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Fresh-state Properties of Self-compacting Mortar and Concrete with Combined Use of Limestone Filler and Fly Ash

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This paper presents the results of a study on the behaviour of self-compacting concrete (SCC) in the fresh and hardened states, produced with binary and ternary mixes of fly ash (FA) and limestone filler (LF), using the method proposed by Nepomuceno. His method determines the SCC composition parameters in the mortar phase (self-compacting mortar - SCM) easily and efficiently, whilst guaranteeing the SCC properties in both the fresh and hardened states. For this, 11 SCMs were studied: one with cement (C) only; three with FA at 30%, 60% and 70% C substitution; three with LF at 30%, 60% and 70% C substitution; four with FA + LF in combinations of 10-20%, 20-10%, 20-40% and 40-20% C substitution. Once the composition of these mortars was defined, 18 SCC mixes were produced: 14 binary SCC mixes were produced with the seven binary mortar mixes, and four ternary SCC mixes were produced with the four ternary mortar mixes. In addition to the methodology proposed by Nepomuceno, the combined use of FA and LF in ternary mixtures was tested. The results confirmed that the method could yield SCC with adequate properties in both the fresh and hardened states. It was also possible to determine the SCC composition parameters in the mortar phase (self-compacting mortar - SCM) that will guarantee the SCC properties in both the fresh and hardened states, as confirmed through the optimized behaviour of the SCC in the fresh state and the promising results in the hardened state (compressive strength). The potential demonstrated by the joint use of LF and FA through the synergetic interaction of both additions is emphasized.

Keywords: *self-compacting concrete, self-compacting mortar, fly ash, limestone filler, fresh properties, compressive strength*

1. Introduction

The main characteristics of self-compacting concrete (SCC) in the fresh state are that, with no need for vibration, SCC can completely fill the formwork and surround the reinforcement adequately (even in densely reinforced areas), leaving no voids and with no segregation either during casting or afterwards. For that, besides high fluidity, the SCC has to show good ability to flow and pass between the reinforcement bars, as well as an excellent capacity to flow like a "viscous fluid"[1].

Those characteristics are achieved by optimizing the mix's proportions and incorporating mineral and chemical admixtures that, apart from influencing the fluidity and viscosity, act to avoid segregation and/or bleeding. This means that the fluidity and viscosity must be adjusted to allow the coarse aggregate to be held in suspension with no segregation, so that the SCC can maintain its properties during casting and until the beginning of the hardening process[2,3].

An efficient method is needed to calculate the mix's proportions to fulfil the fresh state requirements mentioned; it should allow the rapid optimization of the different components to obtain a technically and economically viable SCC.

Ever since SCC was first used, one of the factors that has most influence its wide implementation is the lack of design methods that allow a technical and economic optimization of mixes to make the use of this material more competitive than conventional concrete (CC)[4]. The majority of the methodologies used in the study of the SCC composition are based in prescriptive methods for which limits are defined for the various components or composition parameters. Many of those methods do not allow a wide range of the various components. They are in general very conservative and need to produce numerous experimental mixes for tuning the mix quantities as a function of the requirements both in the fresh and hardened state. The need to adapt a calculation method to the panorama of the demands normally imposed by the construction industry is therefore recognised. That is to say there is a need for a calculation methodology for the SCC mix quantities with the objective of obtaining a given/specific average compressive strength associated with a

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self-compacting mix using a minimal number of experimental iterations. Of the different suggestions for designing the SCC mix proportions, the one proposed by Nepomuceno in his PhD work[5] and presented in several publications[4-7] is highlighted here. This method is based on the Japanese methods proposed by Okamura et al.[8] and by JSCE[9], but introduces new parameters and new correlations (relative to the reference methods), which are appropriate not only to establish the parameters mentioned in the mortar phase to obtain the self-compactability required in the concrete phase, but also to control the mechanical strength of the SCC.

Additionally to the practical application of the original method of Nepomuceno, ternary SCC mixes with cement, LF and FA were produced. In ternary SCC mixes, a synergy effect is expected to occur between these additions. FA is rich in aluminium oxides that will increase the aluminate content in the mix when they react. This effect favours the action/impact of LF on the formation of hydration products, because the beginning of the LF action is triggered by the reaction between $CaCO_3$, C_3A and H_2O (calcium carbonate + tricalcium aluminate + water)[10]. If these additions are used in ternary mixes it is possible to have higher mechanical strength with maintaining the satisfactory fresh properties values.

2. Research Objectives

According to § Preliminary remarks and considering that one of the key questions about the study of SCC mix composition is the need to establish a simple and quick way to directly correlate the properties in the fresh state and the mix's parameters, our study sets out to determine the fresh and hardened properties of SCC produced from binary and ternary blends of limestone filler (LF) and fly ash (FA) using the method proposed by Nepomuceno[5], through the study of self-compacting mortars (SCM).

It was thus possible to evaluate the effect of these mineral admixtures on the performance of the SCM, as well as the efficiency of studying them to obtain SCC with the required behaviour in both the fresh and hardened state. For that purpose, SCM binary and ternary mixes were produced and characterized in the fresh state by their mini slump-flow diameter and mini V-funnel flow time.

After optimizing the SCM mixes, SCC binary and ternary mixes were produced according to NP EN 206-9[11], using the parameters determined in the mortar phase. The efficiency of the method was assessed by evaluating the results in the fresh state of slump-flow, V-funnel, L-box, J-ring tests and sieve segregation. In the hardened state, the compressive strength was evaluated at 7, 28, 91 and 182 days.

3. Experimental Programme

3.1. Materials

The following materials were used: cement (C) complying with NP EN 197-1[12] (cement type I-42.5 R with specific gravity of 3.14), whose chemical composition and grading are provided in Tables 1 and 2, respectively; two mineral admixtures, FA complying with NP EN 450-1[13] and NP EN 450-2[14] with specific gravity of 2.30 and LF complying with LNEC specification E 466[15] with specific gravity of 2.72, whose chemical composition is summarized in Table 1 and 2, respectively; two limestone coarse aggregates complying with NP EN 12620[16], gravel 1 (C_{ag1}) with specific gravity of 2.59, D_{max} of 11 mm and water absorption of 1.46% and gravel 2 (C_{ag2}) with specific gravity of 2.64, D_{max} of 20 mm and water absorption of 0.78% (particle size distribution in Figure 1); two siliceous sands complying with NP EN 12620[16], one coarse 0/4 ($F_{ag0/4}$) with specific gravity of 2.55, fineness modulus of 3.70 and water absorption of 1.10% and one fine 0/1 ($F_{ag0/1}$) with specific gravity of 2.58, fineness modulus of 2.03 and water absorption of 0.70% (particle size distribution in Figure 1); a third-generation high-performance water-reducing admixture (S_p) complying with NP EN 934-1[17] and NP EN 934-2[18] (a modified polycarboxylic high-range water-reducing admixture in liquid form with a density of 1.07); tap water complying with NP EN 1008[19].

Table 1. Chemical composition of raw materials.

Chemical composition of raw materials [%]*	CEM I	FA	LF
Al_2O_3	5.24	24.70	0.13
$CaCO_3$	---	---	98.35
CaO (free)	0.81	0.30	---
CaO (total)	62.71	2.63	---
Cl^-	0.01	< 0.01	---
Fe_2O_3	3.17	5.40	0.03
K_2O	---	1.11	0.02
MgO	2.23	1.01	0.40
Na_2O	---	0.89	---
SiO_2	19.59	54.70	0.30
SO_3	3.13	1.38	---
TiO_2	---	---	0.01
Insoluble residue	1.37	---	---
Loss of ignition	2.94	5.10	43.80

*The data on this table corresponds to indicative values provided by the manufacturers.

Table 2. Grading of the raw materials.

Particle size, in microns*	Passing %		
	CEM I	FA	LF
1000	100	100	100
100	98	96	60
10	38	45	20
1	5	2	0
0.1	0	0	0
Specific surface area (Blaine) cm^2/g	3470	3210	4950

*The data on this table corresponds to indicative values provided by the manufacturers.

3.2. Test methods and sample preparation

3.2.1. Mini-cone slump-flow and Mini V-funnel tests for SCM

The determination of the slump-flow average diameter (D_m) through the mini slump-flow test[7] using a conical mould finds the G_m parameter ($G_m=(D_m/D_0)^2-1$).

The determination of the flow time (t) using the mini V-funnel[7] test allows calculating the Rm parameter ($R_m=10/t$).

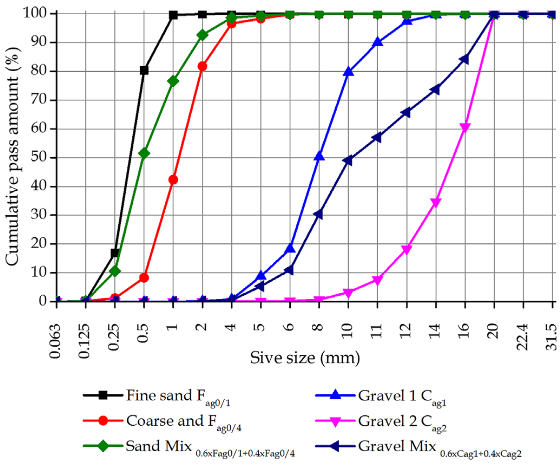


Figure 1. Particle size distribution of aggregates.

Since there are still no standard references for the tests in question, the test procedures used by Nepomuceno[5,7], based in turn on Okamura et al.[8] were followed.

3.2.2. Fresh state tests in SCC

In the case of SCC in the fresh state and according to NP EN 206-9[11], the tests were performed following these standards: for the slump-flow test NP EN 12350-8[20] and for the V-funnel test NP EN 12350-9[21], concerning filling ability; for the L-box test NP EN 12350-10[22] and for the J-ring test NP EN 12350-12[23], concerning passing ability; for the sieve segregation test NP EN 12350-11[24], concerning segregation resistance.

3.2.3. SCC Compressive strength test

The test procedure used to determine the compressive strength was that described in NP EN 12390-3[25]. This test was performed at 7, 28, 91 and 182 days on 150 mm cube specimens and 150 mm diameter × 300 mm high cylindrical moulds, which were kept in a wet chamber (20 ± 2 °C and RH $\geq$ 95%) after demoulding at 24 hours. The specimens were tested immediately after removal from the wet chamber. The test was performed on three specimens for each mix and test age with a 3000 kN hydraulic press and a loading rate of 0.6 ± 0.2 MPa/s (N/mm^2/s).

3.3. Experimental procedure

The mixes' proportions complied with the method presented by Nepomuceno[5], which had already been used in several works, on SCC[4,26-30].

The SCM was studied first to define the various mix parameters required to calculate the SCC mix proportions. In the ensuing SCC study, the coarse aggregate volume and the voids volume were defined, the proportions were determined and the experimental mixes produced.

The determination of the composition parameters in the mixes studied, to evaluate the variation of the unit percentile substitution of cement by admixtures, in volume, depended on the following conditions:

- The ratio, in absolute volume, between the total quantity of fine materials (cement and mineral admixtures) and of fine aggregates in the mix (V_p/V_s) was kept constant (0.80) for all mixes;
- the ratio, in absolute volume, between the total quantity of water and fine materials (V_w/V_p), and the percentage, in mass, of superplasticizer and fine materials in the mix ($S_p/p\%$) are varied as a function of the water and S_p needed in each mix to reach the required self-compactability parameters, based on experimental mixes in SCM according to the proposal of Nepomuceno[5];
- all binary mixes were produced so that the V_p/V_s, V_w/V_p e $S_p/p\%$ parameters respected the conditions previously mentioned, but with two distinct values of the ratio, in absolute volume, between the total quantity of mortar and coarse aggregate in the mix ($V_m/V_g = 2.125$ and $V_m/V_g = 2.625$); a constant value of the void volume ($V_v = 0.03$ m^3/m^3) was considered in the calculations.

For each SCC family produced, the V_p/V_s parameters and the two values of V_m/V_g were considered constant, which implies that: the total absolute volume of the coarse aggregates in the mix (V_g) is constant for each SCC family, thus: mixes with $V_m/V_g = 2.125$, $V_g = 0.31$, and mixes with $V_m/V_g = 2.625$, $V_g = 0.27$; the absolute volume of mortar in the mix (V_m) is constant for each SCC family, thus: mixes with $V_m/V_g = 2.125$, $V_m = 0.66$, and mixes with $V_m/V_g = 2.625$, $V_m = 0.70$.

3.4. SCM study

Under the Nepomuceno[5] method the various parameters needed to calculate the SCM mixes' proportions must be determined at this stage.

The value of V_p/V_s adopted was 0.80, thus meeting the requirement in Nepomuceno method that V_p/V_s should range from 0.60 to 0.80.

The next step is the determination of V_w/V_p and $S_p/p\%$. The values giving the target workability properties of the SCC are estimated through an iterative process of experimental SCM mixes (iterative process as shown in Figures 2 and 3) where these characteristics are quantified by means of a mini-cone and a mini V-funnel, thus the workability parameters are adjusted through the relative slump-flow area (G_m) and the relative flow velocity (R_m). Successive approximations to the target workability values can thus be obtained, namely, Slump-flow, using the slump-flow mini cone for mortars: D_m between 251 and 263 mm or G_m between 5.30 and 5.90, and Fluidity, using the mini V-funnel for mortars: t between 7.69 and 8.77 s or R_m between 1.14 and 1.30 s^{-1}.

Corrections are made to the parameters mentioned through an iterative process either by varying V_w/V_p and keeping the $S_p/p\%$ value constant or by varying the $S_p/p\%$ and keeping V_w/V_p constant. Successive approximations to the G_m and R_m target values of workability are thus obtained. This process is described in detail in several publications[4-7].

Table 3 shows the mix parameters obtained according to the method used, as well as the workability test results, showing the mix that reached the target values of R_m and G_m.

3.5. SCC study

Once the SCM study was concluded and the V_p/V_s, f_{ad} (percentage replacement of cement by additions), V_w/V_p and $S_p/p\%$ parameters established, the ratio, in absolute volume, between the mortar and the mix's coarse aggregates quantities (V_m/V_g) had to be estimated to allow the calculation of the SCC mixes' proportions.

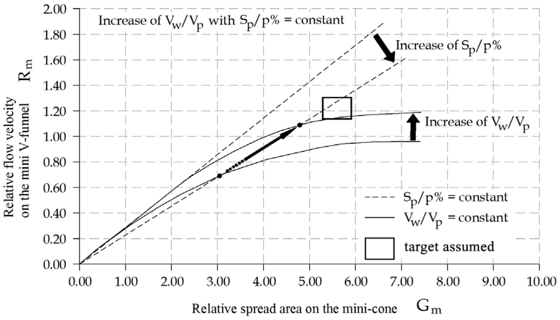


Figure 2. Changes in the workability parameters with the increase of V_w/V_p, keeping $S_p/p\%$ constant[5].

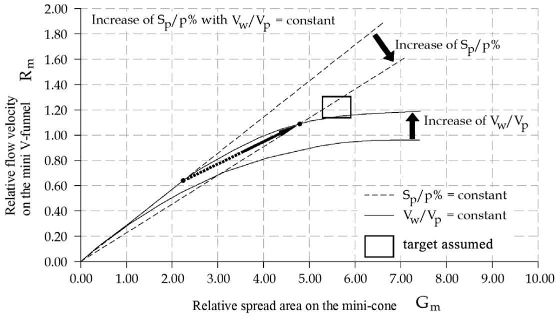


Figure 3. Changes in the workability parameters with the increase of $S_p/p\%$, keeping V_w/V_p constant[5].

The V_m/V_g ratio depends directly on the target degree of self-compactability, which is evaluated by the L-box test, for which the H_2/H_1 (≥ 0.80) parameter has to be obtained. According to Nepomuceno[5], for each combination of V_p/V_s and V_m/V_g there is a 'mix number' (MN) which represents the granular skeleton of the mix (MN = $(V_p/V_s) \times (V_m/V_g)$). Mixes with MN of 1.7 and 2.1 were produced. Considering a constant value of the V_p/V_s ratio (0.8), the mix parameter for the mixes with MN=1.7 is $V_m/V_g = 1.7/0.8 = 2.125$, and for the mixes with MN=2.1 it is $V_m/V_g = 2.1/0.8 = 2.625$. In practice, the mixes with MN=1.7 have a higher volume of coarse aggregate than the mixes with MN=2.1, i.e. less coarse aggregate and more mortar (as seen in § Experimental procedure).

With these proportions the mix was made so that the workability parameters could be tested and, if necessary, the superplasticizer proportions and water content readjusted.

Table 4 presents the SCC mixes' final proportions. The mix proportions in Table 4 were established by determining the ratios between the aggregates. The ratios between the coarse aggregates (C_{ag1} and C_{ag2}) and the fine aggregates ($F_{ag0/1}$ and $F_{ag0/4}$) were established with the goal of maximizing the compacity through the analysis of the reference mixes as well as the corresponding fineness modulus. The purpose was to minimize the voids between particles and optimize the ratios between the various aggregate types (the aggregates mixtures are represented in Figure 1).

Due to the extent of the experimental campaign, all parameters related to durability performance and mechanical properties are presented in detail in Silva & Brito[31,32].

4. Test Results and Discussion

4.1. SCM results

The final results for the mortar mixes' composition are presented in Table 3. Figure 4 shows that the V_w/V_p parameter decreases gradually with the increase of the percentage replacement of cement by additions (f_{ad}). This means that, for higher volume of additions and consequent lower cement volume, less water will be needed relative to the volume of fine materials to comply with the workability requirements

Table 3. Summary of the results obtained in the mortar study.

Mix	V_p/V_s	V_w/V_p	$S_p/P\%$	f_{ad} FA	f_{ad} LF	V_{sp}/V_p [m³/m³]	V_p [m³/m³]	V_w [m³/m³]	V_{sp} [m³/m³]	V_s [m³/m³]	W/C	W/CM	W/FM	G_m	R_m
SCM1.100C	0.80	0.84	1.05	0.0	0.0	0.031	0.320	0.269	0.010	0.401	0.268	0.268	0.268	5.55	1.21
SCM2.30LF	0.80	0.75	0.66	0.0	0.3	0.019	0.331	0.248	0.006	0.414	0.341	0.341	0.249	5.76	1.21
SCM2.60LF	0.80	0.71	0.43	0.0	0.6	0.012	0.337	0.239	0.004	0.421	0.565	0.565	0.246	5.76	1.17
SCM2.70LF	0.80	0.72	0.41	0.0	0.7	0.011	0.335	0.242	0.004	0.419	0.764	0.764	0.253	5.76	1.29
SCM3.30FA	0.80	0.80	0.70	0.3	0.0	0.019	0.326	0.261	0.006	0.407	0.364	0.277	0.277	5.58	1.14
SCM3.60FA	0.80	0.78	0.58	0.6	0.0	0.014	0.328	0.256	0.005	0.411	0.621	0.296	0.296	5.50	1.18
SCM3.70FA	0.80	0.77	0.57	0.7	0.0	0.014	0.330	0.254	0.004	0.412	0.817	0.302	0.302	5.40	1.25
SCM4.10FA20LF	0.80	0.78	0.67	0.1	0.2	0.019	0.328	0.256	0.006	0.410	0.355	0.321	0.262	5.48	1.17
SCM4.20FA10LF	0.80	0.78	0.68	0.2	0.1	0.019	0.328	0.256	0.006	0.410	0.355	0.293	0.266	5.89	1.15
SCM5.20FA40LF	0.80	0.71	0.48	0.2	0.4	0.013	0.336	0.239	0.004	0.421	0.565	0.414	0.253	5.68	1.17
SCM5.40FA20LF	0.80	0.75	0.48	0.4	0.2	0.012	0.332	0.249	0.004	0.415	0.597	0.345	0.276	5.55	1.15

f_{ad} = percentage of replacement of cement with additions; V_{sp} = total content of superplasticizer in absolute volume; V_p =, total content of fine materials in absolute volume (cement and mineral admixtures); V_w = total content of water in absolute volume; V_s = total content of fine aggregates in absolute volume.

Table 4. Mix proportions of SCCs.

Mix proportions [1 m^3]	CEM I	FA	LF	S_p	W	$S_{0/1}$	$S_{0/4}$	G_1	G_2	W/C	W/MC	W/MF
	[kg]	[kg]	[kg]	[kg]	[l]	[kg]	[kg]	[kg]	[kg]			
SCC1.100C(1.7)	664	---	---	7.0	178	409	270	484	328	0.27	0.27	0.27
SCC1.100C(2.1)	707	---	---	7.4	189	436	287	417	283			
SCC2.30LF(1.7)	480	---	178	4.3	164	423	279	484	328	0.34	0.34	0.25
SCC2.30LF(2.1)	512	---	190	4.6	175	450	297	417	283			
SCC2.60LF(1.7)	279	---	362	2.8	158	430	283	484	328	0.57	0.57	0.25
SCC2.60LF(2.1)	297	---	386	2.9	168	457	301	417	283			
SCC2.70LF(1.7)	208	---	421	2.6	159	428	282	484	328	0.76	0.76	0.25
SCC2.70LF(2.1)	222	---	449	2.7	170	456	300	417	283			
SCC3.30FA(1.7)	472	148	---	4.3	172	416	274	484	328	0.36	0.28	0.28
SCC3.30FA(2.1)	503	158	---	4.6	183	443	292	417	283			
SCC3.60FA(1.7)	272	299	---	3.3	169	419	276	484	328	0.62	0.30	0.30
SCC3.60FA(2.1)	290	318	---	3.5	180	447	294	417	283			
SCC3.70FA(1.7)	205	350	---	3.2	167	421	277	484	328	0.82	0.30	0.30
SCC3.70FA(2.1)	218	373	---	3.4	178	448	295	417	283			
SCC4.10FA20LF(2.1)	506	53	125	4.6	180	446	294	417	283	0.36	0.32	0.26
SCC4.20FA10LF(2.1)	506	106	63	4.6	180	446	294	417	283	0.36	0.29	0.27
SCC5.20FA40LF(2.1)	297	109	257	3.2	168	457	301	417	283	0.57	0.41	0.25
SCC5.40FA20LF(2.1)	293	215	127	3.0	175	451	297	417	283	0.60	0.35	0.28

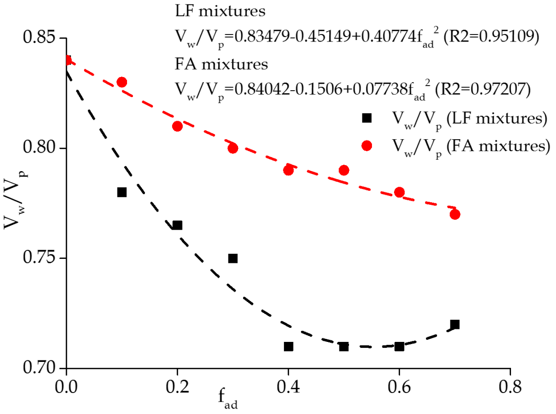


Figure 4. Correlation between V_w/V_p (ratio, in absolute volume, between the total quantity of water and fine materials) and the f_{ad} (percentage replacement of cement by additions).

for mortars (G_m and R_m parameters), which guarantee the self-compactability of the corresponding SCC.

In general, it is found that the V_w/V_p parameter, crucial to setting the water volume for the mix, varies between 0.71 and 0.84. The highest value (0.84) was found for the mix with cement only (SCM1). The use of LF in the binary mixes led to a greater reduction of the water needed compared with the use of FA. In the SCM2 mixes (with LF), the V_w/V_p ratio varies between 0.71 and 0.75, while in the SCM3 mixes (with FA), it varies between 0.77 and 0.80.

Regarding the ternary mixes, the V_w/V_p ratio variation behaves in line with that of the binary mixes with equivalent f_{ad}. For example, for the SCM4 mixes (with global f_{ad} of 30%), this parameter has a value of 0.78, between the 0.75 of SCM2 (with LF) and the 0.80 of SCM3 (with FA).

The $S_p/p\%$ parameter varies in the same way as the V_w/V_p ratio, but with quite distinct orders of magnitude (Figure 5), with the percentage of S_p decreasing significantly for higher f_{ad}. Consequently, a lower S_p was needed relative to the mass of the fine particles in the mix to achieve the target workability requirements, according to Nepomuceno[5].

In general, the $S_p/p\%$ parameter, which determines the quantity of S_p in the mix, varies between 0.41% and 1.05% of the fine materials' mass. Naturally the highest value (1.05%) is for the SCM1 mix (with cement only). As seen for the V_w/V_p ratio, the lower $S_p/p\%$ values are obtained in the binary mixes with LF (SCM2). Therefore, the SCM2 mixes (with LF) only need an S_p between 0.41% and 0.66% of the fine materials' mass, while the binary mixes with FA (SCM3) require slightly higher values, between 0.57% and 0.70%, but still less than those required by the SCM1 mix (with cement only).

The $S_p/p\%$ parameter values for the ternary mixes are perfectly in line with those for the binary mixes with equivalent f_{ad}. The values for the SCM4 mixes (with global f_{ad} of 30%) are between 0.67% and 0.68% in comparison with 0.66% for the SCM2 (with f_{ad} 30% of LF) and 0.70% of the SCM3 (with f_{ad} 30% of FA). Similarly, the SCM5 mix (with global f_{ad} of 60%) has a value of 0.48% in comparison with 0.43% of SCM2 (with f_{ad} 60% of LF) and 0.58% of SCM3 (with f_{ad} 60% of FA).

The V_w/V_p values determined in this work are of a very similar order of magnitude to those reported by Nepomuceno[5-7]. Note the value of 0.86 for the V_w/V_p ratio given by the author for a mix equivalent to SCM1 (with cement only) compared with our value of 0.84. For the mix with f_{ad} of 30% of FA, these authors obtain a V_w/V_p ratio of 0.75 compared with our value of 0.80. Lastly, attention is drawn to a V_w/V_p of

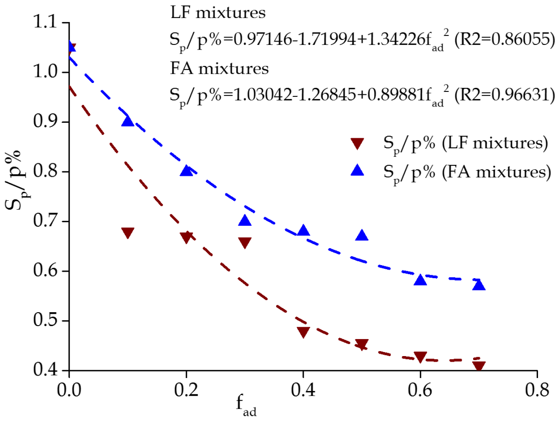


Figure 5. Correlation between $S_p/p\%$ (percentage, in mass, of superplasticizer and fine materials in the mix) and the f_{ad} (percentage replacement of cement by additions).

0.70 in Nepomuceno work[5-7] for the mix equivalent to SCM2 (with 60% LF), compared with 0.71 in our work.

Similarly, Silva et al.[4], using Nepomuceno method, obtained a V_w/V_p ratio of 0.77 for the binary mix of f_{ad} 30% of LF and of 0.70 (with CEM II/B-L 32.5N), compared with 0.75, and a V_p/V_s ratio of 0.80, in our work. Franco et al.[27] also used Nepomuceno method and obtained values of 0.70 for V_w/V_p (the same as in Nepomuceno[5-7]) for the mixes with f_{ad} 60% of LF, compared with 0.71 in our work. António et al.[28] used the same method to produce SCC but incorporating a waste fluid catalytic cracking catalyst. In their control concrete with 100% of cement, equivalent to our SCM1, they got a V_w/V_p value of 0.82, compared with the 0.86 reported by Nepomuceno[5] and 0.84 in our work.

Regarding the $S_p/p\%$ parameter, there are great discrepancies between the various works consulted for the mixes mentioned above. Clearly this value is directly associated with the quality of the superplasticizer itself, enabling the various S_p values used by the authors of these works to be checked from the original work of Nepomuceno[5] until today. In his original work Nepomuceno had an $S_p/p\%$ value of 3.25% for the mixes with 100% cement, compared, for example, with 1.80% reported by António et al.[28] or 1.05% in our work for equivalent mixes, all with different S_p values. There are also $S_p/p\%$ values of 2.50% for the mixes with f_{ad} 30% of FA, obtained by Nepomuceno[5], compared with the 0.70% we found. The same author also reported $S_p/p\%$ values of 0.80% for mixes with f_{ad} 60% of LF, compared with our figure of 0.41% and the even lower value of 0.30% given by Franco et al.[27]. Lastly, Silva et al.[4] report a $S_p/p\%$ of 1.30% for mixes with f_{ad} 30% of LF and V_p/V_s of 0.70 (with a CEM II/B-L 32,5N), compared with our findings of 0.66% and V_p/V_s of 0.8, with various S_p values.

Regarding the variability of the results published on SCM in the fresh state, one should highlight that the variation coefficient of all the individual readings of the various tests performed vary between 3.87% and 13.05% with an average value of approximately 8.28%, indicating that, in general, the results scatter is small and that the values obtained are perfectly within the variation intervals found in the literature.

4.2. SCC fresh state results

Table 4 shows the mix proportions of the SCCs produced based on the parameters presented in Table 3. Figure 6 show the average values obtained in the various tests in the fresh state with the corresponding minimum and/or maximum limits marked according to NP EN 206-9[11].

In terms of both slump-flow time (t_{500}) and diameter, the results of all mixes can be considered satisfactory. In general, distribution of the coarse aggregate was good and no bleeding or segregation occurred. The presence of coarse aggregate can also be observed for the slump-flow limit.

The majority of the mixes belong to slump flow class SF2 and the rest are very close to the class limits. As for slump-flow time, all mixes fall in the VS2 class with all results below 4 seconds. There is a slight increase of the slump-flow time with the use of LF and FA and for higher f_{ad} values, but this increase is not matched by an increase of the slump-flow diameter.

The average values for the V-funnel (Figure 6) allow evaluation of the SCCs' ability to pass through small openings. It is concluded that the average values for all mixes are within the reference values provided in NP EN 206-9[11], ranging generally between 7 s and 13 s, with most classified as class VF2 (t_v between 9 s and 25 s) and the rest as VF1 ($t_v < 9$ s).

Observation of the test showed that the coarse aggregate did not become blocked in the narrow passage and was present at the top of the mould (before opening the sliding gate) and that no bleeding occurred. The concrete continued to look like a uniformly distributed bulk after the test.

The joint analysis of the slump-flow and V-funnel tests indicates that all mixes showed cohesion and had a viscous appearance but did not lose their capacity to deform. The results of the L-box and J-ring tests corroborate this.

The average values for the flow time in the L-box test confirm the filling capacity, the resistance to blocking and the resistance to segregation. The stability of the sample could be checked visually at the end of the test. The average values obtained for all mixes are very well balanced, with only a small decrease in the H_2/H_1 in the mixes with FA, mainly for values of f_{ad} of 60% and 70%, and still without any bleeding and segregation. For this test (L-box), the lowest reference limit of H_2/H_1 in NP EN 206-9[11] is 80%. The results in our study comply with the standard[11], ranging from 79% in the mixes with FA to 90%.

The results of the segregation test are also presented in Figure 6 and are in line with the reference values in NP EN 206-9[11], i.e. always below 20%. In general, the binary mixes with FA (SCC3 with f_{ad} of 70%) and the ternary mixes belong to class SR2, i.e. they are less prone to segregation. The remaining mixes fall in the SR1 class, i.e. higher probability of segregation. Nevertheless, the propensity to segregation and/or bleeding was slight in all SCCs produced.

The results obtained in the J-ring test concerning the passing ability reveal that all the mixes fall within class PJ2, with all values below 10 mm, indicating a good passing ability. In general, the lower results (< 5 mm) were obtained for the SCC1 mixes (with cement only) and the ternary mixes.

For all mixes the relationship between the values in the slump-flow and the V-funnel tests are shown in Figure 7a. Self-compactability was reached with SF values between

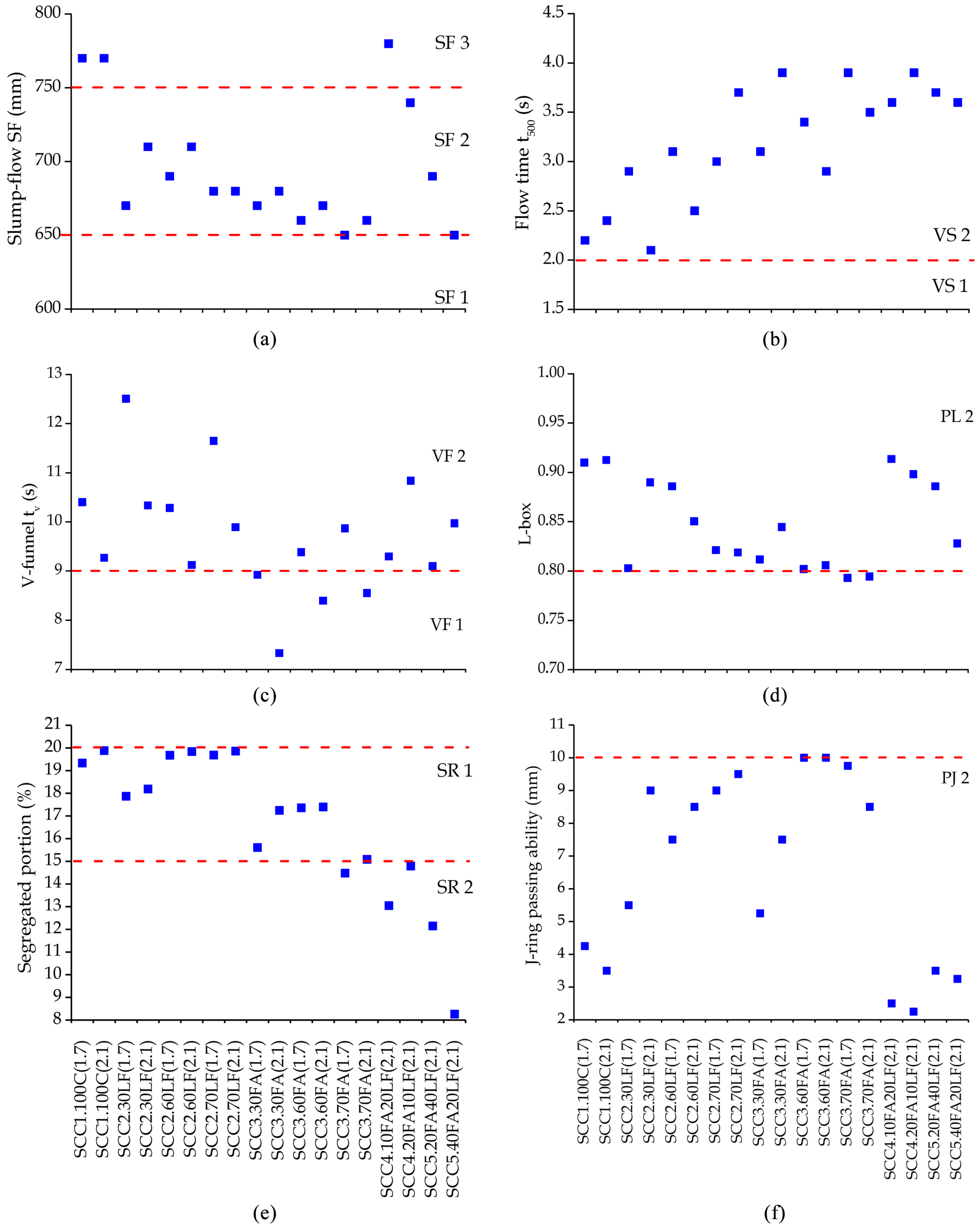


Figure 6. Slump-flow (SF and t_{500}), V-funnel (t_v), L-box (H_2/H_1), Segregation and J-ring (passing ability) tests results.

650 mm and 750 mm (except for the SCC1 and SCC4 mixes, where values were between 740 mm and 780 mm, which are still acceptable) and t_v values between 7 s and 13 s. From the Figure 7a we can conclude that the 'target' properties for the behaviour of fresh SCM defined by Nepomuceno[5-7] are adequate to obtain the self-compactability properties intended for a SCC.

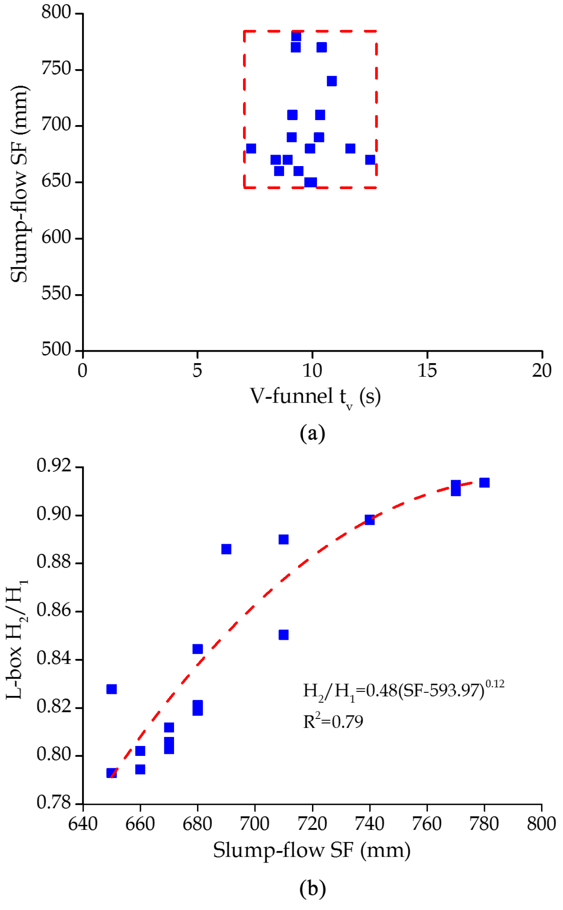
According to Walraven[33], the L-box results indirectly reflect the slump-flow value. Therefore, the Figure 7b shows an increase in the value of H_2/H_1 with the increase of slump-flow. Further joint analysis of the figures presented in Table 4 and Figure 6 shows an increase, albeit small, of H_2/H_1 with a decrease of the volume of coarse aggregate in the mixes and the consequent increase of the paste volume (mixes MN=1.7 vs. MN=2.1). In general there is no correlation between H_2/H_1 and the V-funnel flow results, although within mixes produced from the same SCM but with distinct MN there is an - expected - slight decrease of the V-tunnel flow time for the mixes with a lower volume of coarse aggregate and consequent larger volume of paste.

Regarding the results variability related to the study of SCC in the fresh state, one should highlight that the variation coefficient of all the individual readings of the different tests performed vary between 6.20% and 17.06% with an average value of approximately 9.06%, indicating that, in general, the results scatter is small and that the values obtained are perfectly within the variation intervals found in the literature.

4.3. SCC compressive strength

The results regarding the average compressive strength of the mixes studied show generally acceptable standard deviations and variability coefficients. One should, therefore, highlight the existence of scatters which are slightly higher than normal in the results at 7 days of the mixes SCC1 (21.73%) and, at 28 and 91 days, of SCC2.60LF.1.7 and 2.1 (14.07% and 13.92% respectively). On the other hand, at 182 days, the larger variation coefficient (8.86%) occurs in mix SCC2.30LF.2.1, which still represents an acceptable results scatter. The average variation coefficients obtained for each of the SCC are of 7.08%, 4.63%, 3.27%, 5.15% and 2.63% for the mixes SCC1, SCC2, SCC3, SCC4 and SCC5, respectively, indicating that, in general, the results scatter is significantly small.

Figure 8 shows the evolution of compressive strength ($f_{cm,c}$) over time for all SCC produced and it shows a more pronounced growth of compressive strength in the early ages



(a)

(b)

Figure 7. Slump-flow/V-funnel (a) and L-box/slump-flow correlations (b).

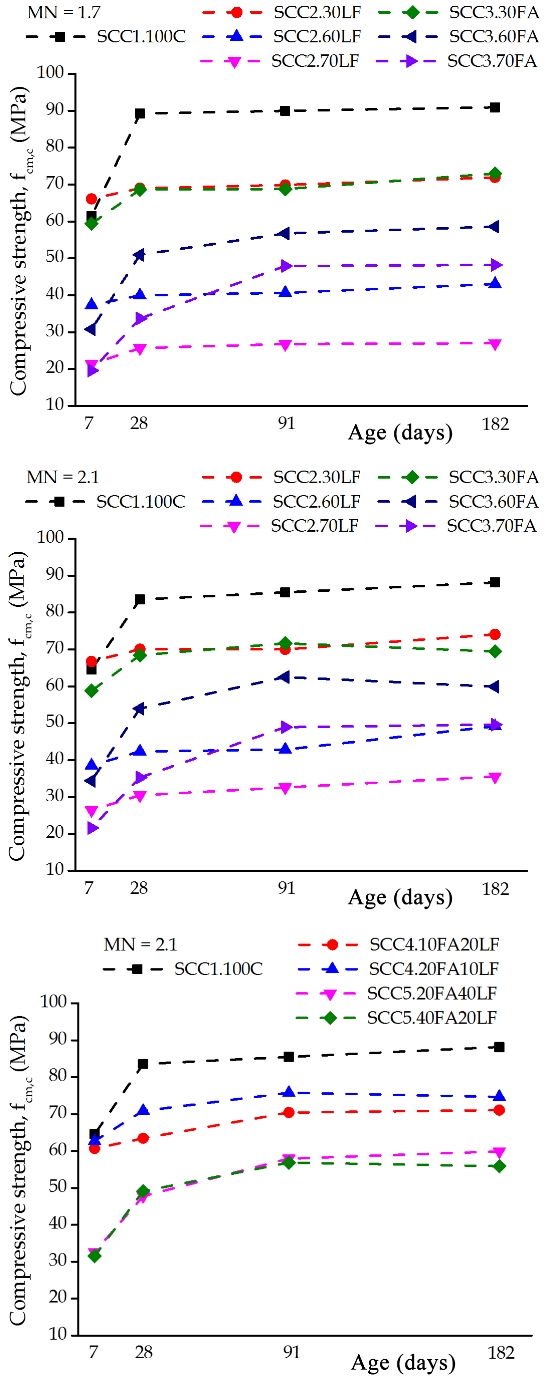


Figure 8. 7, 28, 91 and 182-day compressive strength of binary and ternary mixes.

(7 days) in binary mixes with LF. Binary mixes with FA show a more gradual evolution of the compressive strength as it continues to grow beyond the early ages. The variations mentioned also happen in ternary mixes where those with f_{ad} of 60% have a more gradual and continuous growth than the more pronounced initial growth of those with f_{ad} of 30%. As expected, the mixes with 100% cement behave differently from the others, growing sharply until 28 days and then stabilizing until the last test age (182 days).

Both binary and ternary mixes show a decrease in compressive strength for higher replacement ratios of the additions (f_{ad}), which is mainly due to the dilution effect as the Portland cement content is reduced. In the particular case of FA, the evolution of the compressive strength for higher f_{ad} levels is even slower, mainly at the younger ages, but it stabilizes at 91 days. The compressive strength values of the SCC3.FA mixes compared with those of the SCC1.100C mixes agree with expectations. Considering the lower initial evolution of the SCC3.FA mixes (and because the delaying effect of the FA pozzolanic behaviour limits the FA's contribution to compressive strength to the filler effect at those initial ages), it is expected that at older ages and for f_{ad} levels lower than approximately 30%, the compressive strength should evolve more significantly, and in certain cases even reach values the same as or even higher than the corresponding values in SCC with 100% cement. This behaviour is mentioned by a number of authors for conventional concrete who note that the optimal content of FA substitution for C is lower than 20-30%[34,35].

The values presented in Figure 9 demonstrate that the correlations obtained in our work follow the same trend as those obtained by Nepomuceno[5-7] and that the differences found are perfectly acceptable. The binary mixes with FA exhibit values of $f_{cm,c,28d}$ closer to those predicted by Nepomuceno[5] with any differences being below 10%. Within the binary mixes with FA the ones with f_{ad} of 60% stand out, with values of $f_{cm,c,28d}$ only 2% different from the one predicted by Nepomuceno[5]. The results of the binary mixes with LF are the ones furthest from those predicted, exhibiting differences of approximately 30% in the mixes with f_{ad} of 60% and 70%, and 11% for the mixes with f_{ad} of 30%. Lastly, the differences between the correlations obtained with the ternary mixtures and those of Nepomuceno[5] vary by between 7% and 14%. The ternary mixes with a global f_{ad} of 30% show very similar behaviour to that of the binary mixes with the same f_{ad}, while the ternary mixes with global f_{ad} of 60% are closer to the values of Nepomuceno[5], and to those of the binary mixes with FA.

Figure 10 presents the evolution of the compressive strength of the SCC produced, using the hardening coefficient (C_{hard}), i.e. the correlation $f_{cm,c,id}/f_{cm,c,28d}$ (average compressive strength at age i/average compressive strength at 28 days). Both the C_{hard} values of the SCC and the C_{hard} values for the compressive strength, determined according to Equation 2 suggested in Eurocode 2[36] for CC are presented.

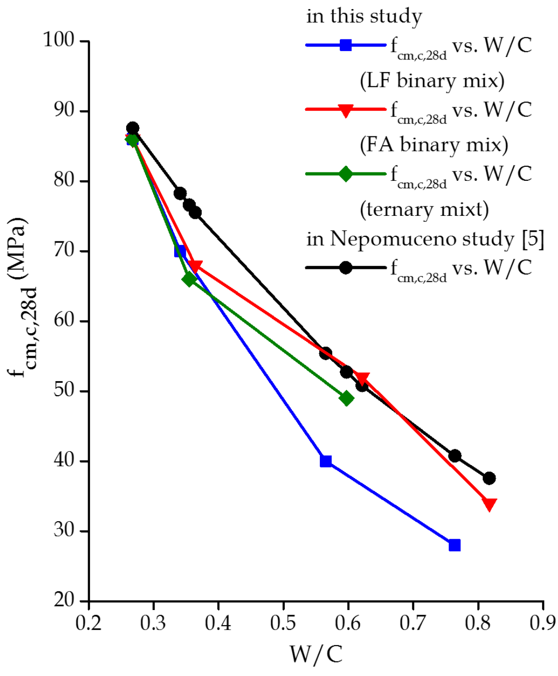


Figure 9. Correlation between $f_{cm,c,28d}$ and the W/C ratio of the SCC produced and the values proposed by Nepomuceno[5].

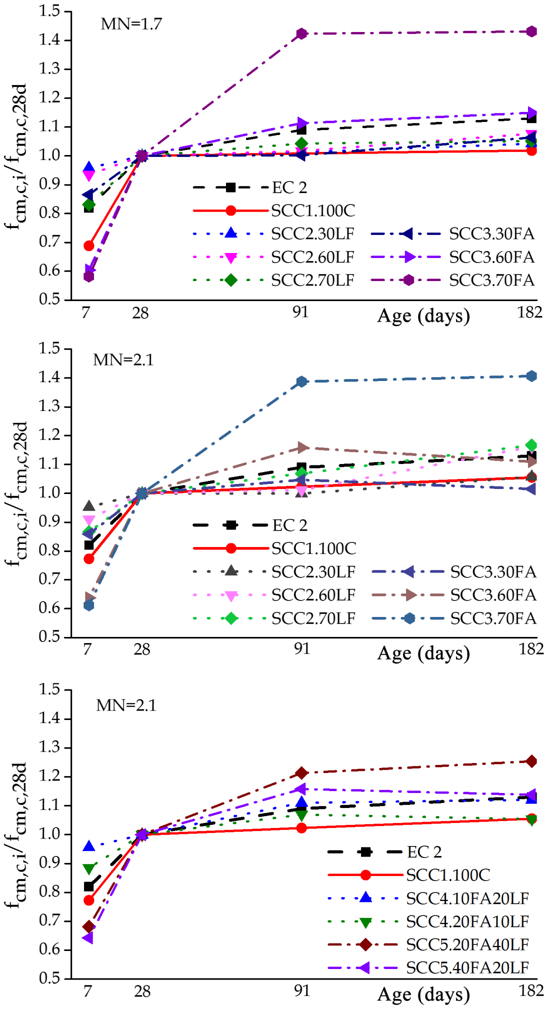


Figure 10. Concrete hardening coefficients of binary and ternary mixes.

$$f_{cm,id} = \beta_{cc,i}\, f_{cm,28d} \quad (1)$$

With:

$$\beta_{cc,i} = \exp\left[S\left(1-\sqrt{\frac{28}{i}}\right)\right] \quad (2)$$

Where: $\beta_{cc,i}$ = coefficient that depends on concrete age; S = coefficient that depends on cement type (0.20 for cement of strength classes CEM 42.5 R, CEM 52.5 N and CEM 52.5 R; 0.25 for cement of strength classes CEM 32.5 R and CEM 42.5 N; 0.38 for cement of strength class CEM 32.5 N).

Comparison of the hardening coefficients of the SCC produced with those obtained through the compressive strength evolution models suggested in Eurocode 2[34] for CC shows the SCC2.LF mixes have the most similar behaviour and the SCC3.FA the most distinct behaviour. For FA, C_{hard} values at 7 days are lower than those determined by the Eurocode 2 proposal (except for the mixes with 30% f_{ad}). After 28 days, the C_{hard} values vary depending on the f_{ad} value. For FA mixes with 30% f_{ad}, the C_{hard} value was below the one proposed by Eurocode 2. For mixes with 60% f_{ad}, the values are of the same magnitude and, for mixes with 70% f_{ad}, the values are significantly higher, with an increase of approximately 40% at 91 days relative to the 28-day compressive strength.

The C_{hard} values of the ternary mixes are higher at 7 days for SCC4 mixes and of the same magnitude after 28 days, compared with the compressive strength evolution models in Eurocode 2. For SCC5 mixes they are lower at 7 days and the same or even slightly higher than those of the model after 28 days.

The changes in the hardening coefficients presented here are confirmed by Holschemacher & Klug[37], where there is a scatter of the C_{hard} values for both the SCC2 and the SCC3 mixes at 7, 28 and 91 days, very similar to our results.

A relationship was found between the compressive strength results for 150 mm diameter × 300 mm tall cylinders and 150 mm cubes (Figure 11), as expected. The conversion factor is approximately 0.80 (leaving out factor "a" of the linear relationship obtained $y = a + b \cdot x$) and agrees with the values presented in NP EN 206-1[38] for CC that vary between 0.80 (class C16/20) and 0.82 (class C70/85).

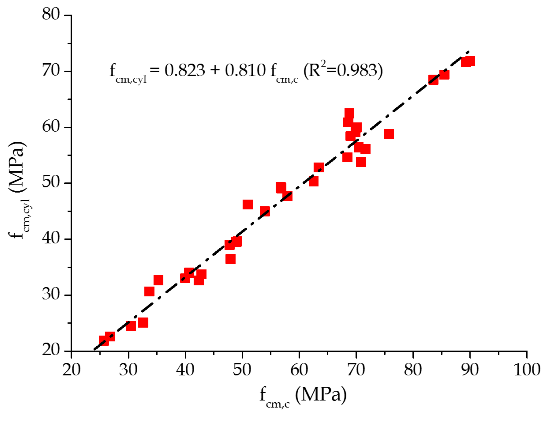


Figure 11. Overall relationship between average compressive strength in cubic and cylindrical specimens.

5. Conclusions

With the study of SCC using SCM, without the coarse aggregate, it is possible to significantly reduce the iterations that would be necessary if the composition were studied using SCC alone. The greater ease and simplicity of the SCM study should be stressed, too. In this approach, the behaviour of fresh SCM, which is correlated with the defined rheological parameters, is used to simulate and reach target ranges of fresh SCC behaviour.

In general, our results indicate that, in the absence of segregation, bleeding and blocking of the SCM mixes, the values established by Nepomuceno for the variation ranges of the mini slump-flow diameter and the mini V-funnel flow time parameters can be considered adequate to obtain self-compacting mixes.

The results confirm that using mineral admixtures such as LF and FA in binary and ternary mixes improves the workability of SCC. In general, it was found that the use of LF led to a slight greater reduction of the need for both water and superplasticizers to comply with the SCM workability requirements that ensure self-compactability of the related SCC, compared with FA. The ternary mixes show water and superplasticizer consumption values that are perfectly in line with those obtained in the binary mixes with equivalent f_{ad}. The use of ternary mixes turned out to be more advantageous to the behaviour of hardened SCC.

Regarding the SCCs produced, it was found that all mixes reached the workability parameters required to be classified as self-compacting according to European standards. The SCCs had adequate filling and passing ability as well as good resistance to segregation. The observations on SCM are equally valid for SCC. In this phase (SCC) only the V_m/V_g parameter was considered, with the goal of accounting for the volume of coarse aggregate. The quantification of the volume of coarse aggregate using the V_m/V_g parameter, through the definition of the MN, turned out to be adequate; according to expectations, slight differences were observed in the fresh state behaviour of the SCCs with a higher volume of coarse aggregate (mixes with MN = 1.7) and the SCCs with a lower volume of coarse aggregate (MN = 2.1).

The results of compressive strength allowed concluding that, even for higher level of f_{ad}, it is possible to obtain reasonable strength values within those expected. The results also demonstrate that partially replacing cement with LF accelerates the hydration process and causes an increase in compressive strength at young ages. FA retards the development of the compressive strength of SCC, despite the fact that at more advanced ages these mixes reach higher strengths than those of the mixes with LF. This effect is essentially due to the pozzolanic reactions of FA being slower than the cement hydration. The ternary mixes show an extremely favourable behaviour, with very satisfactory strength values right at the earliest ages, compared with the binary mixes. This behaviour is usually attributed to a synergetic effect between the mineral admixtures. This more pronounced synergy between LF and FA can be attributed to the formation of more aluminates and less ettringite owing to the presence of FA (relative to concrete without FA). The presence of LF (in the mix FA + C) will cause a less marked impact of the FA effect and more ettringite will be available. As a consequence, a higher total hydrates volume, a decrease in porosity and an increase in mechanical strength are obtained.

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