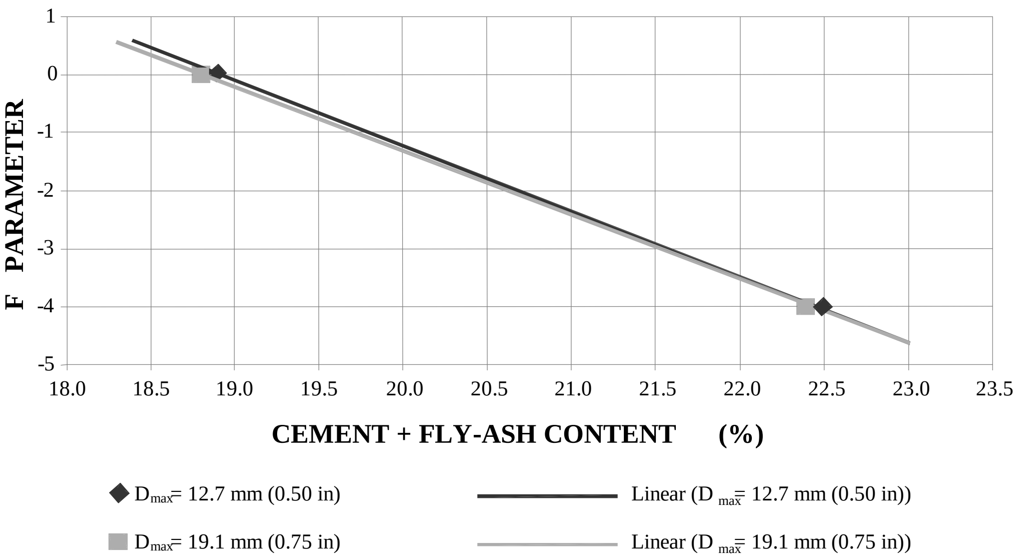

Figure A.1 - Calibration of parameter F (Ferreira 2001)

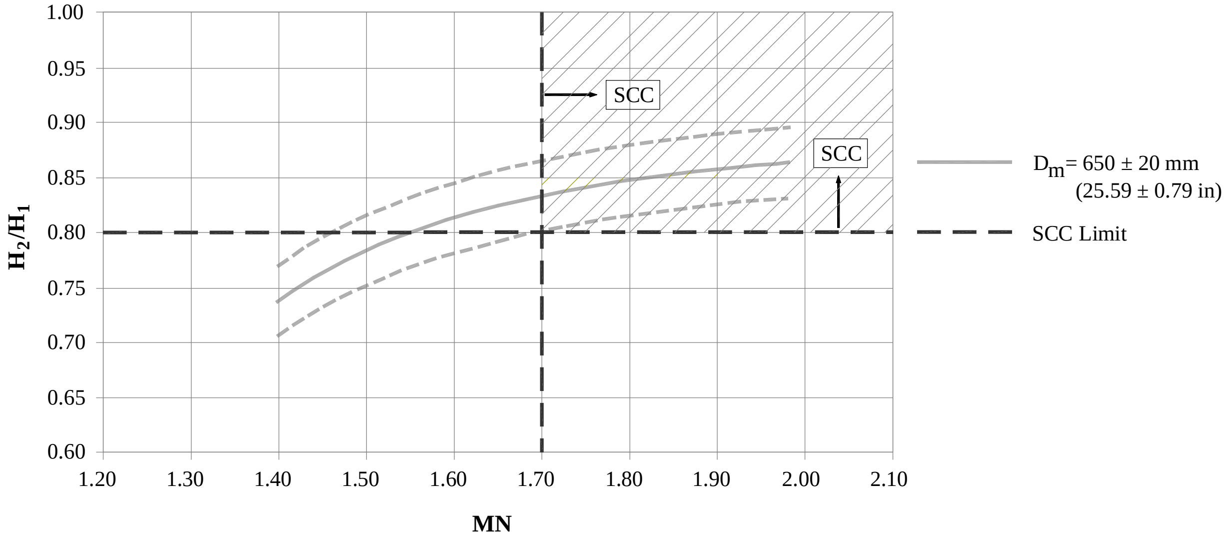

Figure A.2 - Relationship between MN = (V_p/V_s) (V_m/V_g) and H_2/H_1 (result of the L-Box test) for D_m (flow diameter in the slump-flow test) between 630 mm and 670 mm (24.80 in and 26.38 in) (Nepomuceno 2005)

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