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Compressive strength and electrical properties of concrete with white Portland cement and blast-furnace slag

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ABSTRACT

Electrical resistivity is an important characteristic of concrete because it allows evaluation of the accessibility of aggressive agents prior to the beginning of the corrosive process and estimation of the corrosion propagation. This study investigated the apparent electrical resistivity of concrete mixes with white Portland cement and with and without blast-furnace slag using Wenner's four-electrode method. The compressive strength of concrete cylinders and the electrical conductivity of the pore solution were tested. Examined slag contents were 50% and 70% by mass and the results were compared to reference mixtures of 100% white Portland cement and 100% grey Portland cement, as well as to mixtures with equal percentages of slag and grey Portland cement. Larger amounts of slag resulted in increased electrical resistivity and decreases in the electrical conductivity of the pore solution, when compared to the reference concretes. The mixture made of 50% slag and 50% white Portland cement showed, on average, compressive resistance levels between 35 MPa and 60 MPa, electrical resistivity values that were approximately five times greater, costs that were 14.6% less per m^3, and whiteness similar to the reference concrete. These results indicate that white Portland cement can be partially substituted by blast-furnace slag.

1. Introduction

The corrosion of steel in concrete is the main cause of concrete structural deterioration, causing the need for costly repairs, and occasionally necessitating the reconstruction of affected structures. The main factors that trigger the corrosive process are reductions in the alkalinity of the aqueous solution due to carbonation of the concrete and attack by chloride ions. The rate of corrosion is a function of the availability of oxygen and the electrical resistivity of the concrete [1].

Electrical resistivity provides a measure of the difficulty of ion movement in concrete. Therefore, it is a property that can be used as a measurement of structural durability because prior to the beginning of corrosion, it indicates the ease with which CO_2 and chloride ions can enter the mixture and, after corrosion begins, it indicates the speed of this corrosion [2–4].

A methodology and framework to quantify in-place permeation measures of concrete based on electrical resistivity has been proposed [5].

Resistivity can be used to indicate durability and corrosion, and it can also be used as a performance parameter to determine the progress of standard specimens at certain ages [6]. Because it is a non-destructive test, it can be used for on-site quality control [7].

Due to its dependence on the paste's microstructure and the conductivity and ionic concentration of the pore solution, electrical resistivity is influenced by the chemical composition, the cement level, the water to binder ratio, and the presence of additional minerals, chemical activators and additives [8,9]. It also depends on temperature; temperature increases lead to resistivity reductions because temperature influences ion–ion and ion–solid interactions [10].

Researchers have reported that the electrical resistivity of concrete increases due to the partial substitution of cement by blast-furnace slag [11]. The use of slag in concrete alters the paste's microstructure, which refines the pore structure [12] and, in turn, affects electrical resistivity. Electrical resistivity increases as the slag content increases, resulting in more durable concretes [13,14].

The light coloration of blast-furnace slag enables its use in concretes composed of white Portland cement. The production of white Portland cement is different from that of grey Portland cement, primarily as a result of the care required to maintain its light coloring. During production and application, white cement concrete requires extra care, making it significantly more expensive than grey Portland cement concrete. However, structures made from white Portland cement have a special architectural appeal, justifying the search for alternatives to reduce production costs and increase the durability of these concretes.

Several authors have discussed the quality performance of concrete made from grey Portland cement and slag in terms of

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reductions of the charge passed [15], the capacity for chloride fixation [16], oxygen permeability [17], drying shrinkage [18,19], and increases in electrical resistivity [14] which improve the durability of concretes. However, few studies have addressed the durability criteria of concretes made from white Portland cement and blast-furnace slag.

The electrical resistivity and compressive strength of concrete mixtures, made from white Portland cement and blast-furnace slag, as well as the electrical conductivity of the pore solution, were evaluated for different water/binder ratios and slag content. The results were compared with those of concretes made from grey Portland cement and the same slag and aggregates [20].

To accelerate the hydration reaction, a chemical activator, Na_2SO_4 was used according to previous experiences [21].

The mixtures were also evaluated based on equal compressive strengths, because this is the reference parameter for designing concrete structures and such a comparison enables an analysis of the costs of concrete per m^3.

2. Experimental program

2.1. Materials

The binders used included white Portland cement, high-early strength Portland cement and ground granulated blast-furnace slag. The chemical composition and physical properties of the cementitious binders are summarized in Table 1.

The NBR 12989 standard [22] allows for the addition of 25% ground limestone, which explains the high levels of loss on ignition, (Table 1).

The minimum whiteness level that the NBR NM 3 (2000) standard requires [23] for white Portland cement is 78%. The white Portland cement, the blast furnace slag and the mixtures that contained 50% and 70% slag had whiteness index values of 82.2%, 77.1%, 79.8% and 78.6%, respectively.

The coarse aggregate consisted of 19-mm maximum size basalt with a specific gravity of 2.5 and a fineness modulus of 6.87. The fine aggregate consisted of river sand with a maximum characteristic size of 4.75 mm, a fineness modulus of 2.45 and a specific gravity of 2.63. Both aggregates were washed to remove impurities and to prevent changes in the final concrete coloration. This procedure was implemented due to the lack of limestone aggregate in the region, and the objective was to verify the feasibility of partially substituting cement for slag.

Table 1
Properties of cementitious materials.

Constituent/property	White Portland cement	Portland cement	Slag
Loss on ignition (%)	11.60	2.09	–
SiO_2 (%)	17.95	19.34	33.84
Al_2O_3 (%)	2.98	4.55	10.35
Fe_2O_3 (%)	0.21	2.77	0.67
CaO (%)	59.40	62.43	44.50
MgO (%)	2.87	2.61	7.99
SO_3 (%)	3.09	2.89	–
Na_2O (%)	0.43	0.09	0.20
K_2O (%)	0.36	0.74	0.40
Specific gravity kg/dm^3	2.97	2.92	2.89
Blaine – specific surface (m^2/g)	5070	4490	4090
Compressive strength (MPa)			–
1 day	–	22.5	–
3 days	25.7	35.1	–
7 days	29.4	41.2	–
28 days	42.9	49.6	

The chemical activator was commercially available sodium sulfate (Na_2SO_4), added at 4% by mass of binder, as defined in previous articles [21].

2.2. Mixture proportions

Four mixtures were tested in this research: a reference mixture of 100% white Portland cement (Ref W), two mixtures made with 50% and 70% slag (50S W and 70S W), respectively, and a mixture made with 50% slag and a chemical activator, Na_2SO_4 with a 4% binder (50AS W).

The amount of fine aggregate was adjusted to compensate for substitutions of Portland cement with mineral additives and to maintain the mortar content at 52%.

Three water-to-binder ratios were evaluated for each mixture: 0.30, 0.42 and 0.55. A superplasticizer additive, a modified carboxylic ether, was used when necessary to obtain the previously established consistency of 90 ± 10 mm.

The casting temperature was set at 18 ± 1 °C, and the mix water was heated or cooled based on the temperatures of the other materials [1].

The results were compared with those obtained by Rosa [20], who investigated the same binder mixtures, aggregates, and testing conditions using grey Portland cement. Because the *w*/*b* ratios used by Rosa [20] were different, a regression analysis was conducted to obtain compressive strength and apparent electric resistivity values for the same *w*/*b* ratios of white Portland cement.

Table 2 presents the masses of materials used (kg/m^3) and the corresponding costs per m^3 for each of the binder mixtures.

2.3. Testing procedures

The electrical resistivity of the concrete mixes was determined using the four-electrode method (Wenner's Method). In this method, four electrodes are inserted in the concrete during the casting of the test specimens. The electrodes are aligned and placed at equal distances from one another. An AC current passes through the two outer electrodes, and the voltage difference between the inner electrodes is measured.

The apparent electrical resistivity value is calculated using the following equations [24]:

$$\rho = \frac{(4 \cdot \pi \cdot d \cdot V)}{i \cdot \left[1 + \left(\frac{2 \cdot d}{\sqrt{d^2 + 4b^2}}\right) - \left(\frac{d}{\sqrt{d^2 + b^2}}\right)\right]}$$

where ρ = electrical resistivity of concrete (Ω cm); V = measured voltage (V); I = measured current (A); d = distance between the axes of the electrodes (cm); and b = depth of insertion of the electrodes in the test specimens (cm).

For this test, test specimens measuring $10 \times 10 \times 17$ cm were cast for each mix. The test specimens were tested non-destructively at 3, 7, 14, 28, 56 and 91 days. For each *w*/*b* ratio, five test specimens were cast. These were removed from the wet chamber immediately before the test at each age and then returned to the chamber immediately after the test. The details are provided elsewhere [25].

The pore solution was obtained from paste samples that had *w*/*b* ratios of 0.30, 0.42 and 0.55, and that had been cured for 3,7,28 and 91 days. At this point, the samples were ground in to powder, and the resulting powder was suspended in deionized water in a 1:1 mass ratio until the pH was stabilized. The solution was filtered, and the chemical analyses were performed. The concentrations of Na^+, K^+, and Ca^{2+} were determined using atomic absorption spectrometry. The concentration of OH^- was established using direct titration with HCL. The concentration of SO_4^{2-}

Table 2
Composition of the concrete mixtures (kg/m^3) and costs per m^3 of concrete.

Mixture	*w*/*b*	Portland cement	Slag	Fine agg.	Coarse agg.	SP	Activator	Water	Cost U$
Ref W	0.30	517	–	641	1064	1.70	–	154	231.53
	0.42	415	–	706	1038	0.33	–	174	183.06
	0.55	306	–	820	1040	–	–	168	141.40
Ref G	0.30	521	–	645	1073	1.72	–	155	153.70
	0.42	418	–	711	1045	0.33	–	175	120.43
	0.55	306	–	824	1045	–	–	168	94.74
50S W	0.30	259	259	624	1071	1.46	–	155	164.39
	0.42	208	208	696	1042	0.27	–	175	130.29
	0.55	153	153	813	1043	–	–	168	102.67
50S G	0.30	261	261	626	1075	1.46	–	156	125.54
	0.42	209	209	698	1045	0.27	–	175	98.89
	0.55	153	153	815	1045	–	–	169	79.33
70S W	0.30	155	362	620	1072	1.46	–	155	137.94
	0.42	125	292	693	1043	0.29	–	175	109.56
	0.55	92	214	811	1045	–	–	168	87.25
70S G	0.30	156	365	621	1075	1.46	–	156	114.87
	0.42	125	293	694	1045	0.29	–	175	90.61
	0.55	92	214	812	1045	–	–	169	73.19
50SA W	0.30	259	259	624	1071	5.25	20.80	152	225.34
	0.42	208	208	696	1042	0.13	16.68	175	153.70
	0.55	153	153	813	1043	–	12.23	168	120.66
50SA G	0.30	261	261	626	1075	5.25	20.80	156	226.41
	0.42	209	209	698	1045	0.13	16.68	175	154.27
	0.55	153	153	815	1045	–	12.23	169	120.71

was determined by precipitating $BaSO_4$ in a solution with excess $BaCl_2$. The equations proposed by Shi et al. [26] were used to calculate the specific conductivity of the concrete pore solution. Xi et al. [27] used a similar procedure to assess the pH change of the liquid phase in hardened cement paste. The dilution, dissolution and hydration of the anhydrous grains of cement exposed during the grinding process affected the pH of the solution, thus the measured pH was not the real pH of the pore solution, but it was related to it, and it still provided some information on the alkalinity of the pore liquid [28]. This procedure was used for all mixes and *w*/*b* ratios, and the results were compared.

Compressive strength tests were performed using cylindrical test specimens that measured 10 × 20 cm, in accordance with Brazilian Standards NBR 5738 and 5739. The test specimens were stored in a wet chamber at 23 °C ± 2 °C and RH ⩾ 95%, and tested at 3, 7, 28 and 91 days. Four specimens from each mixture were tested at each testing date.

3. Results and discussion

3.1. Compressive strength

The compressive strength results are presented in Fig. 1. As expected, the compressive strength of all concrete specimens increased with the period of curing and decreased as the *w*/*b* ratio increased. As the percentage of blast-furnace slag in the mixture increased, the compressive strength decreased, an observation valid for white and grey Portland cement. The results agree with those reported by other researches [28–31]. However, mixtures with 50% and 65% blast furnace slag and with a Blaine fineness of 420 m^2/kg yielded values greater than those of the reference mixture at 7 days [32].

The presence of slag also resulted in continued strength increases for the mixtures with white Portland cement. At 7 days, the 50S W and 70S W mixtures presented compressive resistance values between 53% and 70% and between 43% and 76%, respectively, of the values observed at 91 days.

The mixtures with 100% WPC (Ref W) showed higher resistance values that those with 100% grey Portland cement (Ref G) up to an age of 28 days. At 91 days, the resistance values were similar. The strength of the Ref W mixtures increased more quickly than that of the Ref G mixtures. At 7 days, the strength of the Ref W mixtures was between 63% and 85% of the strength observed at 91 days, while the strength of the Ref G mixtures was between 54% and 72% of the strength at 91 days. According to Soroka and Stern [33], the calcareous fillers act as crystallization nuclei, thereby increasing the velocity of CH crystallization and the subsequent velocity of cement hydration. The fineness of white Portland cement also contributes to this phenomenon.

The influence of white Portland cement on the compressive strength for the strength levels of 20 MPa, 40 MPa and 60 MPa at 1, 3, 7, 14 and 28 days was investigated [34]. At 1 and 28 days, the strength of the WPC was greater than that of the mixture made with grey cement, even though the latter presented a higher Blaine fineness. At 1 day, the best performance of the WPC could be explained by the greater percentage of C_3A; and at 28 days, the superior performance was attributable to the greater percentage of C_2S and the sum of C_3S and C_2S.

The alkaline activator effectively accelerated resistance gains in the concretes with slag. The 50SA W mixture showed strength values similar to those of the Ref W mixtures at 7 and 28 days; however, the 50SA W mixture's strength was lower at 91 days. For the grey cement, at 28 and 91 days, the strengths of the 50SA G and Ref G mixtures were practically equal. The effectiveness of activators for accelerating the development of concrete strength with blast-furnace slag has been observed previously [35–37].

3.2. Electrical resistivity of concrete

The electrical resistivity of concrete values at different ages for mixtures with white and grey Portland cements are shown in Fig. 2.

The substitution of Portland cement by slag effectively increased the electrical resistivity of the concretes at 7 days, and this phenomenon has been reported by other researchers [11]. The mixture composed of white cement and 50% slag, 50S W, showed electrical resistivity values that were between 2.52 and 4.76 times greater than those of the reference mixture with 100% white Portland cement, Ref W, at 7 days. The mixture with 70% slag, 70S W, showed electrical resistivity values that were between 2.28 and

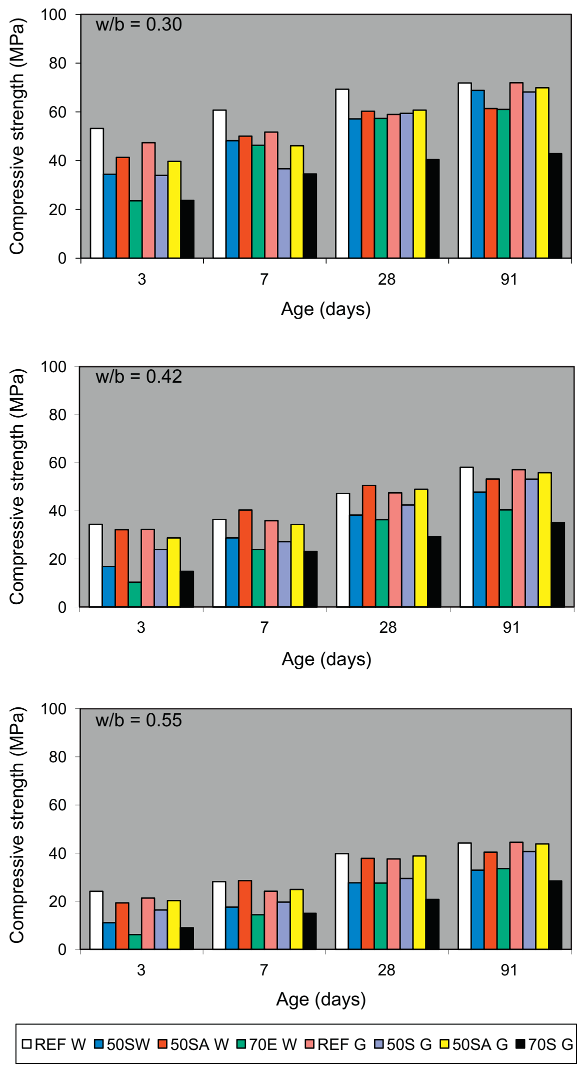

Fig. 1. Compressive strength results at 3, 7, 28 and 91 days.

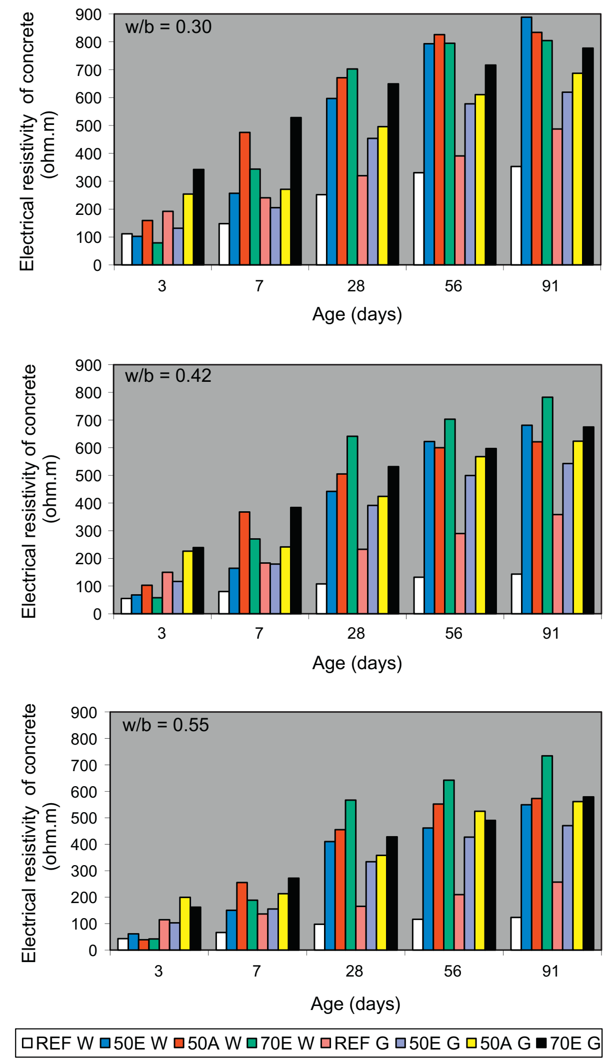

Fig. 2. Electrical resistivity of concrete results at 3, 7, 28, 56 and 91 days.

5.96 times greater than those of the reference mixture at 7 days. The grey cement mixtures, 50S G and 70S G, had resistivity levels that were 1.27–1.83 and 1.41–2.19 times greater, respectively, than those of the reference mixture with 100% Portland cement, Ref G. The presence of slag increased the density of the mixtures, the resistance of the paste matrix and the capillary tortuosity, and decreased the ionic concentration of the pore solution [8,12,14,38,39].

Comparing the mixtures containing only Portland cement, the electrical resistivity of the mixture with white Portland cement was lower than that of the mixture with grey Portland cement for all the w/b ratios and ages tested. The highest value of electrical resistivity was 353 Ω m for the reference white cement mixture (100% WPC, $w/b = 0.30$) after 91 days, and the minimum value was 123 Ω m for a w/b ratio = 0.55. For the grey Portland cement, the electrical resistivity values for w/b ratios of 0.30 and 0.55 were 487 Ω m and 257 Ω m, respectively.

The activator effectively accelerated electrical resistivity gains. For the concretes with white cement, the resistivity of the activated mixture, 50AS W, was greater than that of the 50S W mixture until 56 days. At an age of 91 days, the 50S W mixture showed greater resistivity values. For the concretes with grey Portland cement, the resistivity of the activated mixture, 50AS G, was greater than that of the mixture without the activator, 50S G, for all tested ages. Even for a w/b ratio of 0.55 and an age of 7 days, these mixtures presented electrical resistivity values greater than 200 Ω m, indicating that the corrosion rates were likely negligible [40]. For the early ages, the resistivity gains due to the activator could be attributed to the faster slag reaction, which increased the density of the paste matrix [38,41].

The correlation results for the electrical resistivity of concrete values and the compressive strengths at 28 and 91 days are shown in Fig. 3. As shown in the figure as the strength increased, the electrical resistivity increased correspondingly. This result has been observed previously [42]. The relationship between resistivity and strength was approximately linear because both directly depend on the porosity of the matrix. As the compactness of the structure increases, the compressive strength and the electric resistivity of concrete will both increase, even though the latter is also influenced by other properties such as the conductivity of the pore solution and the degree of concrete saturation.

3.3. Electrical conductivity of pore solution

The electrical conductivity of pore solution values for the mixtures of white Portland cement and grey Portland cement at different ages are shown in Fig. 4. The electrical conductivity of the pore solution decreased with increasing age. Previous results reveal a similar tendency [43]. The reduction of the water-to-binder ratio resulted in an increased conductivity due to the greater ionic concentration of the solution.

The partial substitution of cement by slag resulted in a decrease in the electrical conductivity of the pore solution, and this decrease was more pronounced for higher levels of replacement. Other researchers have also observed this reaction [38–44], which is due to the ability of slag silicates to combine with alkalis in solution, thus reducing the ionic concentration and the conductivity of the pore solution [45,46].

The presence of the alkaline activator resulted in an increase in the electric conductivity of the pore solution. This was caused by the release of ions in the solution by the activator.

Comparing the performance of the two types of cement, the electrical conductivity of the pore solution was greater for the grey cement for all evaluated ages and mixtures, perhaps due to its higher total alkali content (Table 1).

The correlation between the electrical conductivity of the pore solution and the electrical resistivity of concrete is presented in Fig. 5. Both properties increase simultaneously. Because electrical resistivity of concrete is related to electrical conductivity of pore solution, it was expected that one would increase as the other decreased [8,9]. The behavior of these two properties is dependent on the *w*/*b* ratio. As the *w*/*b* ratio decreases, the ionic concentration in the pore solution increases, thereby increasing conductivity. However, the matrix becomes denser, thereby resulting in a decreased porosity and an increased electric resistivity of concrete.

For an equal electrical conductivity of the pore solution, different amounts of electrical resistivity of concrete can be obtained based on the composition of a mixture. This behavior is believed to be a result of the different pore structures of the mixtures.

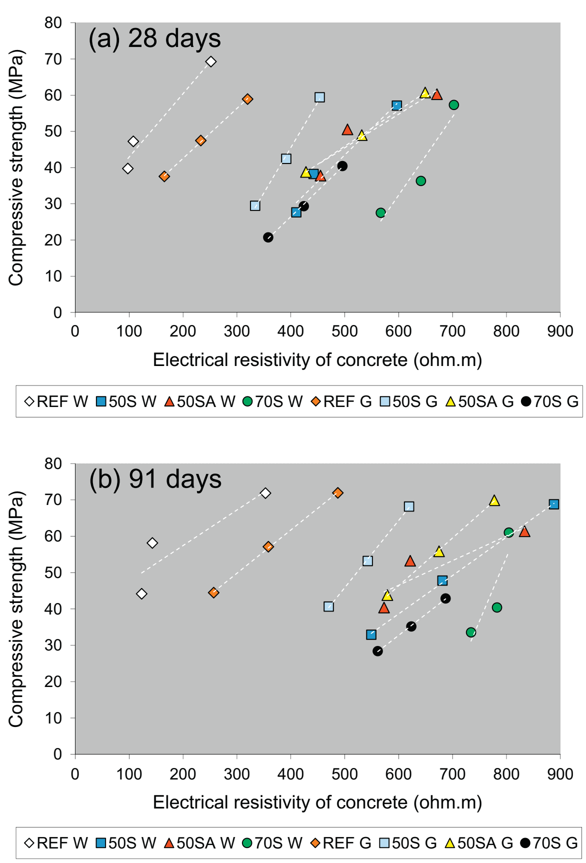

Fig. 3. Relationships between compressive strength versus electrical resistivity of concrete.

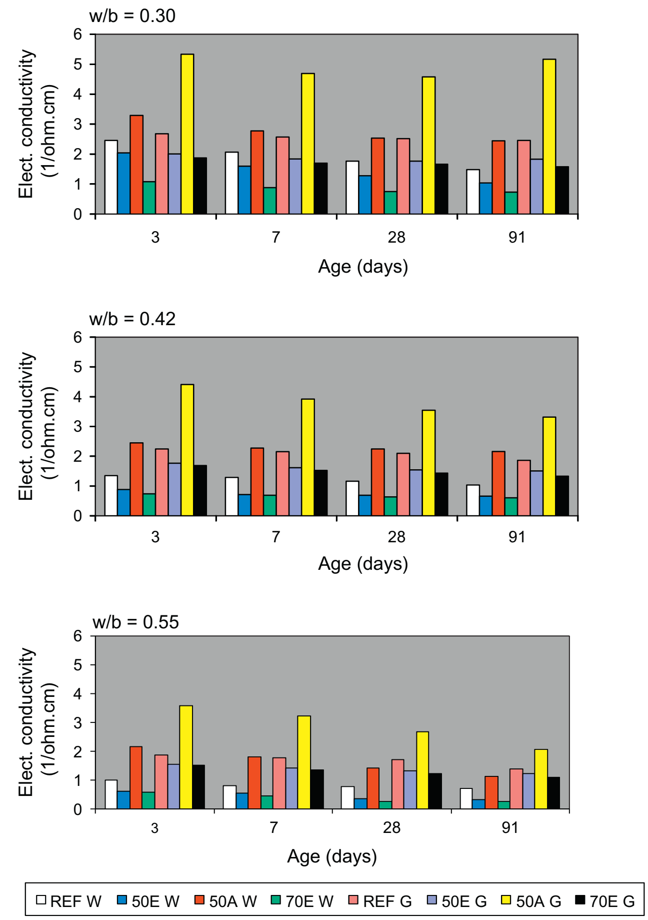

Fig. 4. Electrical conductivity of pore solution results at 3, 7, 28 and 91 days.

4. Assessment of production cost

The costs per m^3 of concretes with equal compressive strengths were compared, because compressive strength is the reference parameter used for designing concrete structures. Concretes with compressive strengths of 35 MPa and 50 MPa were evaluated at 28 days, and those with strengths of 60 MP were analyzed at 91 days.

Table 3 presents results from the following equations: $Cs = A/B^{w/b}$, which was obtained from correlations between the compressive strength values at 28 and 91 days, the *w*/*b* ratios and the corresponding coefficients of determination, R^2; $\rho = C/D^{w/b}$ which was obtained from correlations between the electrical resistivity values at 28 and 91 days, the *w*/*b* ratios and the corresponding coefficients of determination, R^2; and $C = E/F^{w/b}$ which was obtained from correlations between the cost per m^3 values, *w*/*b* ratios and the corresponding coefficients of determination, R^2.

Table 4 presents the electrical resistivity of concrete values, the costs per m^3 and the corrosion risk levels proposed in [40]. The mixture with 70% slag content showed higher resistivity and lower costs per m^3 for the three compressive strengths considered. However, for environments in which CO_2 is the dominant aggressor, the slag level should be less than 50%. According to previous research [47,48], durable concretes with up to 50% slag can be produced, and durability will increase as the fineness of the slag increases, as the period of moist curing increases and as the ratio *w*/*b* decreases.

Previous results [49] have demonstrated the feasibility of using a chemical activator instead of increasing the fineness of the slag to provide higher strength levels. However, the use of chemical additives increases the depths of carbonations. Thus, for the three

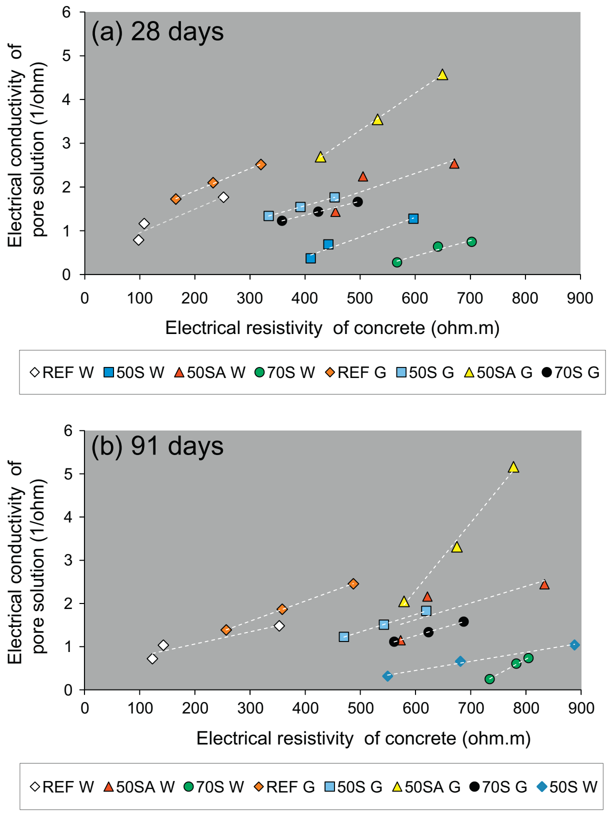

Fig. 5. Relationship between electrical conductivity of pore solution versus electrical resistivity of concrete.

strength levels, the mixture with 50% slag yielded an average electrical resistivity of concrete and a cost per m^3 that were approximately five times greater and 14.6% lower, respectively, compared with the 100% WPC reference concrete. These mixtures also showed lower *w*/*b* ratios for the three strength levels, which is advantageous for durability.

5. Conclusions

The following conclusions can be drawn from the experimental data:

The coloration of the concrete mixtures composed of 50% and 70% slag presented minimal differences from the reference concrete, which was composed of 100% white Portland cement. This indicates the feasibility of partially substituting white Portland cement for slag.

As the proportion of substituted WPC increased the compressive strength decreased. Use of the alkaline activator resulted in accelerated gains in the compressive strength during the first testing dates.

The substitution of white Portland cement by blast-furnace slag resulted in an increase in the concrete's electrical resistivity and a reduction in the electrical conductivity of the pore solution; these changes were enhanced by increasing the percentage of the substitution.

The incorporation of the chemical activator in the 50% slag mixture accelerated the development of electrical resistivity. However, the presence of the alkaline activator also increased the electrical conductivity of the pore solution compared with the mixture without the activator and the reference mixture.

Comparing the costs of the mixtures with equal compressive strengths indicated that replacing white Portland cement with slag

Table 3
Compressive strength and electrical resistivity of concrete at 28 and 91 days and costs per m^3.

Mixture	*w*/*b*	Cost/m^3US $		Electrical resistivity (ρ) 28–91 days (Ω m)		Compressive strength 28–91 days (MPa)	
	0.30	231.53		251.8	$R^2 = 0.88$	69.3	$R^2 = 0.94$
Ref W_{28d}	0.42	183.06	$R^2 = 0.99$	107.8	$\rho = \frac{676.38}{42.48^{w/b}}$	47.2	$Cs = \frac{129.93}{9.12^{w/b}}$
	0.55	141.40		97.6		39.8	
	0.30		$C = \frac{418.69}{7.19^{w/b}}$	352.9	$R^2 = 0.89$	71.9	$R^2 = 1.0$
Ref W_{91d}	0.42			143.1	$\rho = \frac{1073.17}{64.51^{w/b}}$	58.1	$Cs = \frac{129.94}{7.02^{w/b}}$
	0.55			123.2		44.2	
	0.30	164.39		596.7	$R^2 = 0.93$	57.1	$R^2 = 0.99$
$50SW_{28d}$	0.42	130.29	$R^2 = 0.99$	442.2	$\rho = \frac{894.07}{4.42^{w/b}}$	38.2	$Cs = \frac{133.69}{18.1^{w/b}}$
	0.55	102.67		410.2		27.7	
	0.30		$C = \frac{288.48}{6.57^{w/b}}$	888.1	$R^2 = 0.99$	68.8	$R^2 = 1.0$
$50SW_{91d}$	0.42			681.2	$\rho = \frac{1560.42}{6.81^{w/b}}$	47.8	$Cs = \frac{166.06}{19.07^{w/b}}$
	0.55			549.2		32.9	
	0.30	225.34		671.1	$R^2 = 0.95 \rho = \frac{1030.84}{4.86^{w/b}}$	60.3	$R^2 = 0.99$
$50SAW_{28d}$	0.42	153.70	$R^2 = 0.97$	505.1		50.6	$Cs = \frac{107.52}{6.51^{w/b}}$
	0.55	120.66		455.0		37.8	
	0.30		$C = \frac{462.13}{12.06^{w/b}}$	833.7	$R^2 = 0.93$	61.4	$R^2 = 0.97$
$50SAW_{91d}$	0.42			621.4	$\rho = \frac{1252.75}{4.43^{w/b}}$	53.2	$Cs = \frac{103.70}{5.37^{w/b}}$
	0.55			572.9		40.4	
	0.30	137.94		702.5	$R^2 = 1.0$	57.3	$R^2 = 0.97$
$70SW_{28d}$	0.42	109.56	$R^2 = 0.99$	641.3	$\rho = \frac{912.66}{2.36^{w/b}}$	36.2	$Cs = \frac{132.87}{18.61^{w/b}}$
	0.55	87.25	$C = \frac{238.05}{6.24^{w/b}}$	566.9		27.5	
	0.30			804.5	$R^2 = 0.98$	61.0	$R^2 = 0.94$
$70SW_{91d}$	0.42			782.5	$\rho = \frac{903.06}{1.44^{w/b}}$	40.4	$Cs = \frac{119.21}{10.78^{w/b}}$
	0.55			734.3		33.6	
	0.30	153.70		319.8	$R^2 = 0.99$	58.9	$R^2 = 0.99$
Ref G_{28d}	0.42	120.43	$R^2 = 0.99$	233.0	$\rho = \frac{706.03}{14.0^{w/b}}$	47.5	$Cs = \frac{101.14}{6.05^{w/b}}$
	0.55	94.74	$C = \frac{273.48}{6.92^{w/b}}$	165.3		37.6	
	0.30			487.2	$R^2 = 0.99$	71.9	$R^2 = 0.99$
Ref G_{91d}	0.42			358.3	$\rho = \frac{1049.78}{12.93^{w/b}}$	57.1	$Cs = \frac{128.10}{6.84^{w/b}}$
	0.55			256.8		44.5	

Table 4
w/*b* Ratio, electrical resistivity of concrete (ρ) and costs per m^3 for compressive strength values (Cs) of 35 MPa and 50 MPa at 28 days and 60 MPa at 91 days.

Mixture	Cs = 35 MPa at 28 days				Cs = 50 MPa at 28 days				Cs = 60 MPa at 91 days			
	w/*b*	ρ (Ω m)	Cost/m^3U$	Corrosion risk	*w*/*b*	ρ (Ω m)	Cost/m^3U$	Corrosion risk	*w*/*b*	ρ (Ω m)	Cost/m^3U$	Corrosion risk
Ref W	0.59	74	130.8	h	0.43	135	179.3	m	0.40	203	190.2	m
50S W	0.46	451	121.4	m	0.34	539	152.1	L	0.35	797	149.3	L
50AW	0.60	408	103.7	m	0.41	547	166.5	L	0.33	766	203.2	L
70S W	0.46	615	102.5	L	0.33	687	130.1	L	0.29	812	140.0	L
Ref G	0.59	149	87.4	m	0.39	252	128.6	m	0.39	387	128.6	m

Cs = compressive strength. Evaluation of corrosion risk in reinforced concrete structures: *h* = high m = moderate *L* = low and *n* = negligible.

is economically viable: as the level of replacement increased, the cost of the mixture decreased.

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