Electrical resistivity and capillarity of self-compacting concrete with incorporation of fly ash and limestone filler

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Abstract. Electrical resistivity is a property associated with both the physical and chemical characteristics of concrete. It allows the evaluation of the greater or lesser difficulty with which aggressive substances penetrate the concrete's core before the dissolution of the passive film process and the consequent reinforcement's corrosion begin. This work addresses the capillary absorption of self-compacting concrete (SCC) with various types and contents of additions, correlating it with its electrical resistivity. To that effect, binary and ternary mixes of SCC were produced using fly ashes (FA) and limestone filler (LF). A total of 11 self-compactable mixes were produced: one with cement (C) only; three with C + FA in 30%, 60% and 70% substitution ratios; three with C + LF in 30%, 60% and 70% substitution ratios; four with C + FA + LF in combinations of 10-20%, 20-10%, 20-40% and 40-20% substitution ratios, respectively; and four reference mixes according to the LNEC E 464 specification, which refers to the NP EN 206-1 norm. The evaluation of the capillarity of the mixes produced was made through the determination of the water absorption by capillarity coefficient according to the LNEC E 393 specification. The electrical resistivity was evaluated using the European norm proposal presented by the EU-Project CHLORTEST (EU funded research Project under 5FP GROWTH programme) and based on the RILEM TC-154 EMC technical recommendation. The results indicate that SCC's capillarity is strongly conditioned by the type and quantity of the additions used. It was found that FA addition significantly improves some of the properties studied especially at older ages.

Keywords: additions; capillarity water absorption; compressive strength; durability; electrical resistivity; self-compacting concrete

1. Introduction

The study and consequent development of self-compacting concrete (SCC), which has been going on all over the world, began in Japan in the 1980's. The main motivation for the study of this type of concrete is associated with concerns relating to the lack of homogeneity and consequent lack of durability of the reinforced concrete structures, which began occurring in Japan. With the reduction of specialised labour in the construction sector and considering that a correct casting of conventional concrete (CC) in the moulds depends, among other factors, on adequate compacting,

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there was a need for concrete allowing correct application without compromising the structures' durability independently of the degree of labour specialization. Thereby studies to obtain a SCC that was able to comply with the required characteristics started (Okamura *et al.* 2000).

Nowadays, SCC's main characteristics, both in the fresh and the hardened state, as well as its economic potential and the improvement of the construction process itself and of the working conditions, leads to an increased use of this material in the pre-casting industry and in that of ready mix concrete.

Due to the necessary changes needed to obtain the stated self-compatibility (increased / improved workability, passing ability and segregation resistance), that is, needed to eliminate the compacting process, the impact of the SCC use is essentially related to the production process, with the concrete casting at the work site and with the changes related to the constituent materials, namely:

• Decrease of the ratio between the quantities of course aggregate and mortar;
• Consequent increase of the mortar volume (more ultra-fine material like cement and additions);
• Adequate control of the aggregates' maximum dimension;
• Use of chemical admixture such as super-plasticizers and/or viscosity modifying agents.

Despite the requirements in terms of the SCC's properties in the hardened state being the same as those for a CC, the cement paste's contents used as well as the proportions in which the different components are combined are different. In that sense, it is possible to state that its properties in the hardened state concerning durability may vary and are still a little uncertain (Zhu and Bartos 2003, Boel *et al.* 2007).

The use of higher contents, both of chemical admixtures and ultra-fine material, necessarily implies a higher cost per m^3 of SCC when compared to CC and that cost, in numerous applications, is compensated only by the reduction of the labour costs (Silva *et al.* 2008). Nevertheless, the use of additions such as limestone filler (LF), fly ashes (FA), among others, in partial substitution of cement may contribute to a reduction of the SCC costs, as well as to an improvement of its behaviour, both in the fresh and the hardened state.

There are numerous studies on the use of additions in SCC with indications/proposals on the optimal/recommended replacement ratios (f_{ad}). Nowadays it is common to have f_{ad} values higher than 30% and, in some cases, reaching up to 70-80% (Khatib 2008, Ramezanianpour *et al.* 2009, Khokhar *et al.* 2010, Isaia *et al.* 2012).

The use of additions such as LF and FA in the production of SCC has increased significantly in recent years. It is expected that it will continue to increase, with numerous advantages, not only in economic terms but also in the SCC behaviour in the fresh and hardened state.

Properly knowing the effect of additions used in SCC is of extreme importance, mainly when high replacement percentages are commonly used. As for CC, it is important to know the behaviour of SCC whose use in more aggressive environments requires an adequate control of its physical and chemical properties to ensure the resistance to the penetration of aggressive substances (pure water or aggressive ions, CO_2 and oxygen, as the ruler of all corrosion reactions of the steel embedded in the concrete).

The penetration of the above mentioned aggressive substances is a complex process that involves several phenomena such as diffusion, capillarity and permeation (which may occur isolated or simultaneously).

SCC's capillarity in aggressive environments strongly influences the degradation mechanisms,

and a correlation can be found between pores structure; transportation mechanisms and degradation mechanisms. The pores structure is one of the factors that condition SCC's capillarity the most.

In that sense, the study of concrete's durability, namely the effect of its pores structure in its capillarity, as well as its diffusion, has an increased importance, not only from the point of view of the concrete structures service conditions through the corresponding maintenance and reparation costs but also from the point of view of the design and capacity to predict its service life regarding the action of the aggressive substances.

As previously mentioned, the SCC's specificity in terms of its formulation (higher paste volume, use of additions and admixtures) will necessarily cause differences in its capillary absorption when compared to a CC. The capillary water absorption, in the dry concrete in general, directly depends on its open porosity, its absorption rate by capillarity and its concrete relative humidity.

In that sense, Zhu *et al*. (2001) found capillary absorption values for SCC lower than those for CC, highlighting that the use of additions, such as LF and FA, causes an even higher decrease of absorption. Nevertheless, Boel *et al*. (2002) present very similar values of absorption by capillarity, between the SCC and the CC produced in their work. They also highlight that the capillary absorption increases with the W/C ratio, essentially due to the higher number of pores and to their larger size, for higher values of W/C. Like Zhu *et al*. (2001), Boel *et al*. (2002) refer the advantage of using LF as an addition in the SCC behaviour relative to capillary absorption.

Several authors highlight the contribution of additions, such as LF and FA, to the improvement of the capillary absorption as a transport mechanism. Mnahoncákováa *et al*. (2008) studied different properties of SCC produced with LF and FA and concluded that both produce favourable capillary water absorption coefficients. Nevertheless, the coefficient mentioned for SCC with FA was approximately four times lower than for SCC with LF. Sahmaran *et al*. (2009) presented coincident results. The authors evaluated the capillary water absorption coefficient, among other durability parameters, of several SCC produced with FA f_{ad} between 30% and 70% at several ages and concluded that the high volume of FA is beneficial in terms of durability, and obtained significant improvements as the test age increased. In the same research path, Liu (2010) studied the durability of several SCC incorporating up to 80% of FA in replacement of cement, in mixes designed to maintain the same behaviour in the fresh state. The author mentions that the capillary absorption decreased gradually with the increase of the value of f_{ad} up to 40%, and increased considerably from there on, and that, for all the mixes, the mentioned coefficient decreased as the test age increased.

Another test also used as an indirect form of evaluating concrete's durability in general but, in a way, correlated to the diffusion phenomenon, is the electrical resistivity test. The electrical resistivity is a property which characterises the higher or lower difficulty of the ions to move in the concrete's core, that is, it controls the ion flux in aqueous solution in the concrete's pores. The most common ions are associated with the deterioration mechanism by penetration of chloride ions (Lübeck 2008).

The electrical resistivity depends on the same properties that the control concrete's pores microstructure. All the changes of those properties, which result in changes in size and distribution of the concrete's pores, together with the variation of its humidity content and the curing conditions to which it is subjected, among others, affect the concrete's electrical resistivity, namely:

• The reduction of the W/C ratio causes an increase in the concrete's electrical resistivity

through the improvement of pore structure due to the reduction of the permeability and consequently makes ionic mobility more difficult (Nagi 2004);
• With the increase of the cement consumption (for the same W/C ratio), there is a reduction of the electrical resistivity, which is a function of the increase of the electrolyte's volume and higher ion concentration in it (Neville 1995);
• With the increase of the aggregate's volume in the mix, the electrical resistivity will tend to increase essentially due to the ascendancy of the paste matrix in the property mentioned, that is, the larger volume of aggregate implies less paste and consequently less "space" for ionic mobility (Shi 2004);
• The use of chemical admixtures does not directly change the concrete's electrical resistivity (Neville 1995), nevertheless, by its use, given that it causes a reduction in the W/C ratio, it is possible to state that indirectly it will cause an increase of the electrical resistivity (Whiting and Nagi 2003);
• The use of mineral additions, until given values of f_{ad}, changes the paste's microstructure, improving the behaviour of the concrete's pore structure and hindering ion mobility in the solution that fills the pores; consequently, its use up to given f_{ad} values increases the concrete's electrical resistivity (Hassan *et al.* 2009, Lübeck *et al.* 2012);
• Concrete's electrical resistivity tends to increase with the hydration process, provided that it is subjected to an adequate curing, due essentially to the influence of the curing process in the development of the pore structure, which can significantly reduce its permeability and consequently hinder ionic mobility (Whiting and Nagi 2003);
• The increase in the concrete's temperature results in the decrease of its electrical resistivity due, essentially, to the decrease of the viscosity of the pores solution with the temperature increase (increasing, in that way, ionic mobility) (Esmaeilpoursaee 2007);
• With the increase in the concrete's moisture content, the electrical resistivity decreases because the higher the humidity, the higher the quantity of the pores solution, making ionic mobility easier and consequently decreasing electrical resistivity (Whiting and Nagi 2003, Esmaeilpoursaee 2007).

In the specific case of the SCC, it is possible to find, in various published studies, sometimes significant differences in the ion diffusion phenomenon, namely chloride (Assié 2004). Tang *et al.* (1999) present SCC chloride diffusion coefficients which are higher than those of the studied CC, even with values of W/C ratio of 0.4 for SCC and 0.5 for CC. The authors state that the differences found can be attributed to a bad dispersion of the LF particles used as additions. On the other hand, Zhu and Bartos (2003) state that SCC with FA incorporation shows values of the chloride diffusion coefficient lower than those of the CC studied by the authors. That is to say that the diffusion process in CC depends on the proportions of the mix's components and can, in that way, be lower, equivalent or higher than that of a CC. The use of larger volumes of ultrafine material and the potential reduction of the W/C ratio, usual in a SCC, can contribute favourably to an improvement of its permeability and consequently of its diffusion. Nevertheless, according to what was said, not all types of ultrafine material, more specifically of mineral additions, have the same effect on the diffusion phenomenon.

2. Research objectives

This paper intends to discuss the capillarity properties correlating them to the electrical

resistivity of SCC with different types of additions. In order to better characterise the mixes produced, a summary of its basic properties is also presented, both in the fresh state through current tests, and in the hardened state through the average value of compressive strength.

For that purpose, a total of 11 self-compacting mixes were produced: one with cement only (C); three with C + FA in 30%, 60% and 70% substitution ratios; three with C + LF in 30%, 60% and 70% substitution ratios; four with C + FA + LF in substitution combinations of 10-20%, 20-10%, 20-40% and 40-20%; and finally four reference mixes according to the LNEC specifications E 464 (2007) which refers to the standard NP EN 206-1 (2007).

3. Experimental programme

3.1 Materials

The materials used in this study were selected taking into consideration their availability in Portugal and the concrete under analysis (SCC). The following materials were therefore used:
• One type of cement complying with NP EN 197-1 (2008) (cement type I-42.5 R with specific gravity of 3.14), for which the chemical composition is summarized in Table 1;
• Two mineral additions: fly ash (FA) complying with NP EN 450-1 (2008) and NP EN 450-2 (2006) with specific gravity of 2.30 and limestone filler (LF) complying with LNEC specification E 466 (2005) with specific gravity of 2.72, for which the chemical composition is summarized in Table 1;
• Two limestone coarse aggregates complying with NP EN 12620 (2010), Gravel 1 with specific gravity of 2.59, D_{max} of 11 mm and water absorption of 1.46% and Gravel 2 with specific gravity of 2.64, D_{max} of 20 mm and water absorption of 0.78%;
• Two siliceous sands complying with NP EN 12620 (2010), one coarse (0/4) with specific gravity of 2.55, fineness modulus of 3.70 and water absorption of 1.10% and one fine (0/1) with specific gravity of 2.58, fineness modulus of 2.03 and water absorption of 0.70%;
• A third-generation high-range/strong water-reducing admixture complying with NP EN 934-1 (2008) and NP EN 934-2 (2009) (a modified polycarboxylic high-range water-reducing admixture in liquid form with a density of 1.07);
• Tap water complying with NP EN 1008 (2003).

3.2 Concrete mixes used

With the goal of scoping all variants of contents used in the mixes and the corresponding analysis of the binary and ternary mixes of FA and LF, 11 SCC mixes were produced according to the NP EN 206-9 (2010) and four reference concretes according to the NP EN 206-1 (2007). These data are shown in Table 2.

The mix contents used were obtained according to the method presented by Nepomuceno (2005) in his Ph.D. thesis. In short, a new methodology to determine the SCC mix's contents is proposed based on the methods of Okamura *et al*. (2000) and JSCE (1998) with the introduction of new parameters that are more adequate for the control of the SCC's mechanical strength and of other properties in the fresh state. Several practical applications of it also exist, namely the verification of its applicability in the work presented by Silva *et al*. (2011).

Regarding the establishment of the mix quantities presented in Table 2, one should mention the

Table 1 Chemical composition of raw materials

Chemical composition of raw materials (%)[*]	CEMI	FA	LF
Al_2O_3	5.24	24.7	0.13
$CaCO_3$	—	—	98.35
CaO	62.71	2.63	55.10
Cl^-	0.01	< 0.01	—
Fe_2O_3	3.17	5.40	0.03
K_2O	—	1.112	0.016
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	—	—	0.007
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 respective producers

Table 2 Mixes composition

Mix proportions		SCC1.100C	SCC2.30LF	SCC2.60LF	SCC2.70LF	SCC3.30FA	SCC3.60FA	SCC3.70FA	SCC4.10FA20LF	SCC4.20FA10LF	SCC5.20FA40LF	SCS5.40FA20LF	RC.XC1&2	RC.XC3&4	RC.XS1&2	RC.XS3
CEM I 42,5 R	(kg/m³)	707	512	297	222	503	290	218	506	506	297	293	240	280	256	272
Fly ash	(kg/m³)	—	—	—	—	158	318	373	53	106	109	215	—	—	64	68
Limestone filler	(kg/m³)	—	190	386	449	—	—	—	125	63	257	127	—	—	—	—
Superplasticizer	(kg/m³)	7.4	4.6	2.9	2.7	4.6	3.5	3.4	4.6	4.6	3.2	3.0	1.0	1.5	1.9	2.3
Water	(l/m³)	189	175	168	170	183	180	178	180	180	168	175	156	168	176	153
Fine aggregate 0/1	(kg/m³)	436	450	457	456	443	447	448	446	446	457	451	593	572	549	562
Fine aggregate 0/4	(kg/m³)	287	297	301	300	292	294	295	294	294	301	297	390	377	362	370
Corse aggregate 1	(kg/m³)	417	417	417	417	417	417	417	417	417	417	417	551	532	511	523
Corse aggregate 2	(kg/m³)	283	283	283	283	283	283	283	283	283	283	283	374	361	347	355
W/C	(–)	0.27	0.34	0.57	0.76	0.36	0.62	0.82	0.36	0.36	0.57	0.60	0.65	0.60	0.69	0.56
W/CM	(–)	0.27	0.34	0.57	0.76	0.28	0.30	0.30	0.32	0.29	0.41	0.35	0.65	0.60	0.55	0.45
W/FM	(–)	0.27	0.25	0.25	0.25	0.28	0.30	0.30	0.26	0.27	0.25	0.28	0.65	0.60	0.55	0.45

different mix parameters considered. In that way, the ratios between the coarse aggregates (coarse aggregate 1 + coarse aggregate 2) and between the sands (sand 0/1 + sand 0/4) were established with the goal of obtaining the maximum compacity possible through the analysis of the reference mixes as well as the corresponding fine aggregate modules. In this way, the intention was to

Table 3 Overview of the fresh state parameters of the concrete mixes

Fresh proportions	SCC1.100C	SCC2.30LF	SCC2.60LF	SCC2.70LF	SCC3.30FA	SCC3.60FA	SCC3.70FA	SCC4.10FA20LF	SCC4.20FA10LF	SCC5.20FA40LF	SCS5.40FA20LF	RC.XC1&2	RC.XC3&4	RC.XS1&2	RC.XS3
Slump-Flow (SF) (mm)	770	675	678	620	648	613	595	775	738	685	645	140	180	210	200
V-funnel (t_v) (s]	9.3	10.3	9.1	9.9	7.3	8.4	8.6	9.3	10.8	9.1	10.0	—	—	—	—
L-box (PL) (-)	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.8	—	—	—	—
J-ring (SF_J) (mm)	760	603	620	560	605	523	538	770	738	675	638	—	—	—	—
J-ring (B_J) (-)	3.5	11.0	8.5	9.5	7.5	13.0	8.5	2.5	2.3	3.5	3.3	—	—	—	—
Sieve segregation (SR) (%)	24.1	19.1	23.8	21.8	18.1	19.1	16.6	13.1	14.8	12.8	9.1	—	—	—	—

minimize the empty spaces between the particles and optimize the ratios between them.

In order to assign the content parameters of the studied mixes so as to be able to evaluate only the change in the unitary substitution ratios of cement by mineral additions, the following conditions were taken into account:

• The volumetric ratio between mortar and coarse aggregates' content (V_m/V_g = 2.625), as well as the absolute volumes of coarse aggregate (V_g = 0.268 m^3/m^3) and mortar (V_m = 0.702 m^3/m^3), were kept constant;
• For calculations purposes, the value of voids volume (V_v = 0.03 m^3/m^3) was considered constant;
• The volumetric ratio between the total powder content, cement and mineral additions, and fine aggregates in the mix (V_p/V_s = 0.80) was kept constant;
• The volumetric ratio between water and fine material content in the mix (V_w/V_p), as well as the percentile ratio in mass between the high-range water reducing admixture (S_p) and fine material content in the ($S_p/p_\%$), varied depending on the need for water and S_p of each mix in order to obtain the self-compacity parameters.

To establish the parameters V_w/V_p and $S_p/p_\%$, experimental mixes of self-compacting mortars produced according to the work presented by Nepomuceno (2005) and by Silva *et al.* (2011) were used.

The composition of four mixes produced according to the specifications in E 464 (2007) is also shown in Table 2 with references RC.XC1&2, RC.XC3&4, RC.XS1&2 and RC.XS3. The goal of these four mixes is to check how the SCC mixes studied fit in considering the environmental exposure classes, namely in the case of chloride action, as well as to evaluate the suitability of the mixes' content parameters presented in E 464 (2007) in the particular case of the SCC in order to comply with a 50 year service life.

The reference mixes were established according to Table 7 of E 464 (2007), namely in terms of the maximum *W/C* ratio, minimum cement content and minimum strength class. The calculation of mortars' contents followed, as far as possible, the methodology used for the remaining mixes, maintaining the aggregates contents. Cement type I 42.5 R was used as supplied by the producer, while type IV/A for the reference mixes was combined in the mixing stage respecting the

prescriptions of NP EN 197-1 (2008), according to the following ratios per mass: 80% CEM I 42.5

3.3 Properties of fresh concrete

The SCC specification, in terms of its properties in the fresh state, can be defined/characterised by three parameters considered essential, namely: filling ability, passing ability and segregation resistance.

In order to characterise the properties mentioned, the following tests in the fresh state were made (Table 3):

• Slump-flow according to NP EN 12350-8 (2010) and V-funnel according to NP EN 12350-9 (2010) for filling ability;
• L-box according to NP EN 12350-10 (2010) and J-ring according to NP EN 12350-12 (2010) for passing ability;
• Sieve segregation according to NP EN 12350-11 (2010) for segregation resistance.

3.4 Test methods and sample preparation

3.4.1 Compressive strength test

The test procedure used in the determination of the compressive strength was the one described in NP EN 12390-3 (2011). This test was performed at 7, 28, 91 and 182 days for SCC and at 28 days for RC.

For that purpose, 150 mm cubic moulds were used, which were kept in a wet chamber (20 ± 2ºC and RH ≥ 95%) after demoulding at 24 hours. The specimens were tested immediately after having been taken from the curing chamber. The test was performed in three moulds for each reference and test age with a 3000 kN hydraulic press and a loading rate of 0.6 ± 0.2 MPa/s (N/mm^2/s).

The compressive strength is given by the Eq. (1), in which: f_c = compressive strength (MPa (N/mm^2)); F = maximum load at failure (N) and Ac = cross-sectional area of the specimen (mm^2).

$$f_c = \frac{F}{A_c} \tag{1}$$

3.4.2 Capillarity water absorption test

The test procedure used to determine the capillarity water absorption was presented in the specification LNEC E 393 (1993). This test was performed at 28, 91 and 182 days for the SCC and at 28 days for the RC.

For that purpose, cylindrical moulds with 150 mm diameter and 300 mm height were used, from which three moulds of 150 × 100 mm (three for each reference and test age) were cut. After the adequate time of wet curing (20 ± 2ºC and RH ≥ 95%), the moulds cut were stored in a dry chamber at temperature of 40 ± 5°C for 14 days until the test date.

Later, the moulds were placed in a tray, dully supported and with the cut surface facing down. The tray was filled with water until it reached a level of 5 ± 1 mm above the lower face of the mould. The level mentioned is kept constant throughout the test.

The mould's mass is measured after 0, 3, 6, 24 and 72 hours. Zero hours correspond to the moment which immediately precedes the one in which the moulds comes in contact with the water. Based on the weightings made, it is possible to calculate the value of the capillarity water

absorption, per unit of area for each of those times, as well as the respective absorption coefficient that was considered as the slope of the regression line of the values referring to the first 6 hours of water absorption, according to Eq. (2), in which: A = water absorption per unit area (kg/m^2); S = capillary absorption coefficient (kg/(m^2.s^{0,5}) or mm/min^{0,5}) and t = test time (s).

$$A(t) = S \times t^{0,5} \qquad (2)$$

3.4.3 Electrical resistivity test

The test procedure which served as base for the determination of the electrical resistivity is presented in the proposal of the European norm EU-Project CHLORTEST (EU funded research Project under 5FP GROWTH programme) (Luping 2005), in the manual for inspecting, evaluating and diagnosing corrosion in reinforced concrete structures (DURAR 2000) and in the technical recommendation RILEM TC-154 EMC (Polder 2000). This test was performed at 28, 91 and 182 days for SCC and at 28 days for RC.

For that purpose, cylindrical moulds with 100 mm diameter and 200 mm height were used, from which three moulds of 100 × 50 mm were cut, for each mix and test age (cutting off approximately 20 to 25 mm of each extremity). After the adequate time of wet curing (20 ± 2°C and RH ≥ 95%), the moulds cut were preconditioned in vacuum and immersed in distilled water.

Later, the saturated 100 × 50 mm moulds with the surface cleaned from excess water were placed between two copper plaques with the help of two sponges humidified with water and with a 2 kg mass to compress the set (Fig. 1). Next, as seen in Fig. 1, an electric potential of 60 V (dc) is applied through the copper plaques placed on the flat tops of the moulds and the value of the electrical current which crosses the mould is registered.

Based on the current measurement made, on the applied electrical potential, on the mould's dimensions and on the weighing of the sponges electrical resistance, it is possible to calculate the electrical resistivity from Eq. (3) in which: ρ = concrete's electrical resistivity (Ω.m); U = applied voltage (V); I = current intensity (A); A = top area of the specimen (m^2) and L = length of the specimen (m).

$$\rho = \frac{U}{I} \times \frac{A}{L} \qquad (3)$$

4. Tests results and discussion

4.1 Properties of fresh concrete

The studied properties of the SCC in the fresh state are listed in Table 3. The results corresponding to the slump-flow are in the 600-800 mm range, indicating a good filing ability. The lowest values of the slump-flow were obtained in the binary mixes with f_{ad} of 70% both of LF and of FA.

The results related to the V-funnel flow test are within the 7-11 seconds range and those of the L-box are all higher than 0.8 indicating a good passing ability.

The slump-flow results in the J-ring test are proportionally lower than those of the slump-flow test. The difference in the slump-flow measured in both tests decreases as the value of the slump-flow test increases. In other words, the higher the result of the slump-flow test, the lower the difference between this one and the value obtained with the J-ring test. The B_J value obtained

Fig. 1 Electrical resistivity setup

in the J-ring test is constant for the binary mixes, varying between 7 and 13 approximately. The values related to the mix with 100% cement and to the ternary mixes are significantly lower (between 2.5 and 3.5). The values mentioned for the B_J parameter are coherent with the differences obtained for the slump-flow with and without the J-ring.

In general, it is possible to state that the values obtained for the properties in the fresh state of the SCC produced are within the recommendations of The European Guidelines for Self-Compacting Concrete (EPG 2005).

4.2 Compressive strength

Figs. 2-4, show the evolution of compressive strength values with age and with the additions substitutions ratio (f_{ad}) for all the SCC produced. Fig. 5 presents the compressive strength values of the RC.

Figs. 2-4 show a more pronounced growth of the compressive strength in the early ages (7 days) for the binary mixes with LF. As for the binary mixes with FA, they show a more gradual evolution of the compressive strength which continuously grows beyond the early ages. The variations mentioned also happen for the ternary mixes, where those with f_{ad} equal to 60% have a more gradual and continuous growth, compared to the more pronounced growth of those with f_{ad} equal to 30%. The mixes with 100% cement, as expected, show a distinct behaviour from the remaining mixes, growing sharply until 28 days and stabilizing from that value on until the last test age (182 days).

In absolute terms, for all the mixes studied, and just as expected, compressive strength increases with age and decreases with the substitution ratio of cement with additions.
The SCC1 mixes, corresponding to the SCC without additions, have the highest compressive strength, up to 90 MPa at 182 days. The SCC2 mixes (with LF) show, at 7 days, higher values than those found for the SCC3 mixes (with FA). Nevertheless, with age, the compressive strength of the SCC2 mixes tends to stabilize at 28 days, while that of the SCC3 mixes still show some evolution at 91 days, ending up by stabilizing at 182 days at higher values than those of the SCC2 mixes. For the SCC3 mixes with f_{ad} of 60% and 70%, the final value of the compressive strength at 182 days increases significantly, especially the one with f_{ad} of 70%, when compared with the corresponding values of the SCC2 mixes. The variations mentioned can be seen in the different slope of the curves shown in the right graphs of Figs. 2-4, relating to the variation of the compressive strength with the value of f_{ad}.
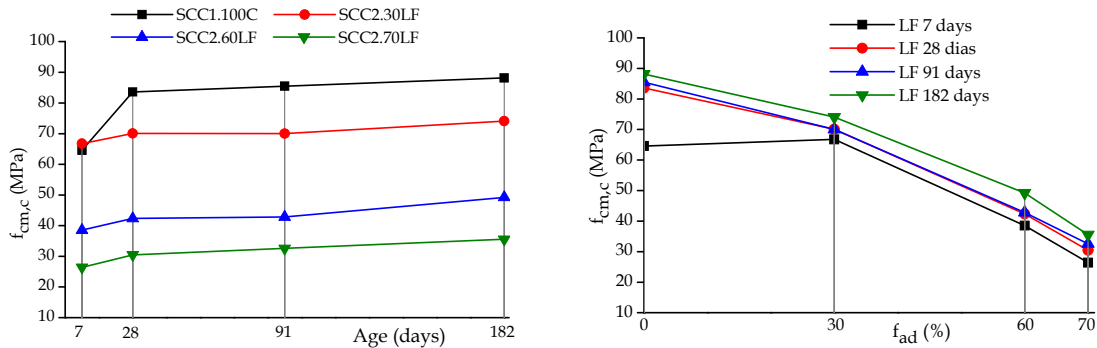
Fig. 2 7, 28, 91 and 182-day compressive strength for binary mixes with LF
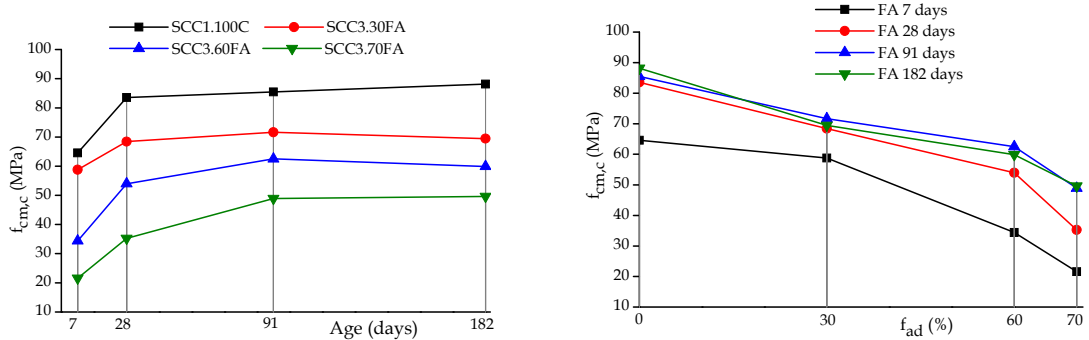

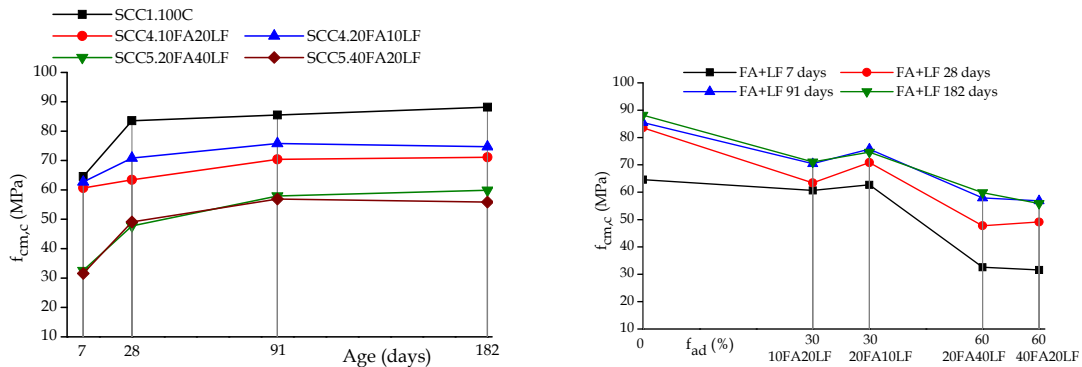Fig. 3 7, 28, 91 and 182day compressive strength for binary mixes with FA

Fig. 4 7, 28, 91 and 182-day compressive strength for ternary mixes

Analysing Fig. 3, it is possible to observe the effect of the FA in the behaviour of the studied SCC. Like in the remaining mixes, both the binary and the ternary, one can find a decrease in the compressive strength with the increase of the additions substitution ratio, which is mainly due to the dilution effect related to the reduction in Portland cement content. In the particular case of the FA, it is even possible to observe a slower evolution of the compressive strength for higher f_{ad} levels mainly in the younger ages and stabilizing at 91 days. The values of compressive strength presented by the SCC3 mixes compared with the values of SCC1.100C are according to expectations. Considering the lower initial evolution of these SCC with FA (essentially due to the

later effect of the FA pozzolanic behaviour, relegating the FA contribution to the compressive strength, at those initial ages, to the filer effect), it is expected that, at older ages and for f_{ad} levels lower than approximately 30%, the compressive strength evolves in a more significant way, being able to, in certain cases, reach values which are equal or even higher than the corresponding values in SCC with 100% of C. This behaviour is mentioned by different authors for conventional concrete, stating that the optimal contents of FA substitution for C are lower than 20-30% (Neville 1995, Mehta and Monteiro 2005). Accordingly, Cyr *et al*. (2006) state that, from a certain content (growing with the amount of cement), the FA stop working as an addition, and work solely as a fine aggregate, which can be confirmed by the lower values of the compressive strength of SCC3.30CV compared to those of SCC1.100C.

For the values of FA' f_{ad} present in this work, the FA act more on the porosity decrease and the microstructure refinement (which can be confirmed by the results such as, for example, the capillarity or the electrical resistivity) than by the pozzolanic effect (very important in the development of the compressive strength), that is, the use of FA, for these levels of f_{ad}, had little effect on the evolution of the mechanical strength mainly for the older ages and was more affective in the improvement of the SCC durability. The porosity decrease and microstructure refinement mentioned is essentially due to the physical action of the FA by filler and nucleation effect through a greater germination of the hydration products in the paste, increasing its volume.

The compressive strength variations of the ternary mixes (Fig. 4) are similar to those of the binary mixes. The ternary mixes with a global f_{ad} value of 30% (SCC4) have a more pronounced growth of the compressive strength in some way similar to that of the SCC2 mixes (with LF). The SCC5 ternary mixes (global f_{ad} of 60%) show a similar behaviour to that of the SCC3 mix (with FA). The SCC4 mixes reach, at 182 days, compressive strengths similar to those of the remaining families, while the SCC5 mixes reach higher values (except for the SCC1 mixes).

The values for the RC (Fig. 5) fall within the strength classes required by the E 464 (2007) specification.

4.3 Capillarity water absorption

Figs. 6-9 show the average values of the results obtained for the capillary absorption for the 3 ages studied (28, 91 and 182 days). With the values of the capillary absorption, the corresponding absorption coefficients were determined, whose values are shown in Fig. 10.
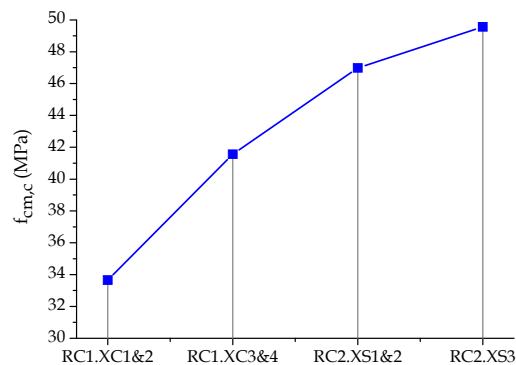

Fig. 5 28-day compressive strength for the reference mixes

In a first analysis of the results obtained, it is possible to see that capillarity is conditioned by the use of additions, as well as by their type, in the production of SCC. This point can be seen in the level of the lower values, of the SCC3 mixes with FA, when compared to those of the SCC2 mixes with LF, as well as in the differences obtained with the age increase.

For all the mixes studied, capillarity decreases with the curing period and increases with the f_{ad}. As seen in these figures, there is no significant difference for the mixes with f_{ad} of 30% (for those with LF and with FA) when compared to the SCC without additions). The same happens with the ternary mixes, in which the behaviour mentioned is extended in the same way to the mixes with f_{ad} of 60%, which reveal, from that point of view, a very favourable behaviour at all ages.

The ternary mixes show an excellent behaviour at all ages tested both in capillarity water absorption and in the corresponding absorption coefficient. One should highlight the results which refer to the absorption coefficients obtained by these mixes at 28 days. The main motive for the results mentioned are the synergy effect between FA and LF and consequently the refinement of the microstructure or, as mentioned by Mounanga *et al*. (2011), by the substitution of FA by LF that accelerates the setting process. The results obtained by Mounanga *et al*. (2011) in his work on *Improvement of the early-age reactivity of fly ash and blast furnace slag cementitious systems using limestone filler* confirm the values mentioned, that is, the cement with LF and FA makes it possible to obtain ternary mixes with improved performances, in comparison to binary mixes containing only cement and FA. The best reactivity of the B4 and B5 mixes could be mainly explained by the acceleration of the cement hydration, related to the presence of LF by nucleation site effect. Mounanga *et al*. (2011) claim that this acceleration of hydration involves a faster production of $Ca(OH)_2$ and thus an increase in the pozzolanic reaction rate.

The values obtained by SCC generically fit those of the mixes corresponding to the composition limits established for the environmental exposure classes XS and XC of LNEC E 464 (2007) specification referring to NP EN 206-1 (2007) presented in Fig. 10 and for the age studied (28 days according the what was specified). Nonetheless, one should highlight that the ternary mixes with f_{ad} of 30% comply with the specified limits and that those with f_{ad} of 60% only comply with the value of XS3, but by a minimal margin. As for the binary mixes with FA, they have higher values than the ternary ones. Only the SCC3.30FA complies with all the limits and the SCC3.60FA and SCC3.70FA only comply with the limits for classes XC. The binary mixes with LF have higher values than both the binary with FA as well as the ternary mixes. The SCC2.70LF does not comply with any of the limits shown. The SCC2.60LF complies with just the limits of class XC1&2 and the SCC2.30LF fails to comply in all classes except the XS3. Nevertheless, comparing the values obtained for SCC in more advanced ages (91 and 182 days) with those of RC, a significant reduction in the capillary absorption can be observed, except for the SCC2.70LF which always maintains high values.

For the mixes with LF, the results confirm those obtained by Ramezanianpour *et al*. (2009), among others. These authors state that, in the specific case of the use of LF, it can only be competitive in terms of permeability for low values of f_{ad}, of the order of 10-20%. Similar results can be found in the work of Assié *et al*. (2007), which compares SCC and CC with various mechanical strengths and values of f_{ad}. Zhu and Bartos (2003) present a comparative study where they use FA and LF in the production of SCC and CC for the mechanical strength classes of 40 MPa to 60 MPa, where it is observed that, as in this work, SCC with additions show capillary absorption values slightly lower than its equivalent in CC and that the differences between SCC with FA and SCC with LF are minimal, despite the fact that the SCC with FA show slightly more favourable results.
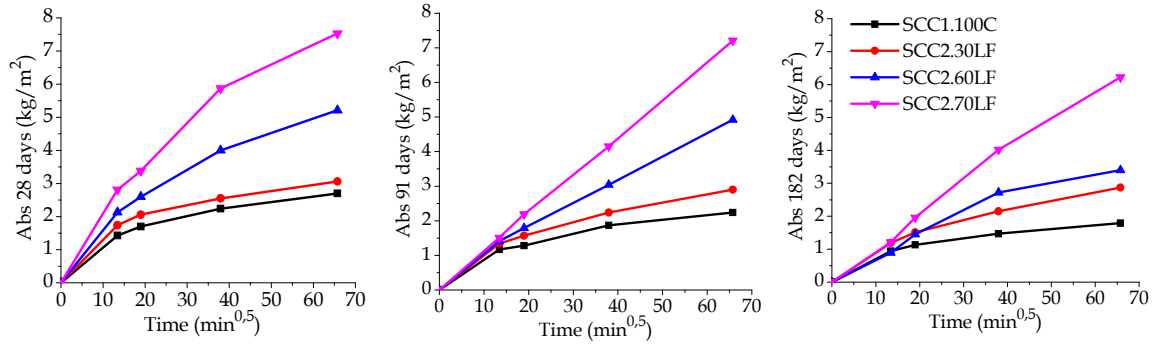
Fig. 6 28, 91 and 182-day capillary water absorption for binary mixes with LF
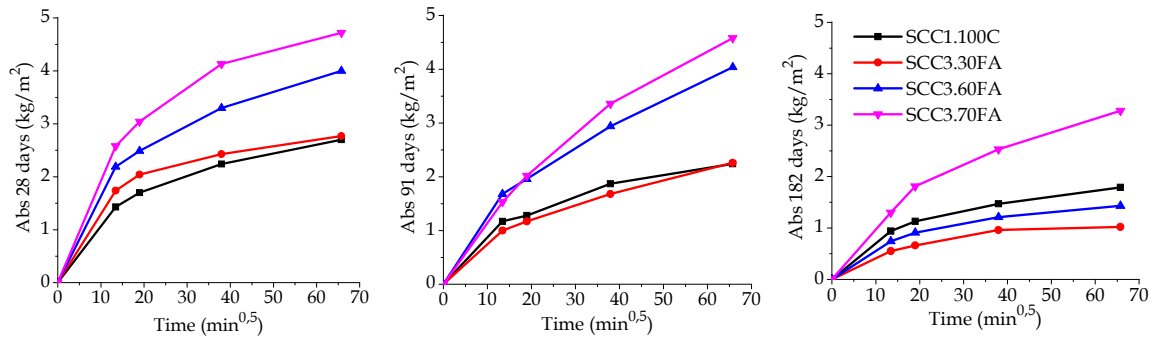

Fig. 7 28, 91 and 182-day capillary water absorption in binary mixes with FA
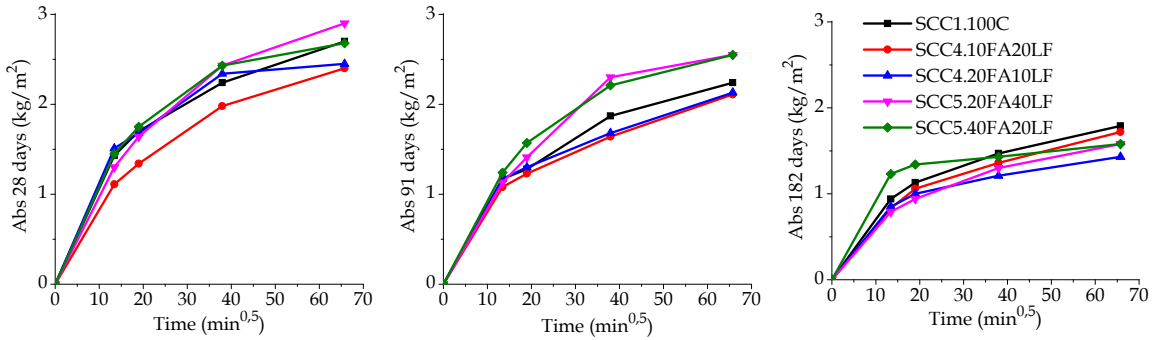

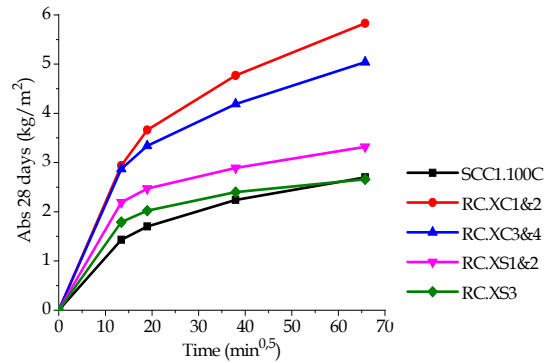Fig. 8 28, 91 and 182-day capillary water absorption in ternary mixes

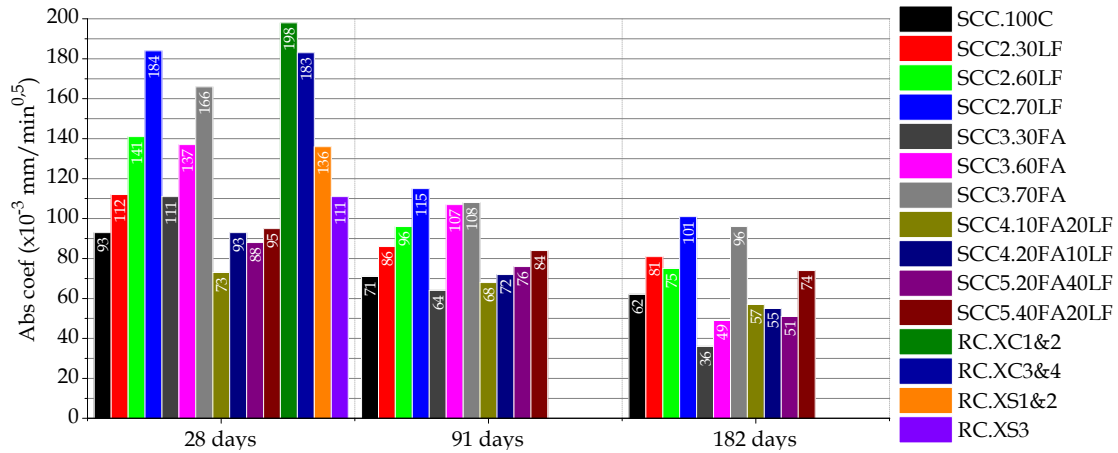Fig. 9 28-day capillary water absorption in reference mixes
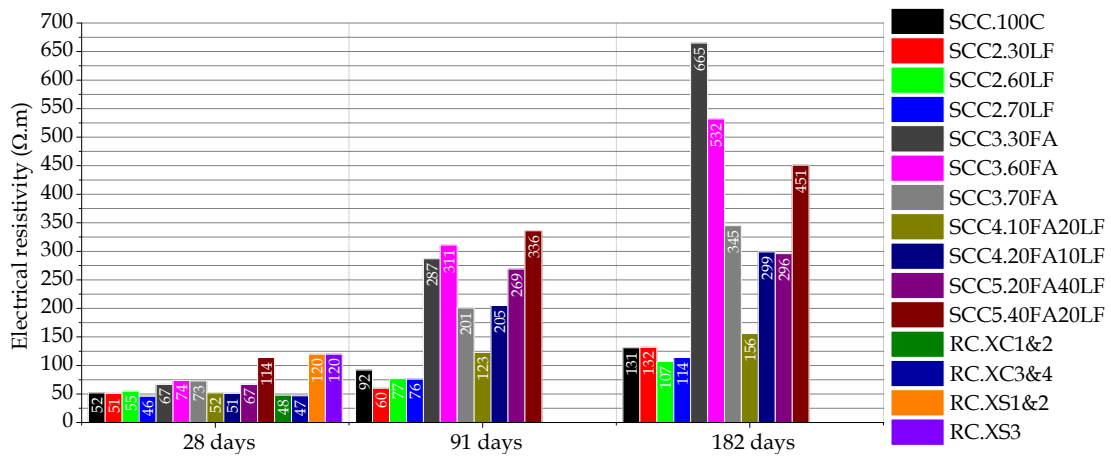
Fig. 10 Capillary absorption coefficient for all mixes

Fig. 11 Electrical resistivity for all mixes

4.4 Electrical resistivity

The average values of the results obtained in the electrical resistivity test for the ages studied are those shown in Fig. 11. Unlike what is observed for the capillary absorption coefficient, the binary mixes show a significantly distinct behaviour, not only by comparison between each other, but also in its evolution with the curing time. The use of FA is notoriously favourable to the increase in the SCC electrical resistivity, which can be confirmed both in the binary as well as the ternary mixes.

Analysing the results, it is found that the SCC1.100C and the SCC with LF are the ones with the lowest values of electrical resistivity and without a significant evolution with the curing time. On the contrary, the SCC with FA shows a very significant evolution with time. For example, the electrical resistivity of the SCC3.30FA increased 9.92 times between 28 and 182 days. Still concerning the SCC with FA, at 28 days, the values corresponding to different f_{ad} are practically

constant while with the increase in time one can see a clear differentiation between them, i.e., an increase in the electrical resistivity with the decrease in the value of f_{ad}.

The ternary mixes show a more constant evolution not only as a function of the curing time but also of the different f_{ad}. It is found that the SCC5.40FA20LF (total f_{ad} of 60%) shows an excellent compromise between the evolution of the electrical resistivity and its value right at early ages. Analyzing the results of the ternary mixes, one can see that the value of the electrical resistivity also appears strongly conditioned by the addition of FA. The presence of LF in these mixes is practically inconsequent when one compares, for example, the SCC4.20FA10LF and SCC5.20FA40LF mixes. Regarding the RC, it is equally notorious the difference between the RC.XC (without FA) and the RC.XS (with FA).

Comparing the results presented here concerning the binary mixes with FA with those obtained by Dinakar *et al*. (2008) (in mixes with 30%, 50% and 70% of FA), a similar dispersion of results is observed, despite the differences in terms of order of magnitude. As for the evolution of the electrical resistivity with the curing time, in the binary mixes with FA, it is confirmed in the work of Sengul and Gjørv (2008), among others.

The results obtained in the binary mixes (with 20%, 40% and 60% of FA) by Gesoglu *et al*. (2009) at 90 days of curing, show a smaller dispersion and an lower order of magnitude not only when compared to those of the present work but also to the results of Dinakar *et al*. (2008). The main differences observed are associated with the evolution of the electrical resistivity with the variation of the f_{ad} in the binary mixes with FA for the longer curing times, namely 182 days. While in this work the binary mixes of FA have at 182 days a maximum value of electrical resistivity for f_{ad} of 30%, in the Dinakar *et al*.'s work there is an increase of the value mentioned with an increase of f_{ad}, reaching maximum values for higher f_{ad}. The differences shown can be explained by two factors: the establishment of the mixes' contents and the test procedure. In this work, the parameters V_p/V_s and V_m/V_g are considered constant, which causes a decrease in the W/C ratio with an increase in f_{ad}. The specimens pre-conditioning, namely the solution used in their saturation is different in practically all works consulted. It is frequent, for example, that some authors take advantage of the pre-conditioning process of the chloride penetration test (calcium hydroxide $Ca(OH)_2$ solution saturated in distilled water) to evaluate, in those same specimens, the initial electrical resistivity or use other solutions, such as different contact pressures, which produce distinct results from those obtained with pre-conditioning, in this case, in distilled water and with a contact pressure corresponding to a 2 kg mass. The differences mentioned can be verified in the work of Newlands *et al*. (2008).

For the binary mixes with LF, the work of Ramezanianpour *et al*. (2009) studies different f_{ad}, with different W/CM in three ages (28, 90 and 180 days). It is confirmed that in these SCC's the electrical resistivity slightly increases with the curing time and that it does not vary significantly with f_{ad}. The main condition in these mixes is the W/CM ratio. The electrical resistivity decreases with the increase in the W/CM ratio. In the mixes with higher W/CM ratio (around 0.55) the variation of the electrical resistivity with the curing time is still lower than that of the remaining mixes with a lower W/CM ratio.

No results of ternary mixes of FA and LF were found that would allow the evaluation of the results obtained. Nevertheless, Gesoglu *et al*. (2009) produced binary, ternary and quaternary mixes of FA, silica fume and blast-furnace slag and, as in the present work, the ternary mixes show a very satisfactory behaviour regarding the electrical resistivity.

4.5 General analysis

The main differences found in the results obtained can very likely be explained by the difference between the pore structure of SCC incorporating different types of additions (namely FA and LF) and the corresponding substitution ratios, given that a larger volume of open pores implies a greater water absorption capacity.

According to Section 3.2, the consideration of the *Vp/Vs* and *Vm/Vg* parameters as constants in absolute value implies that, with the additions' volume increase and due to the decrease in cement (maintaining a constant *Vm* value), the *W/C* ratio increases and the *W/FM* ratio stays almost constant. With the increase in fad and the con-sequent increase in the *W/C* ratio, a SCC with more accessible pore structure and greater water absorption capacity is expected. Nevertheless, one should highlight the results obtained both with the binary mixes with FA (30FA and 60FA) at 182 days and with the ternary mixes at all ages, which, despite the variation in the *W/C* ration mentioned, but with an almost constant *W/CM* in these cases, show values of capillarity water absorption lower than those of the SCC1.100C.

In the case of SCC with FA and considering the non-application of pressure in the absorption by capillarity test, it is possible that a weaker interlink between the pore system in these SCC has such an influence that it decreases the corresponding water absorption. In fact, if the system of smaller pores (smaller diameter) were more interlinked, a higher absorption would occur due to the capillary forces that, in these pores, are stronger.

The difference in the result dispersion found between the two tests analysed and the fact that no direct correlation was found between them for all ages and f_{ad} values can be related to the pre-conditioning used in each of the tests. Nevertheless, without forgetting the differences between the transportation phenomena involved (water absorption by capillarity vs. electrons transportation through an electrolyte embedded in the concrete's pores structure), one should mention that, while in the case of capillarity the moulds are dried in a pre-set humidity and temperature chamber before the beginning of the test and this is performed without resorting to external pressure (the absorption happens exclusively by capillary forces), in the electrical resistivity test the moulds are saturated resorting to vacuum. This last procedure will probably cause more saturation of the pores structure making it less significant to the phenomenon under study when compared to the capillarity and consequently obtaining lower results' dispersion.

5. Conclusions

All the mixes produced reached the required workability parameters so that they could be classified as self-compacting. The SCC produced had adequate filling and passing ability as well as a good resistance to segregation.

In terms of compressive strength, even the mixes with f_{ad} of 70% reached 30 MPa at 28 days, in the case of the mixes with LF, and 35 MPa in the mixes with FA. The ternary mixes with a global f_{ad} of 60% have a compressive strength of approximately 48 MPa at 28 days.

The SCC's capillarity as well as its electrical resistivity is strongly conditioned by the capillary pores and by their interrelation. A smaller capillary pore structure and with lesser interrelation contributes significantly to a decrease of the transportation properties of the aggressive agents, increasing the SCC durability. The increase in the electrical resistivity makes the electrons movement from anodic areas to cathodic areas more difficult, consequently decreasing the

premature evolution of the steel corrosion processes.

The use of FA instead of LF can improve the transportation properties mentioned mainly in older ages. The mix with the most favourable results was SCC3.30FA. The ternary mixes show interesting results, mainly in the relation between the higher values right at the younger ages and the more modest but still significant values at older ages. The mixes with LF show results, at younger ages, of the same order of magnitude of the mixes with FA. Nevertheless, at 182 days, the differences presented are significant.

With the exception of the SCC with 60FA, 70FA, 60LF and 70LF, all the SCC produced have lower capillarity coefficients than all the reference mixes produced according to specification LNEC E 464 (2007). The SCC 60FA, 70FA, 60LF and 70LF only comply with the values corresponding to the reference mixes of the XC environmental exposure classes.

Acknowledgments

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