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## CORROSION RESISTANCE OF CONCRETE INCORPORATING SUPPLEMENTARY CEMENTING MATERIALS IN A MARINE ENVIRONMENT

Andrew Fahim, Edward G. Moffatt and Michael D.A. Thomas

**Synopsis:** This paper presents results obtained from steel-reinforced concrete specimens retrieved after 25 to 27 years of exposure in a marine environment. The specimens included mixtures with various SCM blends (25% fly ash, 10% silica fume and 50% slag), as well as a mixture without any SCM, all at a W/CM of 0.50. Testing included chloride-ion depth determination, rapid chloride permeability test, bulk electrical resistivity test and electrochemical corrosion-monitoring. The chloride profiles revealed that SCM incorporation leads to a significant decrease in chloride-ion penetration, which was supported by rapid chloride permeability and bulk electrical resistivity tests. Electrochemical corrosion-monitoring showed passivity for all reinforcements at a cover depth of 70 mm or more for specimens incorporating SCMs, while for specimens not containing SCMs, all reinforcements, up to a cover depth of 140 mm, showed active corrosion. Finally, it was found that the reinforcement corrosion rate in SCM concrete was significantly lower than that for portland cement concrete.

**Keywords:** chloride ingress, corrosion, corrosion monitoring, marine environment, servicelife modeling, supplementary cementing materials, durability.

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# INTRODUCTION

Chloride-induced corrosion of steel reinforcement is one of the most common forms of deterioration in concrete exposed to harsh marine environments and/or de-icing salts. Although concrete is commonly being designed to withstand chloride ingress, it is inevitable that chlorides will eventually reach the surface of the reinforcement and initiate corrosion. Increased resistance to chloride ingress can be achieved by, among other things, the implementation of a low water-to-cementitious-materials ratio (W/CM), the incorporation of supplementary cementitious materials (SCMs) and the application of membranes and sealers. Although reducing the W/CM is beneficial in reducing the penetration of chlorides, a number of studies have reported that the effect was small compared to the presence of SCMs<sup>1-3</sup>. The incorporation of SCMs does not only result in a lower diffusion coefficient but also in a higher chemical binding capacity, for concrete containing fly ash and slag compared with plain portland cement (PC) systems<sup>4,5</sup>.

The level of chlorides required to reach and depassivate the passive layer surrounding the steel reinforcement is referred to in the literature as the chloride threshold value. The threshold values reported in the literature show a large scatter, ranging from 0.04% to 8.34% by weight of cement<sup>6</sup>. The range in thresholds has been ascribed to a number of factors including cement type, cement content, temperature, electrical potential of the steel surface, moisture content of the concrete, oxygen content of the concrete pore solution, concentration of hydroxyl ions in the concrete pore solution, the compound associated with the chloride and the method of threshold determination<sup>7-11</sup>. The addition of SCMs has been reported to decrease the pH of the pore solution, which has been found to decrease the chloride threshold for SCM systems<sup>9,11,12</sup>. However, the extent of this decrease is currently not well established. In a recent study, Trejo and Tibbits<sup>9</sup> found, based on short-term laboratory testing, that systems containing 20% to 40% fly ash and 40% to 60% slag have an average chloride threshold that is 12% and 6%, respectively, of that of the chloride threshold of systems without SCMs. This raises the question as to whether the incorporation of SCMs actually increases the time to corrosion initiation due to the significant decrease in the diffusion coefficients or if the threshold decrease, associated with these systems, may lead to decreasing the time of corrosion onset. The same concerns were raised recently by ACI 222 (Corrosion of Metals in Concrete) Committee, and it was concluded that more long-term testing is required to ascertain the effect of SCMs on the corrosion initiation time.

This paper reports corrosion performance results of reinforced concrete specimens prepared with and without SCMs after 25 to 27 years of exposure to a marine environment tidal zone.

In 1978, the Canadian Centre of Mineral and Energy Technology (CANMET) initiated a long-term study to determine the effect of W/CM, SCM incorporation, use of lightweight aggregate, air entrainment, epoxy coated reinforcements and ASR reactive aggregate on the performance of concrete exposed to a marine environment<sup>13</sup>. In order to achieve this, 14 series of concrete mixtures were placed at the Treat Island exposure site between 1978 and 1994 and have been monitored since then<sup>1,3,13</sup>. Treat Island is an outdoor exposure site operated by the U.S. Army Corps of Engineers, and is located in Passamaguoddy Bay, which runs into the Bay of Fundy. The site is exposed to the highest tides in the world (6 m [20 ft.]) as well as approximately 100 cycles of freezing and thawing per annum making it one of the harshest concrete environments in the world<sup>3</sup>. Phase IX of this study consisted of placing eight reinforced concrete blocks, two blocks from each mix, at the mid-tide level of the exposure site in 1987. One concrete mixture was produced using 100% Portland cement (PC) with no SCMs, while the three other mixtures contained either 25% fly ash, or 10% silica fume, or 50% slag. The specimens contained rebars at a cover depth of 30, 50, 70 and 140 mm (0.78, 1.96, 2.75 and 5.51 in.). In the period between 2012 and 2014, the specimens were retrieved in order to be tested as shown in the next sections.

## **RESEARCH SIGNIFICANCE**

This paper presents a unique opportunity to study the performance of reinforced concrete specimens containing various levels of SCMs when exposed to a severe marine environment. This research is unique since limited published field durability data exist on such systems exposed for 25 to 27 years. This research will serve as a valuable tool to help determine the long-term performance of these systems and answer the question of whether SCMs increase the time to corrosion initiation or if decreases in chloride threshold associated with these systems may have a substantial effect on the service life of SCM concrete.

## **EXPERIMENTAL PROCEDURE**

In 1987, eight reinforced concrete blocks from Phase IX of the CANMET investigation<sup>13</sup> were placed on a deck at the mid-tide level on the exposure site in Treat Island, Maine. Between 2012 and 2014, the eight blocks were retrieved from Treat Island and shipped to the University of New Brunswick, to be tested in the laboratory, after being exposed to tidal conditions in the Bay of Fundy for 25 to 27 years and approximately 18,250 cycles of wetting and drying and 2,500 cycles of freezing the thawing. Details of the specimens' fabrication and exposure history as well as laboratory testing performed can be found in this section.

#### Materials

Mixture proportions used in this investigation are presented in **Table 1**. All concrete specimens were cast using a W/CM of 0.50 and incorporating either no SCM, 25% fly ash, or 10% silica fume or 50% slag, by mass, as a replacement of cement. The fine aggregate used was a natural sand, and the coarse aggregate was a graded river gravel with a nominal maximum size of 19 mm (0.75 in.). In all mixtures, a sulphonated hydrocarbon type airentraining admixture was used in order to achieve an air content of 5% to 7% in addition to a high-range naphthalene-based superplasticizer to score a slump of 75  $\pm$  25 mm (3  $\pm$  1 in.). The portland cement used met the requirements of ASTM C150 Type I and had a C<sub>3</sub>A content of 11.4%. The slag used was a ground pelletized blast-furnace slag, the silica fume used was from a silicon and ferrosilicon plant and the fly ash used was a low-calcium ash. The chemical analysis of the above materials is given in **Table 2**.

# Specimens

The configuration of the reinforced concrete prims is shown in **Fig. 1**. The specimens had dimensions of  $305 \times 305 \times 915 \text{ mm} (1 \times 1 \times 3 \text{ ft.})$  and were reinforced with 20M longitudinal reinforcements (nominal diameter of 19.5 mm [0.77 in.]) and 2 tied 10M stirrups (nominal diameter of 11.3 mm [0.44 in.]) black steel at various cover depths (30, 50, 70 and 140 mm [0.78, 1.96, 2.75 and 5.51 in.]). All prisms were fabricated, in 1987, at the University of New Brunswick. The prisms were cast in two layers of equal depth with each layer vibrated with an internal vibrator. Upon completion, the concrete was struck off with a wooden straight edge trowel and then covered with wet burlap and plastic in order to cure. The prisms were demoulded after 24 hours of curing in laboratory air and then covered in wet burlap and plastic sheeting to be cured for 90 days prior to being shipped to the mid-tide deck at Treat Island.

In 2007, after 20 years of exposure, one block from each mix (specimens Z2, Z4, Z6 and Z8) was moved to the upper deck (above high-tide level) of the wharf at Treat Island to be exposed to oxygen for longer durations. This was done since no rust staining or cracking was observed, and it was hypothesized that the main reason for this was oxygen starvation. In 2012, after 25 years of exposure, the four blocks that remained on the mid-tide deck (specimens Z1, Z3, Z5 and Z7) for the entire exposure period were retrieved. These specimens were cored and tested as described in the next section. The blocks that were moved to the upper deck were retrieved in 2014, after 27 years of exposure, to be exposed to corrosion-stimulating conditions in the laboratory (in terms of relative humidity), and in order to perform corrosion monitoring. The blocks were put in containers with a 50-mm (2-in.) deep layer of water and the containers were covered with wet burlap and plastic in order to sustain the humidity required for corrosion propagation.

# **Parameters Investigated**

Two 102 mm (4 in.) diameter cores were drilled in each of the four prisms that were in the mid-tide level for 25 years. The cores were drilled through the entire prism, at the midpoint between the longitudinal reinforcement; such that the edge of the core was approximately 100 mm (4 in.) from the edge of the block. These cores were cut in order to produce specimens for testing rapid-chloride permeability (RCPT), bulk electrical resistivity and existing chloride profiles. Specimens for RCPT and electrical resistivity were cut from the center of these cores. The outermost portion of the core, which was directly exposed to chlorides, was finely ground in 5-mm (0.2-in.) depth increments and the powder was collected and tested for acid-soluble chloride content using potentiometric titration. Powder from the first millimeter of the core surface was also collected and tested similarly. RCPT was conducted using the procedure described in ASTM C1202. Bulk electrical resistivity test was performed on 50mm (2-in.) long specimens that were vacuum saturated as specified in ASTM C1202 prior to testing. In this test, an AC current is applied between two conductive plates fixed at both flat ends of the specimen, at a specified frequency (1 kHz was used for this study), and the potential difference between the plates is recorded. The electrical resistivity of concrete,  $\rho$ , (in kOhms.cm) can be calculated using equation 1.

$$\rho = R \frac{A}{L} \tag{1}$$

where R is the resistance of concrete (ratio of measured potential to applied current), A is the cross-sectional area of the specimen (in  $cm^2$ ) and L is the length of the specimen (in cm).

In order to measure the risk of corrosion, small notches were cut over the rebar at each cover depth, using a jackhammer, to allow an electrical connection to be made with the rebar. Halfcell potential measurements were conducted using a silver/silver chloride (Ag/AgCl) electrode mounted over each rebar location. Linear Polarization Resistance (LPR) and Electrochemical Impedance Spectroscopy (EIS) testing were performed using Gamry potentiostat reference 600. LPR relies on the assumption that there is a linear relationship between a small polarization ( $\Delta E < 20$  mV) around the corrosion potential and the corresponding current change ( $\Delta I$ ) resulting from such polarization. The slope of this linear region can be used to calculate the corrosion current density<sup>14</sup>, if the contribution from concrete's ohmic resistance is removed; this is performed using equations 2 and 3. The polarization scan rate used in this test was 0.167 mV/sec starting from  $E_{corr} - 10$ mV to  $E_{corr} + 10$  mV using an Ag/AgCl half-cell electrode.

$$R_p = \frac{\Delta V}{\Delta I} - R_\Omega \tag{2}$$

$$i_{corr} = \frac{B}{R_p A} \tag{3}$$

where  $\Delta V$  is the potential shift (in volts),  $\Delta I$  is the corresponding change in current (in amperes), A is the polarized area (in cm<sup>2</sup>), B is the Tafel coefficient (assumed to be 26 mV<sup>14</sup>) and R<sub> $\Omega$ </sub> is the ohmic system resistance (in ohms) (obtained from EIS through curve fitting).

EIS relies on the assumption that the reinforced concrete system can be modeled through simple circuit models. In EIS, a sinusoidal AC voltage is applied in a wide range of frequencies, and the impedance characteristics of the system (real and imaginary impedance as well as phase angle) are recorded through analyzing the applied voltage shift and the corresponding current for each frequency. The resulting impedance spectra are then fitted to the impedance spectra of circuit models with known components, in order to determine, quantitatively, the system characteristics ( $R_p$ ,  $R_\Omega$  and double layer capacitance). For this portion of testing, Potentiostatic EIS mode was used with an applied AC voltage of 10 mV with an initial frequency of 10,000 Hz and a final frequency of 0.001 Hz. EIS spectra were fitted to the circuit models proposed by Christensen et al.<sup>15</sup> or by John et al.<sup>16</sup> depending on the shape of the spectrum. The test setup for both LPR and EIS is shown in **Fig. 1**. For all of the testing, measurements were taken after the surface was wetted and the half-cell potential was monitored till stabilized.

#### **EXPERIMENTAL RESULTS AND DISCUSSION**

#### **Chloride Ingress**

**Figure 2** presents the measured chloride profiles for the four mixtures after 25 years of marine tidal exposure, together with results from a service-life prediction model and a previously reported chloride profile from another phase of the CANMET investigation<sup>1</sup> in which plain PC concrete with a W/CM of 0.40 was tested after 25 years of exposure in the mid-tide level at Treat Island. The advantageous effect of SCM additions on concrete resistance to chloride penetration is evident from the measured profiles. The profiles show substantially lower chloride penetration depths for all SCM concrete compared to plain portland cement concrete. The differences in chloride content at a depth where steel should be encountered, considering specified minimum cover depths for marine concrete, is dramatic. For example, at a depth of 60 mm, which is the minimum cover specified in CSA

for marine concrete, the chloride contents were all below 0.015% for the SCM concretes compared with approximately 0.350% (20 times higher) for PC concrete.

It is well established that there is currently no single value that can represent the critical chloride threshold. Values in the range of 0.02% to 0.15% (chlorides by mass of concrete) have typically been reported in the literature for outdoor exposure conditions or actual structures<sup>6</sup>. It can be seen that the PC specimen showed chloride contents higher than these values for all of the cover depths in this study. It should be noted that the portland cement used for this study contained a  $C_3A$  content of 11.4%. Therefore, such reductions in chloride penetration clearly highlight the effect of SCM incorporation even in cases where the portland cement is expected to have a high binding capacity and subsequently a high chloride ingress resistance. The substantial decrease in chloride penetration is reported elsewhere from previous results of the CANMET study<sup>1,3</sup> and is believed to be mainly attributed to the beneficial effect of SCMs in densifying the paste microstructure and partially to the increased chloride binding capacity, for fly ash and slag systems<sup>4,5</sup>. It should be noted that the results did not allow for calculating diffusion coefficients. Firstly, due to observing that chlorides penetrated throughout the full depth of the PC specimen, which shows 2-dimensional diffusion (specimen dimensions were 305 x 305 mm [1ft. x 1ft.]) and secondly, due to the noise observed in the first 25 mm for the SCM concrete, which may be attributed to the effect of surface scaling, chloride washout and carbonation.

**Figure 2** also shows a previously published chloride profile from another phase of the CANMET investigation, in which plain PC concrete prisms, having the same dimensions, at a W/CM of 0.40, were exposed in mid-tide level in Treat Island for 25 years. The profile shows chloride contents that are significantly higher than those for SCM concrete presented in this study. This shows that the effect of SCM addition on the chloride penetration resistance is substantially higher than the effect of solely decreasing the W/CM. These results, as well as previously published results<sup>1,3</sup>, provide evidence that plain portland cement concrete is not expected to reach the commonly required service lives in similar exposure conditions, without the incorporation of SCMs; regardless of the W/CM, cover depth, or the associated threshold for such systems.

It is now well established that W/CM values similar to those used in this investigation are not accepted for marine environments. Even with the substantial increase in chloride-ion penetration resistance obtained through SCM incorporation, concrete at such W/CM is also not expected to reach the commonly required service lives. Although the effect of SCM incorporation on chloride penetration resistance is evident and is much higher than that of only decreasing the W/CM, the chloride profiles show that service lives in the range of 50-100 years in harsh exposure environments can only be attained through the synergetic effect of decreasing the W/CM, increasing the cover depth sufficiently and the use of SCMs.

**Figure 2** also shows the predicted chloride profiles using the service-life model Life- $365^{17}$  using the mixture proportions shown in Table 1 and the (built-in) climate data for Eastport, Maine. Note that Life-365 normally assumes a constant surface chloride concentration of Cs = 0.8% (by mass of concrete) for the tidal zone, but this value was changed to 0.5% for this analysis. The lower surface concentration is thought to be the result of the relatively low paste content of these mixtures and, perhaps, the loss of paste at the surface during exposure. The predicted profile for the portland cement concrete mixture assumed that the chlorides are penetrating the exposed face where the core was taken and from the two adjacent faces parallel to the direction of coring. Generally, the predictions from Life-365 are quite close to the measured profiles although the model predicts slightly increased penetration for the

concrete with SCM. The predicted profiles are, practically, acceptable, albeit, conservative for SCM concrete; considering that the only model inputs required were W/CM, age and SCM type and percentage. Life-365 uses two parameters to determine the chloride resistance of a concrete mixture; the first is the early-age diffusion coefficient,  $D_{28}$ , and the second is the m-value, which defines the rate of diffusion coefficient reduction with age. The values for the concrete mixtures used here are shown in **Table 3** together with the predicted diffusion coefficient at 25 years calculated from  $D_{28}$  and m-value.

## **Rapid Chloride Permeability and Bulk Electrical Resistivity Tests**

The results from the RCPT and electrical resistivity tests are presented in Table 3. The results are consistent with the chloride penetration results; with SCM incorporation showing much improved performance. Both electrical tests ranked the mixtures in the same order found through the chloride profiles with the slag mixture showing the largest improvement, compared with PC concrete, and the silica fume showing the least. However, the extent of the improvement was somewhat less pronounced in these tests compared with the chloride profile results. SCM concrete showed reductions in the RCPT value in the range of 2.0 to 3.5 times, when compared to PC concrete, and increases in electrical resistivity in the range of 1.9 to 3.4 times. On the other hand, the decrease in chloride ion penetration, as a result of SCM incorporation, was much more significant as shown in the chloride profiles obtained after 25 years of exposure (the measured chloride contents were less than 0.01% for 65 mm depth for SCM concrete and more than 0.19% for 140 mm depth for PC concrete). This leads to major concerns about using the results from such test methods to predict concrete longterm performance or diffusion coefficient. The correlation between RCPT and bulk resistivity is expected since both tests essentially measure the electric current flowing through the capillary pore system of the concrete or the overall conductivity of concrete, which depends on the pore structure tortuosity and connectivity as well as the pore solution composition and conductance. Both tests do not actually measure concrete resistance to chloride ingress, instead the result is a function of the amount, type and mobility of ions in the pore solution; not specifically chloride ions.

It has been demonstrated that the application of a potential gradient across specimens, in the RCPT test, for instance, will lead to mobilizing different ions in the pore structure (OH-, SO4<sup>2-</sup>, K<sup>+</sup>, Na<sup>+</sup> and Ca<sup>+</sup>) in order to carry the current passing through the cell<sup>18</sup>. The total current is exerted in moving all these ions not only chlorides. It should also be stressed that a number of authors<sup>19,20</sup> have suggested that the application of a difference in potential of 60V results in the RCPT test results in a rate of ionic transport that is much faster than the kinetics of chloride binding. Castellote et al.<sup>21</sup> supported this by noting that the equilibrium of the binding process is not instantaneously achieved, which causes the effect of binding to be negligible on the local ionic concentration since the applied voltage is usually sufficiently strong to overcome the tendency of paste to bind chlorides. The same authors also hypothesized that the electrical field could alter the nature of the double layer of the pore walls. Therefore, changing the double layer potential and, consequently, causing a different interaction between the chlorides and the paste. This can explain the reason behind different authors finding different correlations between ion-migration tests and diffusion coefficients for different mixture compositions or different ages and some authors not finding a correlation at all<sup>22-24</sup>. The result shows the conductivity, tortuosity and connectivity of the pore structure and does not draw the full picture by putting the effect of chloride binding into consideration. It should also be mentioned that in actual field exposure conditions, diffusion due to concentration gradients is not the only mechanism of chloride ingress, capillary

suction and sorption and in some cases wicking action does happen; which contributes further to the uncertainty about the applicability of ion-migration testing.

# Half-Cell Potential

Half-cell potential results can be found in **Fig. 3** together with the typical specification limits used for Ag/AgCl electrode shown by dashed lines<sup>25</sup>. The plotted results are the average of four half-cell potential tests performed in two locations over the reinforcement at different times. It should be noted, first, that the chloride profiles presented earlier were obtained for specimens exposed at the mid-tide level for 25 years, while the electrochemical tests are for specimens that were exposed at mid-tide for 20 years and above high-tide for 7 years. The profiles were also obtained from a core located between rebars. The chloride concentration over the rebar will be different due to chloride penetration from both edges nearest to the reinforcement. Therefore, results from the profiles should not be viewed as chloride threshold results. The thresholds associated with these specimens will be presented in a subsequent paper. The results show that for the specimen not incorporating SCMs, all of the reinforcements, at all cover depths, showed active corrosion. For the specimens incorporating SCMs, the results showed passivity for all reinforcements at a cover depth of more than 50 mm (2 in.). It should be noted that the half-cell measurements were taken by connecting a half-cell electrode to the stirrup. However, the measurement will include a mixed potential of both the transverse and the longitudinal reinforcement due to these bars being directly connected. The results clearly show the beneficial effect of the addition of SCM on the time to initiation. It can be seen that for systems incorporating SCMs, lower cover depths are sufficient to produce the required service life compared to those for concretes with no SCMs. As expected, the results demonstrate that high concrete cover depths can significantly delay the time to initiation if the concrete is well designed (W/CM kept sufficiently low and SCMs are used). It can be seen that at 70 mm (2.75 in.) of cover, the potentials for 25FA and 10SF mixes were more negative than -106 mV, which falls in the uncertainty range reported in the literature<sup>25</sup>. It should be stressed that the half-cell potential results cannot detect with certainty if corrosion has initiated or not, due to the results being affected by the oxygen availability<sup>25</sup>. Such negative potentials found at 70 mm (2.75 in.) cover depth can be attributed to the limited oxygen availability. The 70 and 140 mm (2.75 and 5.5 in.) cover depth reinforcements were tested again in the air-dried condition, and the results ranged from -30 to -70 mV, which confirms that the result is attributed to oxygen deprivation.

# **Corrosion Rate Determination**

**Fig. 4** presents corrosion current density results obtained through LPR together with typical specification limits used which are shown by dashed lines<sup>25</sup>. The results plotted are the average of two tests done on the same rebar. The results support those found by the half-cell potential technique. It can be observed that, regardless of the cover depth, all of the reinforcements embedded in the 100PC mix are actively corroding. For the specimens incorporating SCMs, the corrosion rates reveal, with certainty, that the reinforcements with 30 mm (1.2 in.) cover depths are actively corroding. However, the corrosion rates are much lower than those found for the specimens not incorporating SCMs. The results for reinforcements with 50 mm (2 in.) cover depths show corrosion rates that are in the range of low to moderate corrosion behavior for 25FA and 50SG specimens and moderate to high range for 10SF mixture. The reinforcements with 70 and 140 mm (2.75 and 5.5 in.) both fall in the range of low to moderate corrosion rates. It should be noted that this range is typically treated in the literature with some uncertainty and the results do not indicate corrosion initiation. The results from half-cell potentials lead to the belief that reinforcements at a cover

depth of 70 mm (2.75 in.) remained passive. The corrosion rates fell in the range of 0.3  $\mu$ A/cm<sup>2</sup> for the 70 and 140 mm (2.75 and 5.5 in.) cover depths for SCM specimens. Having equal corrosion current density results, for both cover depths, also supports this hypothesis. These results may be attributed to polarization area or ohmic resistance compensation errors. LPR results generally showed that the corrosion propagation rate for SCM concrete is less than that observed for Portland cement concrete, regardless of the cover depth or SCM type. This will be investigated further using EIS.

EIS results are shown in **Fig. 5**. The results plotted are the average of two tests done on the same reinforcement. The results prove that reinforcements at 30 and 50 mm (1.2 and 2 in.) of cover initiated corrosion for all of the specimens included in this study and that the 70 and 140 mm (2.75 and 5.5 in.) of cover reinforcements remained in the range of low to intermediate corrosion rates only for SCM concrete. As noted earlier through LPR results, the corrosion rates for SCM concrete, for both 30 and 50 mm (1.2 and 2 in.) cover depths, are lower than the corrosion rates for Portland cement concrete. In order to investigate this further, the ohmic resistance obtained through EIS is plotted versus the corrosion rates in Fig. 5. It can be seen that there is an inversely proportional relationship between the logarithmic of ohmic resistance and corrosion rate. This agrees with the results found by Alonso et al.<sup>26</sup> and Lopez and Gonzalez<sup>27</sup>. The resistivity influences the corrosion rate through the electrolyte's ohmic drop, which happens between anodic and cathodic sites. This is mainly due to the potential difference between the equilibrium potentials of the cathode and anode (the driving force for the corrosion process) being dissipated in overcoming the electrolytic resistance. Another factor that contributes to the decreased corrosion rates is cathodic control due to the lower porosity and oxygen diffusion rate associated with SCM additions. These results provide evidence that the time to cracking for systems will be higher than that associated with portland cement concrete. It should be noted that the passive reinforcements were included in the figure only for completeness. The passive reinforcements' corrosion rate is expected to be under passivation control and not ohmic resistance control and the corrosion rate will be dependent on the passive film properties<sup>27</sup>.

# FURTHER RESEARCH

A subsequent paper will present the threshold values associated with the specimens along with chloride binding results using X-Ray diffraction and electrochemical corrosion-monitoring using Tafel plot technique testing. The results of this study highlight the need to find reliable chloride threshold values for SCM concrete in order to predict the extent of service-life extension. Finding a standardized chloride threshold test is, subsequently, one of the major challenges facing the industry at the moment.

## CONCLUSIONS

The following conclusions can be drawn based on the presented results:

- 1. The incorporation of SCMs leads to a significant increase in the resistance to chloride ingress, even in cases where high C<sub>3</sub>A cements are used. The effect was more pronounced than that of solely decreasing the W/CM.
- 2. Life-365 service-life prediction model can predict chloride profiles with a reasonable degree of accuracy with very simplistic inputs.