Relationship between Concrete Resistivity and the Indication of Chloride Penetration by ASTM C1202 in Concrete made with OPC, and Admixed with Slag and/or Limestone Powder

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ABSTRACT

One of the most widespread methods to assess concrete ability to resist chloride penetration is the one described in ASTM C1202. This method consists in the determination of the amount of electrical charge that passes through a concrete sample in a 6 h period, whereas an electrical potential is applied. This highly empirical method has received some criticism due to its lack of representativeness of the actual process of chloride ingress into concrete. Moreover, the result of the test is a qualitative value that cannot be used for service life design based on performance. In this sense, even more practical methods can be considered with the same aim. This paper shows experimental results from the application of the method in ASTM C1202 and the measurement of resistivity in both conventional concrete and concrete admixed with slag and/or limestone powder, as these constituents significantly affect conductivity. A correlation between results from both methods is made, and some considerations are presented regarding the practicality of applying one method or the other in relation with the information they provide. The results reveal that the correlation between resistivity and results from ASTM C1202 is independent from the composition of the concrete.

Keywords: Chloride migration, resistivity, slag, limestone powder.

1 INTRODUCTION

Corrosion due to chlorides is a major issue regarding the durability of reinforced concrete structures in the marine environment. The ingress of chlorides into concrete leads to reinforcement pitting. In the marine environment, the presence of chloride in the surrounding atmosphere is inevitable, and chlorides eventually ingress into concrete. When certain chloride content is reached at the level of reinforcement, namely chloride threshold content, a localized rupture of the passive layer on reinforcement occurs. Then, the main factors that determine the time required for reinforcement depassivation in concrete in the marine environment are the porosity, the pore size distribution and the thickness of cover concrete.

The chloride ingress profile (chloride content as a function of depth) in concrete in the marine environment depends on time [1, 2], environmental conditions, material properties, and the design and construction practices [3]. Transport mechanisms for the chloride ingress into concrete are complex and combined with other interfering processes; its theoretical description is then not easy to complete.

From a regulatory point of view, the quantification of the rate of chloride ingress into concrete is highly significant, not only as a way of establishing prescriptive criteria but also, and perhaps more importantly, to provide design tools for durability. An appropriate evaluation method shall be reliable, repeatable, representative, and practical and economical at the same time.

Chloride diffusion tests require long-term evaluations, and they are then unsuitable for control procedures during construction. Several accelerated methods have been developed with the aim of assessing rapidly the rate of chloride transport in concrete. These experiments are based on an electric field imposed across the material that speeds up the ingress of chlorides. This electric field affects ions so that they migrate towards the oppositely charged electrode. The value of electrical potential gradient should be limited as high gradients in the electrical potential involve the development of heat that increases the temperature of the sample. However, even when transport indexes from diffusion and migration tests differ from each other, from the theoretical and the numerical points of view, a comparison is still possible for practical purposes [4].

One of the most widespread chloride migration tests is the so-called Rapid Chloride Permeability Test, described by ASTM C1202 [5]. Early since its implementation, this method has received some criticisms due to its lack of representativeness of the actual process of chloride penetration into concrete [6-9]. However, this criticism has not impeded that it is still one of the most used methods to assess the resistance of concrete against chloride penetration, probably due to the absence of a more simple procedure for the same purpose.

In this sense, resistivity can also be proposed as a durability index in relation with chloride ingress. A correlation between concrete resistivity and chloride ingress has been indicated by both theoretical and experimental studies [10-12]. This relationship between the chloride diffusion coefficient and concrete resistivity has been suggested as inversely proportional, in relation to the fact that, for a particular pore structure, larger pore connectivity will lead to a comparatively lower resistivity and faster chloride penetration rate. Despite this, the method according to ASTM C1202 is still more widespread than resistivity regarding the evaluation chloride ingress rate. This is based on the assumption that it provides additional information than resistivity, as it includes a chloride solution in the procedure. However, it is unclear what additional information is provided, whereas any additional information is in any case only qualitatively included. Resistivity, on the other hand, shows the advantage of being much simpler and cheaper than any migration method.

In this paper, results of chloride migration tests according to the ASTM C1202 method applied to concrete made with ordinary Portland cement, slag and limestone powder are presented and compared with the resistivity of saturated concrete. The proposed objective is to establish a basis for judging the suitability of ASTM C1202 method depending on its complexity in relation to the qualitative information it provides. The comparison includes not only conventional concrete but also concrete containing slag (as this constituent significantly affects the conductivity of concrete).

2 ON THE ASTM C1202 METHOD

The basis for the ASTM C1202 [5] method was developed by the Federal Highway Administration (FHWA) of the United States in 1981. This method had a great diffusion initially, but it can currently be put into question in terms of its representativeness of the rate of chloride ingress and its qualitative nature. This is the reason for which it is restricted to the application of prescriptive design for durability.

A major issue regarding the representativeness of the method arises from the high electrical gradient that it is applied (60 V). This value results in significant heat development (depending on the electrical resistance of the sample) and a consequential increase in the temperature of the specimen. Thus, high conductivity concretes will increase temperature to a great extent, and therefore, the chloride penetration rate will increase as well. On the other hand, the resulting current through the sample is a result of the sum of all ions moving in the pore solution, not only chloride. This is one of the main reasons for which there are significant differences in cases in which mineral admixtures are used (especially slag), as they show a lowering action of the ionic strength of the pore solution.

For practical applications, Berke and Hicks [13] proposed an empirical relationship between chloride permeability according to ASTM C1202, defined by the total electrical charge being transported (Q_e), and the effective chloride diffusion coefficient (D_s) (Eq. 1).

$$D_s = 0.0103 \cdot 10^{-8} \cdot (Q_e)^{0.84} \ [cm^2/s] \quad (1)$$

However, Q_e must be considered as a merely qualitative factor. It is also very doubtful whether or not the chloride binding capacity of concrete can be fully developed in the short period during which the migration method is applied [14]. The recommended interpretation of results is made according to criteria in Table 1. Broad ranges of variation for the results are specified in the standard [5], 12,3% (1σ) and 42% (2σ) of variation between results from the same operator, increasing to 18% (1σ) and 51% (2σ) for inter laboratory results. These quite high variation ranges indicate a limited precision for a quantitative description of concrete properties.

Table 1: Interpretation criteria for results from ASTM C1202 method [5]

Charge passing (C)	Penetrability of chlorides
>4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
<100	Despicable

Some studies have previously shown a direct relationship between the initial current and the charge passed during the 6 h that the test lasts, Qe [15-18]. Therefore, the results of this same method indicate that even with the experimental setup specified in the standard it might be unnecessary to conduct the test for 6 h considering that the initial measurement of the current might be sufficient, especially when Qe <1000 C. In addition, there are no reasons to believe that a different setup would lead to different results between the assessment of the initial current in the migration method and the measurement of the conventional bulk resistivity.

3 MATERIALS AND METHODS

The studied concretes included the use of ordinary Portland cement (OPC), blended Portland cement (BPC, containing slag and limestone), blast furnace slag and limestone powder. Slag is the mineral addition that affects concrete resistivity the most and it is frequently used in ternary blends together with limestone powder. The aggregates used were two siliceous river sands, fine (FSS) and coarse (CSS), and granitic crushed stone with

19 mm of nominal maximum size (GCS). The proportions of studied concretes are presented in Table 2. The naming corresponds to the type of binder (N: pure OPC; E: OPC+slag; F: OPC+limestone; EF: OPC+slag+limestone; C: BPC), followed by the water to cementitious materials ratio (w/cm) multiplied by 100. For example, N35 refers to concrete made with OPC and w/cm = 0.35.

Table 2: Proportions of concrete mixes.

Series	N35	N40	N41	N45	N50	N60	E40	F40	EF40	C40	C60
w/cm	0.35	0.40	0.40	0.45	0.50	0.60	0.40	0.40	0.40	0.40	0.60
Materials (kg/m^3)											
Water	133	140	140	144	150	164	140	140	140	140	168
OPC	380	350	350	320	300	274	227	262	227	-	-
BPC	-	-	-	-	-	-	-	-	-	350	280
Slag	-	-	-	-	-	-	123	-	88	-	-
Limestone powder	-	-	-	-	-	-	-	88	35	-	-
FSS	189	190	190	193	193	242	190	190	190	190	187
CSS	749	754	754	766	767	726	755	755	755	754	742
GCS 6-20	980	980	980	980	980	959	980	980	980	980	980
Water reducer (l)	6.2	5.9	5.25	6.0	3.6	2.74	4.9	4.2	4.1	5.25	2.80
Entrained air (%)	3.0	3.1	3.0	3.0	3.1	3.0	3.2	3.5	3.4	3.0	3.0
Properties											
Unit weight (kg/m^3)	2404	2417	2404	2392	2404	2354	2392	2354	2385	2392	2354
Slump (cm)	8.0	10.0	8.0	6.0	6.0	10.0	10.0	9.0	7.0	10.0	10.0
Bleeding (%)	<0.01	<0.01	n/d	3.03	0.40	n/d	<0.01	<0.01	<0.01	n/d	n/d
Porosity (%)	8.03	8.68	8.56	8.90	8.85	10.19	9.83	9.99	9.79	10.53	13.17
Compressive strength 28d (MPa)	60.2	53.8	51.2	48.3	44.3	36.7	52.6	42.2	51.1	40.3	25.3

With the manufactured concretes, 10 cm × 20 cm cylindrical specimens were cast and cured in a humid chamber for 28 days. Methods based on resistivity or other electrical properties allow describing porous properties of concrete largely. A method for measuring resistivity is straightforward and economical, with little influence of the operator excepting for potential variations in the pressure applied to put the electrodes in contact with the sample [19]. Conventional resistivity measurements were performed on concrete samples in the saturated surface dry condition. Here, a potential of 13 ± 1V AC 50 Hz is applied by electrodes consisting in perforated stainless discs on each side of the cylindrical specimen of 10cm x 5cm in diameter and thickness. These samples were obtained by cutting the section between 3 and 8cm from the base of the 10 cm × 20 cm specimens. The electrical contact between electrodes and concrete surface was ensured by interleaving wet natural fiber clothes. The ensemble was joined by pressure exerted by a sergeant screw. The applied pressure on the electrodes on the surface of the samples was approximately 0.2 kg/cm^2. Determinations on six samples for each series were performed.

On these same samples, also the resistance to chloride penetration according to ASTM C1202 method was tested. This method determines the amount of electric charge passing through the sample, Qe, in a period of 6 hours. The test is performed using a two-compartment cell separated by the concrete sample. An electrical potential is applied between the anodic and cathodic compartments, causing a chloride flow from the cathodic compartment containing chloride to the anodic compartment, which is filled with a chloride-free alkaline solution. The potential gradient is 60 V, and the current passing through the saturated cylindrical sample is measured at regular time intervals (every 30 min in this work).

4 RESULTS AND DISCUSSION

Resistivity values are presented in Figure 1. The series Nxx includes concrete mixes N35, N40, N41, N45, N50, and N60. The electrical resistivity of saturated concrete is directly related to the accessible pore volume and connectivity, since the electrical conductivity in concrete is due to the relative volume of pore solution, the ions it contains, and the structure of the pore system. Then, this inverse variation of the resistivity of saturated concrete with the w/cm ratio is to be expected.

A very significant increase of resistivity values with the use of slag can be observed. Differently, the use of limestone powder does not significantly alter the value of resistivity. The concrete ability for conducting electric current increases significantly with increasing w/cm ratio, but this relationship is very dependent on the type of binder used in the mixture, as the action of mineral additions involves a significant alteration of the pore solution chemistry and the connectivity of the pore structure.

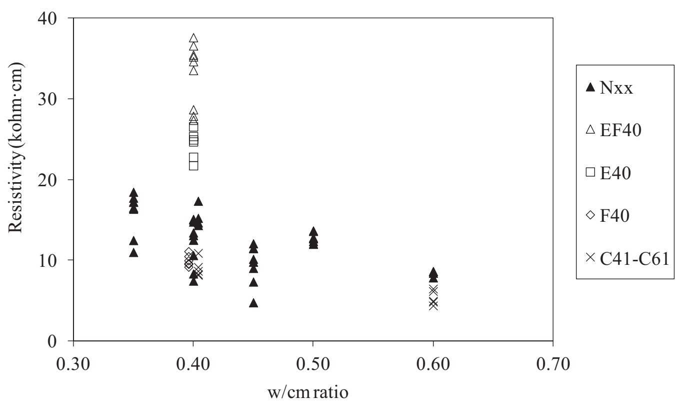

Figure 1: Resistivity values for concrete in saturated surface dry condition.

In Figure 2, results of resistance to chloride penetration are presented. These values show, as expected, an increasing trend with w/c. Still, the influence of slag on Qe is less evident than on resistivity.

Figure 3 presents the relationship between resistivity and Qe determined according to ASTM C1202. A particular common aspect of these two methods is that neither of them can consider the influence of chloride binding capacity of concrete, which is widely influenced by the use of supplementary cementitious materials. Indeed, these are some of the limitations for their application for durability assessment in the marine environment. Regarding resistivity, chloride binding capacity is not reflected as the electrical current transported through the pore solution is the result of the sum of all dissolved ionic species. For the case of ASTM C1202 method, even when it exposes concrete to a 30 g/l NaCl solution and there is chloride ingress into the concrete sample, the test is so fast that it does not allow sufficient time for the retention capacity to develop fully. In this sense, migration tests involving lower electrical potential and lasting around one week have shown results more representative of reality [20]. Moreover, as in the case of resistivity, there are other ions that also carry charge and relativize the net effect of chloride ions on the result of the test.

In Figure 3, a clear relationship between Qe and concrete resistivity arises. This means that ASTM C1202 method is a clear reflection of the concrete electrical conductivity. Thus, this evaluation method does not offer major advantages than the assessment of conductivity in saturated surface dry condition (applying alternating current). This lack of added value implies that the ASTM C 1202 method, which has to be performed for 6 hours, is too laborious and expensive for the information it provides. Then, it is equivalent to measuring resistivity, which requires less than 5 minutes to be performed. In this sense, for all the studied concretes, the qualification based of Qe according to ASTM C1202 can be transferred to the respective resistivity values. The relationship found here (Figure 3) is similar to the one presented in [18], but different from the relationships reported in [21-23] where the surface resistivity was used for the comparison. Being that the case, the pressure exerted on the electrodes when assessing resistivity seems to be of major importance, where manual pressure will always result in higher resistivity values.

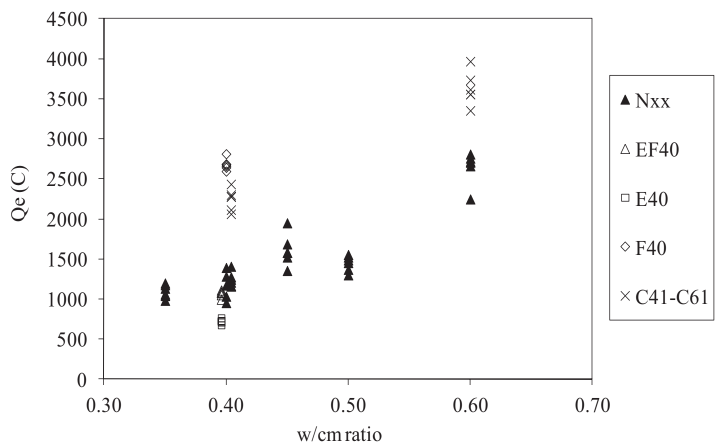

Figure 2: Results from ASTM C1202 test

In Figure 4, the relationship between standard bulk resistivity and the initial resistivity of concrete in the ASTM C1202 test configuration is presented. This comparison must include a differentiation between the variables for each of the two methods: the electrical potential and current type (60 V DC vs. 13 V CA), the type of contacting between electrodes and the sample (chloride solution and alkaline solution vs. pressed wet clothes), and test period (6 h vs. 5 min). Even with all these differences, the trend shows fairly equal values. From the comparison between Figures 3 and 4, it can be seen that the more porous concretes increase Qe more than initial conductivity.

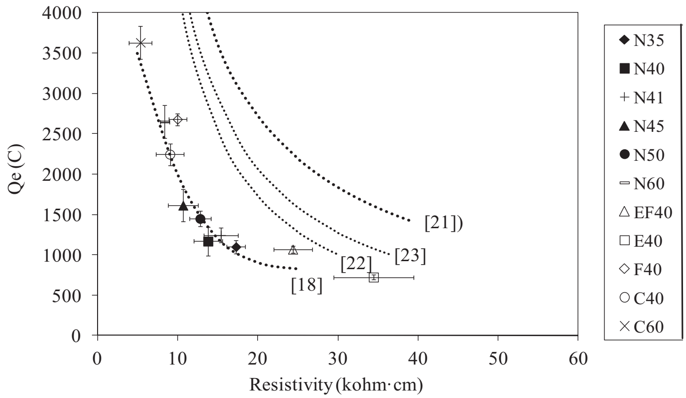

Figure 3: Relationship between resistivity and Qe according to ASTM C1202.

This is very likely connected to the heat produced due to the high electrical potential of 60 V that is applied. A significant temperature increase is caused, which in turns fastens the transport mechanism. This issue brings some doubts concerning the comparison by means of ASTM C1202 method among concretes with significantly different w/cm ratio, as they are ultimately tested at different temperatures.

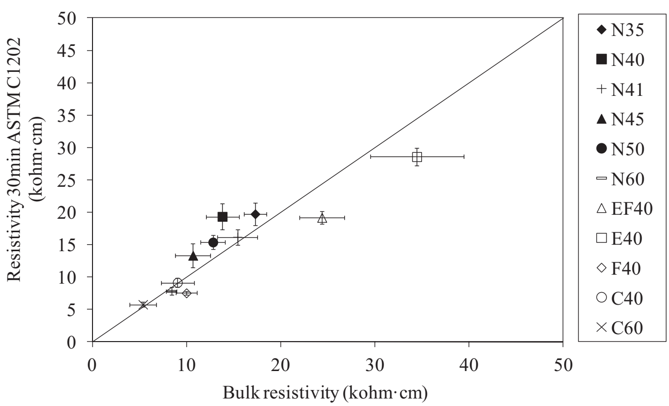

Figure 4: Relationship between resistivity after 30 min with ASTM C1202 configuration and conventional resistivity.

Naturally, the effect of active mineral admixtures on concrete conductivity is also reflected for the charge passing during the ASTM C1202 test. This is also a clear indication of this technique being an electrical conductivity method rather than providing an index of the chloride penetration rate. Additionally, it would be difficult to correct the temperature influence as it varies from one concrete to the other according to the porosity of each one.

Finally, a consideration to be made is that both resistivity and ASTM C1202 methods do not reflect on their results the chloride binding capacity. They are therefore useful in the description of porous properties of concrete but incomplete for the description of the resistance of concrete to chloride ingress. They can be applied as prescriptive indexes, but for performance based design complementary evaluation methods should be considered. This is particularly of interest in concretes containing blast furnace slag, as they usually show a much higher chloride binding capacity.

5 CONCLUSIONS

The results and analyses presented indicate the inadvisability for the application of the ASTM C1202 method. The same description of concrete can be obtained with the aid of the much simpler assessment of resistivity in the saturated surface dry condition, independently of concrete containing only OPC, OPC+slag or OPC+slag+limestone powder. Moreover, this assessment of resistivity does not imply any change in the temperature of the sample, as it occurs in the ASTM C1202 method.

Therefore, it is derived that the ASTM C 1202 method is essentially an electrical conductivity method rather than a method of assessing the resistance to chloride penetration. In fact, any migration method would be related to concrete conductivity, but the ASTM C1202 method is beyond all the rest of techniques, as it only analyzes the value for the charge passed. This is a significant limitation for the applicability of the method. The obtained results show that the information offered by the ASTM C1202 method is the same as that provided by the resistivity of concrete to alternating current. It should be mentioned that different correlations with the bulk resistivity and the four-point resistivity might be expected. In addition, the assessment of resistivity is less laborious, faster and more economical than the evaluation of the concrete's ability to resist the penetration of chloride ion, as defined by ASTM C1202. Moreover, the measured flowing charge show a linear relationship with the electrical current at the beginning of the test, making reasonable to consider a proposal to reduce the time length of the method, with a corresponding adaptation of the qualitative parameters to whether current, conductivity, electrical resistance or resistivity for interpreting the results.

Concrete resistivity shows great potential as a durability index. Besides its application for a qualitative approach, its usefulness would be increased with the characterization of the conductivity of the pore liquid. Then, this would allow to study concrete as a composite material and to infer the relationship between phases. From a pragmatic point of view, the implementation of concrete resistivity as a durability index is equivalent in utility to the ASTM C1202 method, but with a much more practical procedure.

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