Applicability of the charge passed and resistivity tests on chloride resistance assessment of GGBS concrete mixtures

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Abstract

The RCPT is becoming a popular method to predict the durability of concrete, however many users will be aware that the scientific community has raised doubts about its ability to give a true result when cement replacements are used. This paper describes the reasons for these concerns and then presents results from a comprehensive model of the processes which has been shown to provide accurate predictions of experimental results. The results show that, while the process is far more complex that it first appears, observations from tests on concrete containing GGBS do give a good picture of chloride transport in the sample and thus durability.

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INTRODUCTION

((Z)) The test method

A number of tests have been developed in response to growing demands from clients to confirm the durability of structures. One of the most popular of these is described in ASTM C1202 and is known as the Rapid Chloride Permeability test (RCPT) [1]. In this test, a high voltage, normally 60 Volts, is used to drive chloride ions through a test sample and the resulting electric charge passing (current flow) is used as a measure of the ability of the concrete to stop chloride transport. Concretes with low charge passing are therefore selected for structures which may be exposed to salt (sodium chloride) which may penetrate the cover and corrode the reinforcing steel.

The research community have expressed a number of concerns about this test. The most significant of these relates to the problem that, at the start of the test, there is no chloride in the sample so it cannot be measuring chloride transport. The test is normally run for six hours, but even in that time the chloride rarely penetrates right through the sample (if it did, the apparatus would produce chlorine gas). This problem leads to changes in the measured current while the test is running. The standard stipulates that the total charge passing is measured, i.e. the average current, but this does not overcome the fundamental question about what is being measured.

The concerns about the test become particularly acute when cement replacements are used. The reason for this is that it can be shown that, in the absence of chlorides, much of the charge is actually carried by hydroxyl ions [2]. These hydroxyl ions are formed in the cement hydration reaction. When cement is mixed with water the main product is calcium silicate hydrate (CSH) gel which gives it most of its strength but it also forms lime (calcium hydroxide) which goes into solution as calcium ions and hydroxyl ions. In plain cement mixes they remain in solution but if cement replacements are used they react with the replacements. In Ground Granulated Blastfurnace Slag (GGBS) mixes they are not actually depleted (unlike pozzolanic mixes) but the reaction could reduce their availability to carry electric current. If this happened, the RCPT would simply be measuring the progress of this reaction rather than anything relevant to chloride transport.

((Z)) The numerical model

In order to understand what actually happens in the RCPT test the authors have developed a numerical model to simulate it [3]. The model starts from the assumption that the charge is actually carried by four different ions: chloride, sodium, hydroxyl and potassium. These ions move in the sample under the influence of both the voltage gradient (electric field) which causes electromigration and the concentration gradient which causes diffusion. The combination of these two processes is described by the classical Nernst-Plank equation which was developed over 100 years ago but is very simply represented by computer code. The programme divides the sample into a large number of thin slices (cells) and calculates the movement between them during a very short time and then keeps repeating the process to give the final result after the six hours. Having considered a number of different proprietary finite element packages the authors chose to write their own code in visual basic which runs in Microsoft Excel. The code has been made available as a free download at.

The key consideration which enables the programme to model the processes is charge neutrality. This is described by Kirchoff's law, which was first demonstrated over 150 years ago and states that the current into anything must be the same as the current out of it. This means that charge neutrality must be maintained. Thus, when the programme has calculated the movement of the ions, it has to keep making adjustments to the electric field and trying again until it has achieved this neutrality. The consequence of these adjustments is that the voltage drop is not linear. An applied voltage of 60 Volts across the whole sample does not give 30 Volts in the middle. As part of their validation of the model, the authors have measured the mid-point voltages and confirmed that they are correctly calculated.

The model requires full data on the various ions in order to run. This data includes the diffusion coefficients and the capacity factors which give a measure on how easily the ions bind to the matrix and stop moving. These are the fundamental properties which determine how well the concrete will perform in a structure and protect the reinforcement from corrosion. The output from the model is a prediction of the current and mid-point voltages which are the results of the test. Unfortunately the model itself cannot work in the other direction and calculate the data for the ions from the results of the test. Thus it was necessary to use an Artificial Neural Network (ANN) which is proprietary software that could input the results of a large number of runs of the model and use this “training data” to calculate the data for the ions from test results [4].

Further data was obtained from a resistivity test. This test is also popular for durability measurements and is particularly well suited for insitu use on completed structures. The measurement must be carried out with alternating current (ac) in order to prevent net ion migration of the type which occurs in the RCPT.

((Z)) Research significance

In this paper a number of concrete samples with GGBS replacement were tested using the RCPT with additional observations which were then used in the computer models to calculate the material properties. These properties were then compared with the standard result of the test (the charge passing). In this way the reliability of the test for GGBS samples was measured. The results show whether the test is reliable and are significant to practitioners who use it.

EXPERIMENTAL METHODS

((Z)) Materials

Two different brands (A and B) of commercial Ordinary Portland cement (OPC) classified as CEM-1 according BS EN 197-1. The Ground Granulated blast furnace slag (GGBS) was obtained from Civil and Marine, a part of Hanson UK. The material was marketed under the standard BS 6699 “Specification for ground granulated blast furnace slag for use with Portland cement”. Sand with a calculated fineness modulus of 3.3 and a dry density of 2660 kg/m^3 was used. Coarse aggregate from a quarry with a mixed surface texture of both rounded smooth and angular rough particles and a dry density of 2650 kg/m^3 was used (5-13 mm).

Samples of OPC and GGBS were cast using different levels of GGBS replacement (0, 10 30, 50 and 60%). The mixes were designed using two water-binder ratios (0.40 and 0.50) and were cured in wet conditions for all cases for more than 90 days (Table 1).

((Table 1)) Mix design

				Binder [kg/m^3]		Water	Sand	Gravel
Mix	**Proportions**	**W/B**	**OPC**	**GGBS**	**Total**	**Kg/m^3**	**Kg/m^3**	**Kg/m^3**
O5-A	100%OPC	0.49	394	0	394	193	692	988
OG5-10-A	90%OPC+10%GGBS	0.49	355	39	394	193	691	987
OG5-30-A	70%OPC+30%GGBS	0.49	276	118	394	193	690	986
OG5-50-A	50%OPC+50%GGBS	0.49	197	197	394	193	690	985
O4-B	100%OPC	0.4	400	0	400	160	705	1058
O5-B	100%OPC	0.5	400	0	400	200	664	995
OG4-30-B	70%OPC+30%GGBS	0.4	280	120	400	160	704	1055
OG4-50-B	50%OPC+50%GGBS	0.4	200	200	400	160	702	1054
OG5-30-B	70%OPC+30%GGBS	0.5	280	120	400	200	662	993
OG5-50-B	50%OPC+50%GGBS	0.5	200	200	400	200	661	991

((Z)) Test Methods

The total electrical charge was measured according to ASTM C1202. In accordance with the standard, the sample was in contact with a solution of sodium hydroxide in the anode and with a solution of sodium chloride in the cathode, and the samples were water saturated before the test.

In addition to the standard measurements, the voltage evolution was monitored at the mid-point of the sample. For this, a salt bridge with a solution of potassium chloride (KCl) was used. The voltage was measured using a saturated calomel electrode (SCE) relative to the cathode cell. The membrane potential was calculated by subtracting the value of the voltage measured at the start of the test from the value of voltage measured at any time in the midpoint position [3]. Figure 1 shows the apparatus used to measure the voltage evolution.

((Figure 1))
Fig. 1: Setup used to measure the voltage evolution

The A.C. resistivity was measured on fully saturated samples before the RCPT tests using two probes at 1000Hz and 5 Volts. The electrodes were the same cells employed during the migration tests with the same solutions in the reservoirs.

The chloride diffusion coefficients and capacity factors were calculated using the computer models.

RESULTS AND DISCUSSION

((Z)) Measurements of transport related properties

Figures 2-5 present the results for basic properties of the samples which were calculated from the electrical measurements using the computer models.

For the OPC-GGBS mixes the apparent chloride diffusion coefficients (non-steady state condition) were found. Figure 2 shows the effects of GGBS on the apparent Cl diffusion coefficient. An increase in GGBS produces a reduction in the diffusion coefficient. The calculated apparent diffusion coefficients obtained were relatively high compared with some reported in the literature. Usually, for a concrete of good quality, a chloride diffusion coefficient in the order of 10^{-12} m^2/s is expected. However, these differences can be explained by the fact that the diffusion coefficients obtained in this research apply to a multi-species system coupled through the charge neutrality, rather than of those obtained in experiments reported in literature where ions are physically affected by the ionic exchange among species, but the coefficients are calculated with equations that account for only chloride diffusion in isolation and no-ionic interaction.

((Figure 2))
Fig. 2: Effect of GGBS on the Cl apparent diffusion coefficient

Figure 3 shows the influence of the proportion of GGBS on the OH^- concentration at the beginning of the test. The individual points show the data calculated from the model and the resulting average is shown as continuous line for each water to binder ratio. As was expected, with the increase of the amount of the mineral admixture, a reduction was found in the initial hydroxide composition of the pore solution. This was previously reported by [5]. The calculated hydroxide reduction of the solution into the pores for the 30% GGBS blended concrete was around 40% with respect to the OPC. Above 30% of replacement, there was no further reduction in the hydroxide ion concentration.

((Figure 3))
Fig. 3: Effect of GGBS replacements on hydroxide composition

The calculated chloride binding capacity factor is shown in figure 4. It was defined in the model using a linear isotherm as the ratio between the total ionic concentration (free + adsorbed ions) per unit volume of the solid, and the concentration of free ions per unit volume of liquid in the pores. It was found that it tends to increase with an increase in the amount of mineral admixture; similar results were found by Dhir et al. [6]. The greatest chloride capacity factor was found in mixes of 60% GGBS for 0.5 w/b and in mixes of 30% GGBS for 0.4 w/b.

((Figure 4))
Fig. 4: Simulated effects of GGBS on the chloride binding capacity

From the integrated model, the calculated porosity was also found. There was a reduction in the porosity with an increase in the amount of admixture and the beneficial effect of GGBS was greatest using 60% of GGBS. Figure 5 shows the variation of the calculated open porosity for different percentages of admixture. As was expected, the porosity increases with an increase of the water binder ratio, especially for low levels of GGBS replacement.

((Figure 5))
Fig. 5: Simulated effects of GGBS on the porosity

The results presented in figures 1-5 therefore show that the method of calculation using the computer models gives results which agree with those in the literature. This gives confidence in the model.

((Z)) Effect of slag replacement on measured charge and resistivity

The effect of GGBS replacement on the charge passed and resistivity is shown in figures 6 and 7 respectively. In figures “A” the relationships for samples of different water binder ratio are shown, and in figures “B” a general relationship obtained using all the data available are shown. The equations that best fit the experimental results are shown in the figures.

((Figure 6))
Fig. 6: Effect of GGBS replacement on the charge passed

((Figure 7))
Fig. 7: Effect of GGBS replacements on the resistivity

These relationships have been observed by many authors and assumed to indicate that GGBS is beneficial to the mix. This assumption is shown to be true by the results in this paper.

((Z)) Correlation of the transport properties with the charge and resistivity

The effects of the resistivity and charge passed on the alkalinity of the pore solution, defined as a function of the OH^- initial concentration, and the chloride capacity factor are shown in figure 8. As was expected, a good correlation was found between both electrical tests and the hydroxide concentration calculated with the computational model (figures A and C).The conductivity of a concrete sample is strongly related with the conductivity of the pore solution as was pointed out by [7]. In the same way, a good relationship was found between the measured electrical properties and the chloride capacity factor (figures B and D). This last observation has great importance because for samples OPC-GGBS, the binding capacity is one of the key factors which dominates the penetration of chlorides. If the electrical tests are, at the same time, dependent on the pore solution concentration and the chloride capacity factor, it can be argued that when the tests are applied to OPC-GGBS mixes, the conductivity of pore solution is measured, but equally the chloride resistance of chlorides is measured.

((Figure 8))
Fig. 8: Effects of charge and resistivity on the chloride capacity factor and initial alkalinity

The final relationship (figure 9) shows that the measured charge passing does give a good indication of the chloride diffusion coefficient, which is the key property (together with the capacity factor) which determines the resistance to chlorides and thus the durability.

((Figure 9))

Fig.9: Relationship between the measured charge passing and the diffusion coefficient for chlorides.

CONCLUSIONS

1. The use of the resistivity and the total electric charge passed as indirect measures of the chloride penetration is suitable in OPC-GGBS mixes. The low values of charge and resistivity are related with the conductivity of the pore solution, but are intimately linked as well to the binding capacity and the diffusivity of chlorides.

2. Using Artificial Neural Networks trained on numerical simulations of the migration test yields viable results for the fundamental properties of concrete. The initial hydroxide composition of the pore solution, the chloride binding capacity, the porosity, and the diffusion coefficients for all the species involved can be obtained.

3. The proportion of slag used in OPC-GGBS mixes affects the measured charge and resistivity. Those relationships are non-linear, an increase in the mineral admixture corresponding to an increase in the resistivity and a decrease in the total charge passed.

4. The low chloride penetration in GGBS blended mixtures may be attributed to many factors; however, it is believed that the binding capacity factor is the predominant one.

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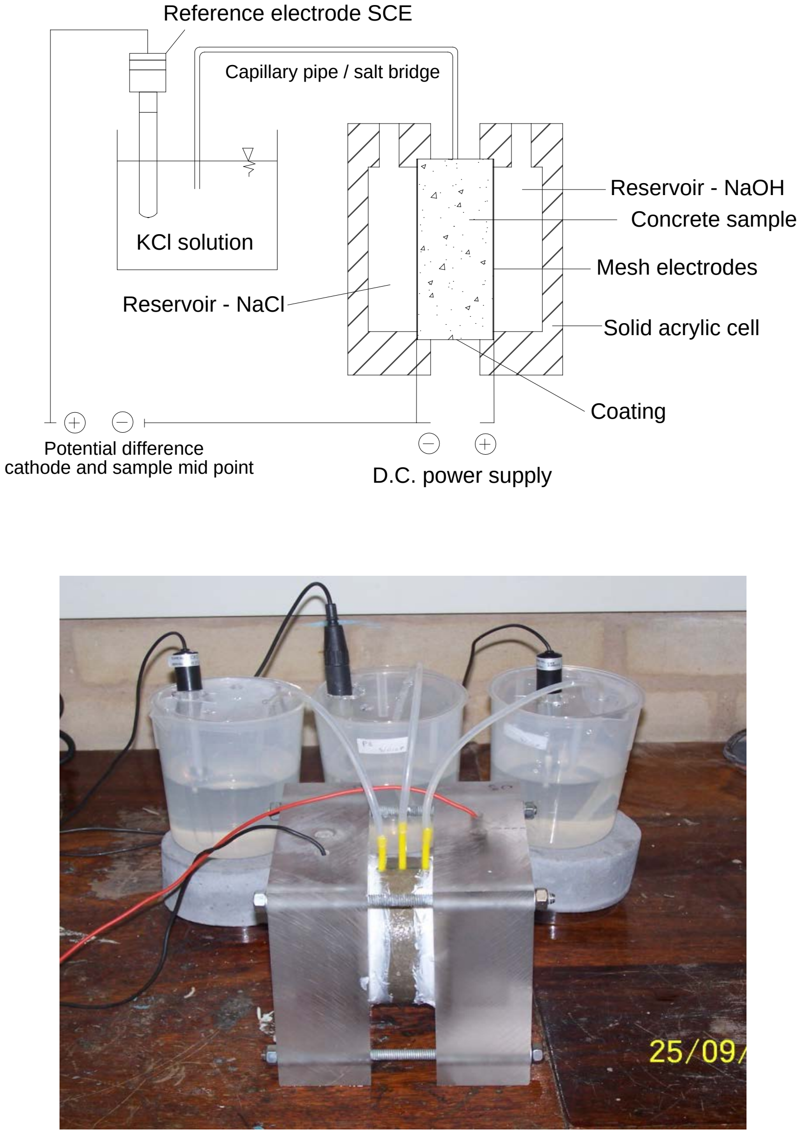

Fig. 1: Setup used to measure the voltage evolution

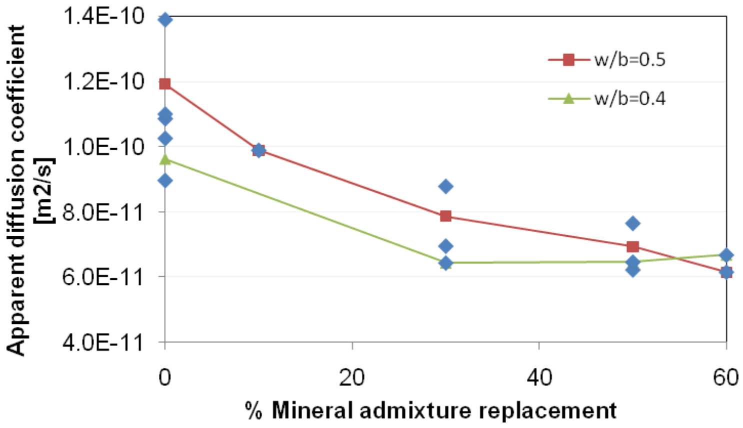

Fig. 2: Effect of GGBS on the Cl⁻ apparent diffusion coefficient

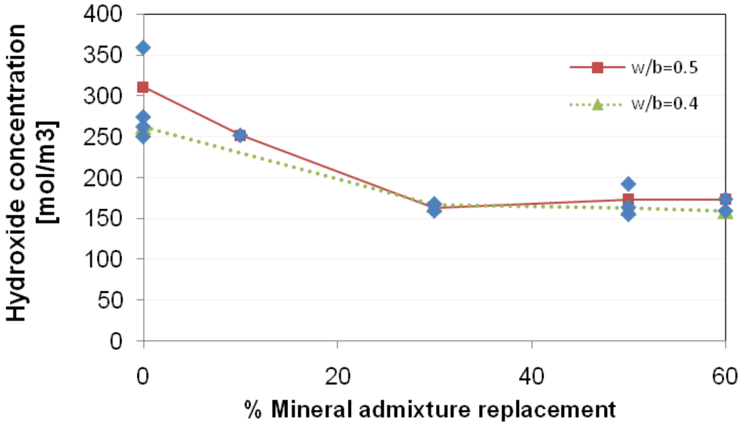

Fig. 3: Effects of GGBS replacements on hydroxide composition

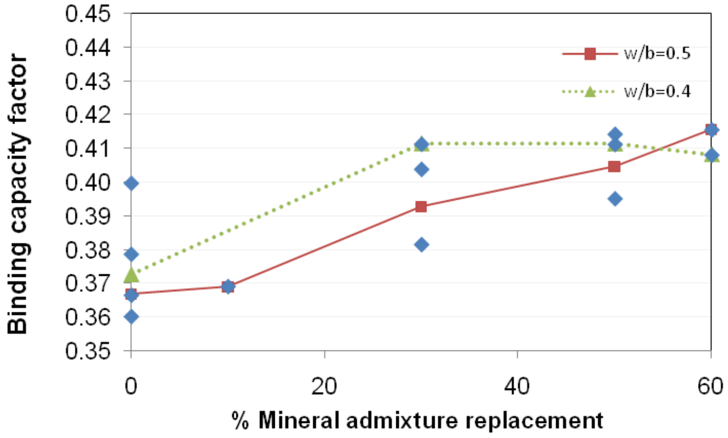

Fig. 4: Effects of GGBS on the chloride binding capacity

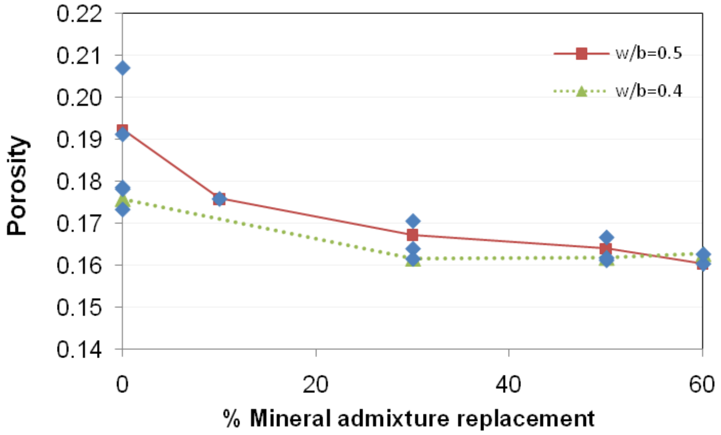

Fig. 5: Effects of GGBS on the porosity

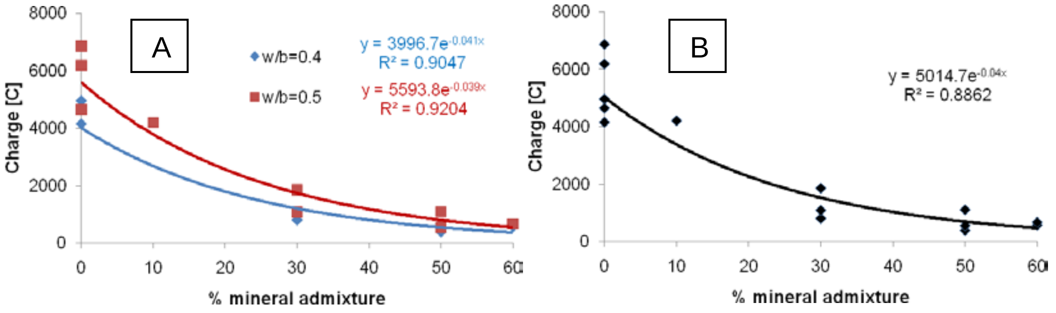

Fig. 6: Effect of GGBS replacement on the charge passed

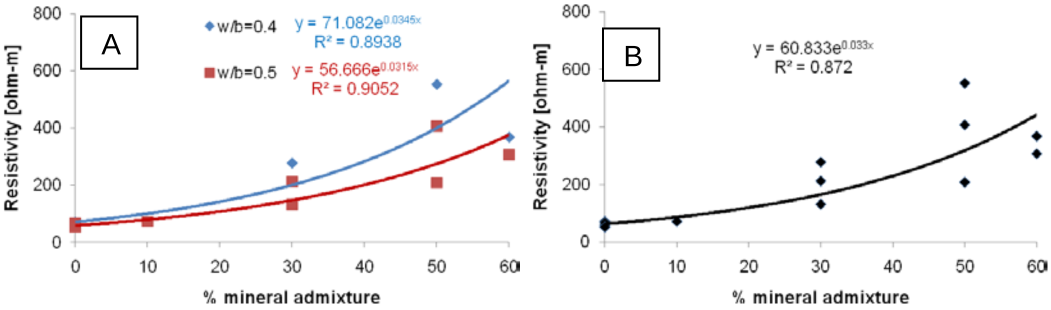

Fig. 7: Effect of GGBS replacements on the resistivity

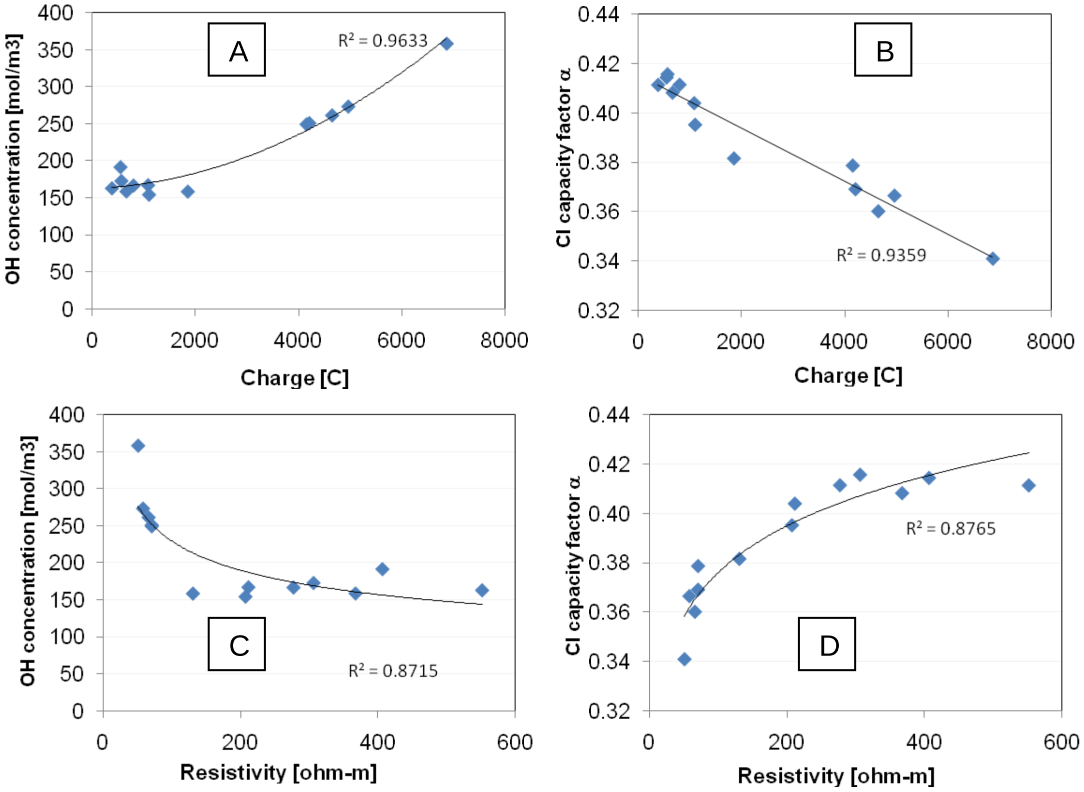

Fig. 8: Effects of charge and resistivity on the chloride capacity factor and initial alkalinity

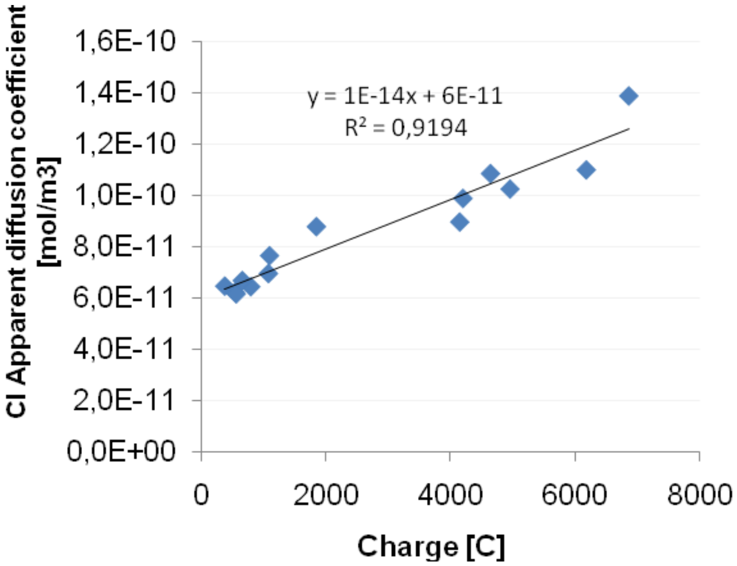

Fig.9: Relationship between the measured charge passing and the diffusion coefficient for chlorides.