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Self-compacting concrete with a high content of coal combustion sub-products

Concreto autocompactante con altos contenidos de subproductos de la combustión de carbón

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Abstract

The self-compacting concrete (SCC) has been considered a great achievement in concrete technology due to its great advantages like self-compatibility. In order to have self-compactability fresh concrete should demonstrate high fluidity, segregation resistance, and good cohesion. With the purpose of evaluating these properties, besides using a byproduct of coal combustion fly ash (FA) and grilled slag (E), also several self-compacting concrete mixes were prepared by replacing the cement in 35 % and 50 % in each one of these additions. Their properties were evaluated in the fresh and hardened state. The fresh properties were evaluated using the slump flow, V-funnel and box in L. While in hardened state mechanical properties were evaluated (compressive strength, indirect tensile and flexural) and permeability (capillary suction, absorption, porosity and chloride resistance). All SCC showed good properties in the fresh state and developed after 28 days curing, compressive resistance in the range of 34 and 48 MPa. The results show that the use of coal combustion sub-products can be incorporated in the production of SCC.

Keywords: self-compacting concrete; fly ash; slag; self-compatibility; fresh properties.

Resumen

El concreto autocompactante (SCC) se ha considerado como un gran logro en la tecnología del concreto debido a sus grandes ventajas como la auto-compactabilidad. Para tener esta propiedad el concreto fresco debe demostrar una alta fluidez, resistencia a la segregación y una buena cohesión. Con el propósito de evaluar estas propiedades, además de utilizar un subproducto de la combustión del carbón como la ceniza volante (FA) y la escoria de parrilla (E) se prepararon varias mezclas de concreto autocompactante remplazando el cemento en un 35 % y 50 % de cada una de estas adiciones. A los cuales se les evaluaron sus propiedades, tanto en estado fresco como en endurecido, las propiedades en estado fresco fueron evaluadas mediante el flujo de asentamiento, el embudo en V y la caja en L, en estado endurecido se evaluaron propiedades mecánicas (resistencia a la compresión, tracción indirecta y flexión) y de permeabilidad (succión capilar, absorción y porosidad y resistencia a cloruros). Todos los SCC mostraron buenas propiedades en estado fresco y desarrollaron a los 28 días de curado resistencias a la compresión en un rango de 34 y 48 MPa. Los resultados muestran que el empleo de subproductos de la combustión del carbón pueden ser incorporados en la elaboración de SCC.

Palabras clave: concreto autocompactante; ceniza volante; escoria; auto-compactabilidad; propiedades en estado fresco.

Introducción

The self-compacting concrete (SCC) is considered a concrete that can be placed and compacted by the action of its own weight with little or no vibration effort, and that at the same time has enough cohesiveness to be manipulated without showing segregation. This composite material is used to facilitate and ensure adequate filling and good performance in structures with highly reinforced and restricted areas (Ryan and O'Connor, 2016, Karakurt, Çelik, Yılmazer, Kiriççi, and Özyasar, 2018). The self-compacting concrete was developed in Japan in the late 1980s, to be used mainly in heavily congested reinforced structures in seismic regions (Bouzoubaâ and Lachemi, 2001; Okamura and Ouchi, 2003; Siddique, Aggarwal, and Aggarwal, 2012; Vakhshouri and Nejadi, 2018;). Recently this concrete has gained wide use in many countries for different applications and structural conFigures, in addition to providing an Eco-friendly way and safe to produce concrete without compromising its quality, due to the high use of industrial or agro-industrial by-products in its manufacture, besides eliminating the use of vibrating equipment for its placement (Ganjian *et al*., 2009; Topçu and Bilir, 2009; El-Gammal, Abdel-Gawad, El-Sherbini, and Shalaby, 2010; Uygunoglu and Topçu, 2010; Rahman, Usman, and Al-Ghalib, 2012; Nguyen, Chang, Shih, and Djayaprabha, 2018).

SCC is a special type of concrete where a high settlement is required that can be easily achieved by adding superplasticizer to the concrete mix. Self-compacting concretes often contain a high amount of fine material that is required to maintain low creep stress to provide adequate fluidity or high enough viscosity to avoid segregation in the mixture (Siddique *et al*., 2012). The use of a large amount of cement increases the cost and results in an increase in temperature, the incorporation of mineral additives, such as limestone dust, fly ash, bottom ash, blast furnace slag, etc. they could increase the settlement without increasing costs (Sonebi, 2004, Mohamed, 2011).

Various investigations have been conducted on the behavior of SCC with various types of pozzolanic materials as partial replacement of cement in orders that can range from 5 % to 40 % depending on the type of supplementary cement material (Khatib, 2008; Uysal and Sumer, 2011 Uysal and Yilmaz, 2011, Valcuende *et al*., 2012, Omrane, Kenai, Kadri, and Aït-Mokhtar, 2017). The addition of fly ash and slag from coal combustion have various effects on concrete properties in Portland cement, both in the fresh and hardened state. Improves the manageability of the mixture in its fresh state due to its great contribution of fine particles, in addition to the stability (Bouzoubaâ and Lachemi, 2001; Khatib, 2008; Liu, 2010), as well as an increase in the density in the matrix pulp. And the interfacial transition zone in the hardened concrete, although at an early age it shows low compressive strength values due to the slow pozzolanic reactions between the cement and the fly ash (Felekoğlu, Tosun, Baradan, Altun, and Uyulgan, 2006). On the other hand, the addition of fly ash or slag contributes to an economic benefit since they are by-products of the industries that currently have no commercialization, in addition to an ecological benefit due to the reduction of cement consumption in the manufacture of concretes.

The objective of this study is to investigate the effect of fly ash and slag as mineral additions on the fresh and hardened properties of SCC.

Experimental methodology

Materials

Portland Type I Cement was used for the present study in accordance with the ASTM C150 standard. As an addition, fly ash and slag by-product of the combustion of coal in different proportions (35 % and 50 %) were implemented as weight replacement of Portland Cement. The chemical and physical characteristics of the cement, the fly ash, and the slag were made by X-ray fluorescence (FRX) and laser granulometry; the results are presented in Table 1. A liquid mixture based on polycarboxylates, trademark ViscoCrete -20HE was used as a superplasticizer. The crushed coarse aggregate had a maximum size of 19 mm in order to avoid the block in the L-box, and as fine aggregate natural river sand was used, the aggregates had a specific weight of 2760 kg/m^3 and 2680 kg/m^3 respectively.

Table 1.

Characteristics of Portland Cement, fly ash and slag

Chemical composition	Cement	Fly ash	Slag
Silica (SiO_2)	21,57	33,85	51,31
Alumina (Al_2O_3)	4,19	24,72	29,3
Iron Oxide (Fe_2O_3)	4,22	6,34	7,5
Calcium oxide (CaO)	58,29	6,92	6,54
Magnesium oxide (MgO)	1,67	2,25	1,18
lost to fire (PF) (% weight)	9,01	21,42	4,85
Specific gravity	3,05	1,53	1,72
Average particle size (mµ)	20,67	23,93	19,57

Source: the authors.

Mix proportions

In the present study, five mixtures were designed, one of control and four mixtures with mineral addition (two with fly ash and two with slag) to examine and quantify the influence on the properties of SCC. Table 2 presents the design of the different SCC mixtures. In the mixtures, the cement was replaced by FAand E in the same content of 35 % and 50 % by mass. After some previous tests, the total content of fines was fixed at 550 kg/m^3. The proportions of the aggregates and the granulometry were kept constant for all the mixtures.

Table 2.

Details of self-compacting concrete mixtures

Mix	Pattern	SCC E 35 %	SCC E 50 %	SCC FA 35 %	SCC FA 50 %
Material	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**
Cement	550	357,5	275	357,5	275
Gravel	800	800	800	800	800
Sand	871	871	871	871	871
Water	198	198	198	209	209
Additive	6,6	5,8	5,5	6,0	5,8
a/c	0,36	0,36	0,36	0,38	0,39
Flying ash	-	-	-	192,5	275
Slag	-	192,5	275	-	-

Source: the authors.

Test of fresh concrete

The mixing sequence consisted of homogenizing the sand and gravel in the first instance, after that, the by-product of coal combustion (fly ash or slag) was added to the cement, and part of the mixing water was added. Finally, the remaining water was incorporated with the superplasticizer. This was done in a concrete mixer. The initial mixing time is more critical for polycarboxylate-based additives, due to its dispersion mechanism. The mixing time was the same for all SCCs.

Part of the mixture was used for testing fresh concrete. The other part to make the test pieces without any type of vibration, to determine the mechanical properties. The demolding was carried out between 22 and 24 h after casting. There were no problems with any of the SCC. The samples were cured in water until the day of the test.

In order to determine the self-compactability properties, fresh tests were performed, such as settlement flow, L-box and V funnel. All measurements of the tests were carried out in duplicate and the average of the measurements was given. The tests were carried out following the recommendations of the EFNARC *(European Federation for Specialist Construction Chemicals and Concrete Systems)* (EFNARC, 2002).

Hardened concrete tests

The compressive strength was obtained from cylinders of 7.62 cm in diameter and 15.2 cm in height. This test was performed under the ASTM C39 standard. The samples were cured at approximately 23 °C until the tests were carried out at ages 3, 7, 14, 28, 90 and 180 days. Three samples for each age were tested and the average value was reported. The indirect tensile strength was determined at 7, 28, 90 and 180 days of curing in cylinders of 7.62 cm in diameter and 15.2 cm in height, following the ASTM C496 standard. The resistance to bending at three points was performed on prismatic specimens (beams) of 7.62 cm wide by 7.62 cm high by 30.5 cm long at 7, 28 and 90 days of curing following the procedure described in the ASTM C293 standard.

Penetration resistance tests

Water permeability tests such as absorption and capillary suction were performed according to ASTM C 642 and SIA 162/1 respectively. The capillary suction test allows calculating parameters such as the resistance to water penetration m (s/m^2), the capillary absorption coefficient K ($kg/m^2 \cdot s^{1/2}$) and effective porosity (ε_0). The chloride ion penetration resistance test was also performed on the Rapid Chloride permeability test equipment, by German Instruments, under ASTM C1202, each test was done in duplicate for all the mixtures.

Results y discussions

In this study, we investigated some characteristics of the additions (FA and E), the properties in the fresh and hardened state of the SCCs using these byproducts of coal combustion. The capacity of SCCs for self-compaction is, in general, the main subject of this study, according to the criteria specified by the EFNARC. In the present study, such properties were evaluated based on tests of the fresh concrete.

Characterization of the additions

The mineralogical characterization of the fly ash and the slag was carried out by means of X-ray diffraction. It was performed on a PAnalytical diffractometer, model X'PertPRO filter from Nickel, using the Kα1 signal from Co. A step of 2 °/min was used within a range of 5 ° - 104 °. Figure 1 shows the diffractogram for fly ash and slag, respectively. It can be observed that the flying ash is not totally amorphous (vitreous), it presents crystalline phases in less quantity like Quartz, Mullite, and Calcite. The diffractogram shows a peak of greater intensity identified with a characteristic angle 2ϴ = 31.02 ° which indicates that the fly ash has a large amount of Quartz (SiO_2). In addition, several characteristic peaks of the Mullita ($Al_6Si_2O1_3$) are observed with low intensity, which indicates that this phase is in a smaller proportion.

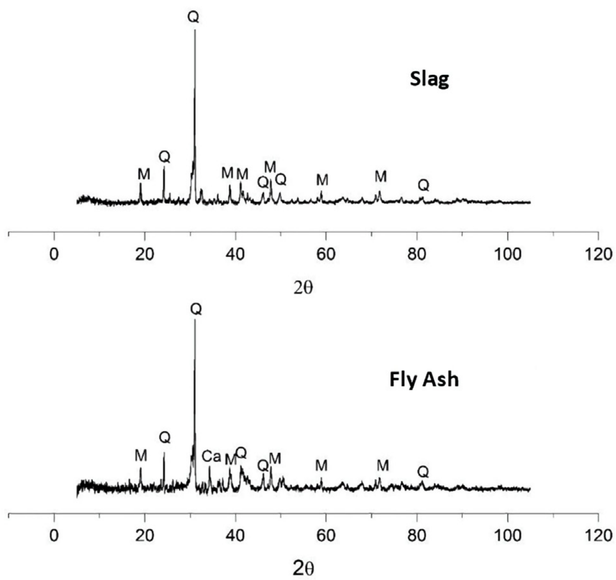

Figure 1. X-ray diffraction pattern of fly ash and slag
Source: the authors.

The slag also has crystalline phases such as Quartz (SiO_2), Mullita ($Al_6Si_2O_{13}$) and Magnetite (Fe_3O_4), which affects its reaction. Like the Flying Ash, a higher intensity peak corresponding to an angle 2ϴ = 31.03 ° characteristic of Quartz is evident.

The morphological characterization of fly ash and slag was performed using the SEM technique as shown in Figures 2 and 3, respectively. Micrographs reveal that the fly ash consists of spherical particles of different sizes identified as cenospheres, as well as containing porous black and irregular particles that are attributed to unburnt coal (Kutchko and Kim, 2006, Medina *et al*., 2010). The slag is observed as irregular particles with different sizes, this is attributed to the coal that it comes from. In addition, it is also appreciated that these particles are more compact than the particles of the fly ash and no agglomeration of particles is observed.

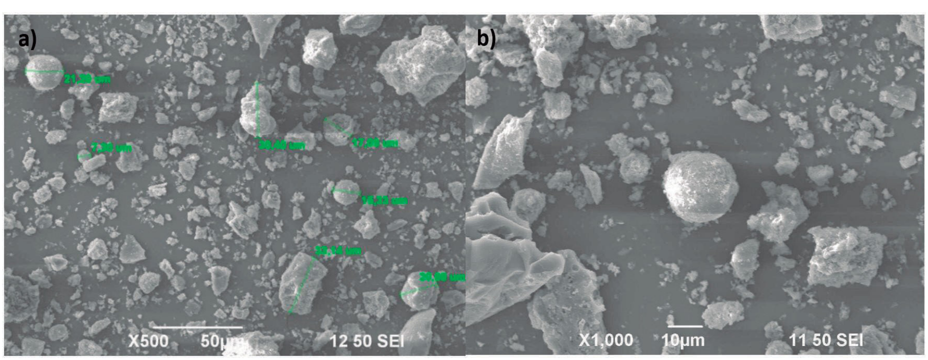

Figure 2. Morphology of flying ash taken at different magnifications. a) x500 and b) x1000
Source: the authors.

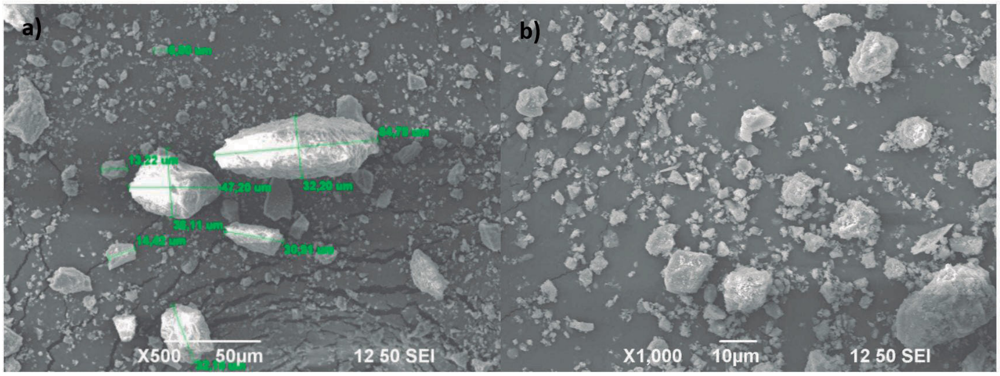

Figure 3. Morphology of the slag taken at different magnifications. a) x500 and b) x1000
Source: the authors.

The RAI resistance activity index was calculated using the ASTM C311 standard; this was carried out by means of the relation of the resistance to compression of mortars with a relation of 1: 2.75 of cement: sand. 20 % of the mass cement was replaced by the addition and compression strength of a Controlled mortar (100 % Portland cement as cementitious material). According to Table 3, the additions have favorable activities, since the IAR exceeds what is established by the norm (75 %).

Table3.

Results index of resistance activity (RAI) after 28 days of curing

Sample	Adittión%	Compresión Resistance (MPa)	RAI (%)
Mortar pattern	0	25,5	-
Mortar added with fly ash	20	32,9	129
Mortar added with slag	20	33,6	131

Source: the authors.

Results of SCCs in a fresh state

The values of the fresh tests of the mixtures of the SCCs are presented in Table 4. The settlement flow test was performed using the Abrams cone, which allows quantifying the capacity of the concrete to deform under the action of its own weight against the friction of the surface without a present restriction (Felekoğlu, Türkel, and Baradan, 2007). All the mixtures showed good workability with settling flow values between 670 mm and 690 mm. The L-box test characterizes the capacity of passage and filling of the SCCs. In general, when the blocking relation of the box in L is less than 0.8 there is a risk of there being blockage (H2/H1), this must be between 0.8 and 1.0. All SCC mixtures are within this range. The V funnel evaluates the filling capacity and the viscosity of the SCC; the times in this test were acceptable for some mixtures of SCC such as those added with fly ash and 50 % slag since its value was less than 12 s, as specified by the EFNARC, however, all self-compacting concrete mixtures filled the molds completely by the action of their own weight without the need for vibration. With these tests, the fresh characteristics of the SCC were validated.

Table 4.
Fresh tests of the SCC

	Abrams cone Spread (mm)	L Box H2/H1	V funnel Time (seg)
Pattern	670	0,82	18
SCC 35% E	690	0,85	13,5
SCC 50% E	685	0,83	11,2
SCC 35% CV	687	0,88	11,1
SCC 50% CV	689	0,96	10,8

Source: the authors.

Results of hardened SCC

The hardened properties were obtained by tests of compressive strength, indirect traction, flexion, absorption and porosity, capillary suction and resistance to chloride ion.

Compression resistance

Figure 4 shows the resistance to compression at different ages of curing. When comparing the reference SCC mixture (Standard) with the SCC with slag, better behavior is observed at all ages. SCCs with slag at 28 days of curing exceed the compressive strength proposed in the design by more than 40 % (35 MPa), while the SCC 50 % FAapproaches it, this is attributed to the fact that it is the SCC that has a higher water / fine ratio, and that pozzolanic reactions for the addition of CVs occur at long ages (Wongkeo, Thongsanitgarn, and Chaipanich, 2012; Lorca, Calabuig, Benlloch, Soriano, and Payá, 2014; Yu, Ni, Tang and Shen, 2018). The good behavior presented by the SCC with slag can be attributed to the fact that the slag particles were thinner than those of the cement which leads to making it easier to occupy or fill available spaces improving the particle distribution of the cement and, consequently, they improve the compactness of the paste achieving a better resistance of the concrete from a better occupation of spaces, in addition, that the replacement of the cement by the by-products of the coal combustion was carried out in weight, which has a lower density, which supposes a greater volume of pasta. At long ages, such as 180 days of curing, the same tendency is maintained, achieving resistance to compression of the mixtures in a range of 50 MPa to 65.8 MPa.

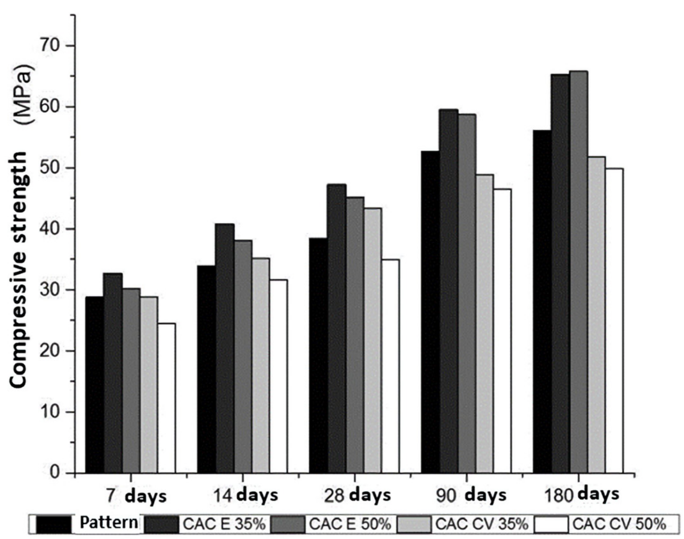

Figure 4. Resistance to compression of SCCs
Source: the authors.

Indirect tensile strength

Indirect tensile strength is defined at the point where failure is due to compression loading, inducing pure tensile stress along the diameter of the specimen (Chhorn, Hong, and Lee, 2018). This resistance depends on multiple factors such as, for example, the type of aggregate, the particle size distribution, the days of concrete curing and the air content (Neville and Brooks, 1988). To make this clear, Table5 shows the indirect tensile strength at 7, 28, 90 and 180 days of curing. In general, the results show that the highest resistances are presented by SCCs with slag. SCCs with fly ash showed a decrease in indirect tensile strength compared to the concrete pattern at different ages of curing. The resistance of the SCCs added with fly ash oscillates between 64 % and 83 % of the resistance of the master mix at 7 days of curing.

Table5.

Indirect tensile strength at different days of curing

	Indirect tensile strength (MPa)			
Curing Days	**7**	**28**	**90**	**180**
Pattern	3,07	3,27	3,30	4,13
SCC 35% E	3,20	3,57	4,03	4,70
SCC 50% E	2,74	3,00	3,98	5,40
SCC 35% CV	2,56	3,70	3,89	4,05
SCC 50% CV	1,98	3,14	3,24	3,90

Source: the authors.

Flexural strength

The flexural strength was measured by applying a flexural load to half the length of a standard concrete beam, held by two supports. As seen in Table 6, at 7 and 28 days of curing the SCC E 35 % had the highest resistance to flexion. After 90 days of curing, the SCC with 35 % slag has resistance 10 % higher than the standard concrete; in addition, it can be observed that at this age even the SCC with 50 % of slag reached values of flexural strength higher than the master mix by 20 %. It should be noted that this behavior does not occur in mixtures containing fly ash (35 % and 50 %), where resistance values of 88 % and 87 % are obtained in relation to the standard mixture. This same behavior was observed in the compressive strength when this amount of addition is incorporated.

Table 6.

Flexural Strength at different days of curing

Mix	Average Maximum Load (N)	Average rupture module (MPa)	Average Maximum Load (N)	Average rupture module (MPa)	Average Maximum Load (N)	Average rupture module (MPa)
	7 Days of curing		28 Days of curing		90 Days of curing	
Pattern	6200,5	5,45	7866,5	6,91	8587	7,55
SCC E 35%	7047,5	6,19	7885	6,93	9506	8,35
SCC E 50%	5744	5,05	6938,5	6,10	10340	9,09
SCC FA35%	5056,5	4,44	7675	6,74	7588,5	6,67
SCC FA50%	4890,5	4,30	6458,5	5,68	7530	6,62

Source: the authors.

Porosity and capillary suction

Table 7 presents the results of the porosity and absorption test carried out in accordance with ASTM C 642, which indicate an increase in the total number of pores in the SCCs added with fly ash (CV), this is attributed to the fact that these SCCs had a higher water/fine relation. Small changes in this parameter can mean appreciable differences in porosity, in addition to the dilution effect of cement (Wongkeo, Thongsanitgarn, Ngamjarurojana, and Chaipanich, 2014). The SCC with 35 % slag replacement had a higher porosity than the SCC with 50 % slag, this can be attributed to the substitution of the cement being made in weight and the slag to have a much lower density, this added a higher volume of the material. Unlike SCCs that contain fly ash, where the highest replacement has a greater porosity due mainly to its higher water / fine relation.

Table7.

Permeability test results

	SCC	PATTERN	E 35 %	E 50 %	FA35 %	FA50 %
Capilary Succion	K (kg/m2seg 1/2)	0,0039	0,0053	0,0052	0,0042	0,0061
	m (107 s/m2)	2,90	6,5	6,67	9,09	7,75
	Effective porosity ε0 (%)	0,036	0,039	0,042	0,039	0,053
Porosity and absorption	Total porosity (%)	10,9	10,25	10,1	10,8	13,35

Source: the authors.

The capillary suction test was carried out using the SIA 162/1 standard. The effective porosity (ε0) is lower for the SCC pattern and the SCC with slag. SCCs with fly ash has the highest values of the coefficient of resistance to water penetration (m) and a lower coefficient of capillary absorption (K). This behavior is attributed to the pozzolanic reaction products that we're able to obstruct the connections between the capillary pores, increasing the resistance to water penetration.

Resistance to chloride ion penetration

Table 8 presents the results of the chloride permeability and resistivity of the SCC. In general, the performance of the added SCC is highlighted, with a reduction of up to 79 % in the chloride permeability, compared with that shown by the SCC pattern. The results of the ASTM C1202 test allow classifying SCCs added with fly ash (FA) as very low permeability materials, SCC with the addition of slag (E) reach to have low permeability and SCC without addition as high permeability. Similarly, the measurement of the resistivity of the added SCCs is significantly greater than that of the SCC without addition. This behavior of the added SCC is attributed to the pozzolanic properties presented by the materials (FA and E), which have been revealed with the tests previously shown. The better behavior of concrete added with fly ash can be attributed to the decrease in the size of the pores and the reduction of the microcracks in the transition zone, which is due to the fact that the spherical particles of the fly ash improve the density in the matrix and in the interface zone between the aggregates and the paste (Nehdi, Pardhan, and Koshowski, 2004; Patel, Hossain, Shehata, and Bouzoubaa, 2004; Siddique, 2011). For the SCC with the addition of slag, the reduction in chloride permeability is due to the improvement in pore structure (reduction of pore size), by pozzolanic reactions (Kasemchaisiri and Tangtermsirikul, 2008). Additionally, this good behavior can be attributed to the bonding capacity of the FA and E with the chloride ion to form the Friedel salt.

Table 8.
Results of permeability to chlorides and resistivity

Test	SCC				
	Pattern	E 35 %	E 50 %	FA35 %	FA50 %
Permeability to chlorides Load (Coulombs)	3425	1395	906	989	715
Resistivity (Ω.m)	59,81	146,87	231,03	182,10	233,83

Source: the authors.

Conclusions

Resistivity (Ω.m) The present investigation has shown that it is possible to design an SCC incorporating several percentages of fly ash (FA) and slag (E). The fresh properties of self-compacting concrete containing fly ash and slag were in the ranges recommended by the EFNARC, reflecting an adequate fluidity, excellent flow capacity, good filling capacity and appropriate resistance to segregation.

The self-compacting concrete with fly ash needed a higher water/cement relation because this addition had a high content of unburned, which is a porous material that demands a greater amount of water to have an adequate fluidity.

The mixtures with slag showed good behavior in the mechanical tests at different ages of curing (7, 14, 28, 90 and 180 days). In the resistance to compression, the SCC with 35 % and 50 % of slag manages to increase the resistance by 17 % and 35 % respectively after 28 days of curing, which is due to its pozzolanic properties. For SCC with fly ash, the mechanical behavior is not as satisfactory at an early age, as compared to SCC with slag. This is attributed to the fact that it is the SCC that has the highest water/fines relation, which has an influence on its hardened state performance.

The SCCs with the additions showed greater resistance to the passage of chlorides, in comparison with the SCC pattern, highlighting the best performance the SCCs added with fly ash, this behavior is attributed to the physical and chemical characteristics of the material, through greater densification in the matrix and in the interface area. This behavior is corroborated with the obtained in capillary suction where the good behavior of the added SCCs is emphasized, highlighting the SCC added with fly ash.

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