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Service-Life Monitoring for the Confederation Bridge

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Abstract: The 12.9-km long Confederation Bridge between Prince Edward Island and New Brunswick was completed and opened for traffic in 1997. The bridge was designed to last 100 years in the aggressive environment of the Northumberland Strait where the reinforced concrete components are exposed to seawater, multiple freeze-thaw cycles, ice abrasion and the application of de-icing salts. The barrier wall which runs a total length of approximately 26 km was cast using slip form construction. Construction began in 1996 and was completed in 1997 and the wall was coated using an acrylic coating on the inside face of the wall. In addition to the barrier wall, two monitoring blocks were cast near the approach of the bridge in order to study the effect of concrete with and without the acrylic coating. Periodic testing of the concrete includes establishing chloride profiles and corrosion monitoring of embedded steel probes located at various depths from the surface. A model has been developed to fit the existing data and to predict the remaining time before corrosion is initiated. The output from the model is used to assist in decisions regarding preventative maintenance. This paper discusses the development of the model and the corrosion-prevention strategies employed in the design and construction of the barrier wall.

1. Introduction

Reinforced concrete structures exposed to marine environments and de-icing salts are prone to corrosion if a sufficient concentration of chloride ions reaches the reinforcing steel embedded in the concrete. The resistance of concrete to chloride penetration is controlled predominantly by the pore structure of the concrete (i.e. the size, connectivity and tortuosity of the pores) and, to a lesser extent, the ability of the cement hydrates to bind chloride ions. This resistance can be increased by reducing the water-to-cementitious material (W/CM) ratio, the appropriate use of supplementary cementing materials (such as fly ash, slag, silica fume and natural pozzolans), and by adopting proper practices to ensure adequate consolidation, curing and measures to minimize cracking. The time to corrosion initiation will be dependent to a great extent on the quality of the concrete but additional strategies can be employed to extend the life of the structure; these include increasing the depth of cover, the application of surface coatings or membranes, the incorporation of corrosion inhibitors and the use of corrosion-resistant steel.

This paper describes the corrosion protection strategies used for the barrier wall on the Confederation Bridge where chloride resistance was provided by the use of low-permeability concrete containing silica fume and the application of an acrylic coating. The performance of the protection system is monitored and the resulting data used to predict remaining life and determine if and when preventive maintenance (such as reapplication of the coating) may be required.

2. Confederation Bridge Background

The Confederation Bridge is a fixed link spanning 12.9 kilometers between New Brunswick and Prince Edward Island that was completed and opened to traffic in the summer of 1997. The bridge reaches an average height of 40 meters in most sections although it increases to 60 meters in order to allow a passage for large vessels.

The bridge is a concrete structure comprised of a pre-cast, post-tensioned concrete box girder design. The barrier wall, which is located on either side of the two-lane bridge, was cast using slip form construction in order to achieve rapid placement of concrete along a total length of approximately 26 kilometers (Lin, 2010). Pouring of the barrier wall began on July 18, 1996, and was mostly completed by November, 1996, although some sections were not completed until April 1997. Soon thereafter the bridge was open to the travelling public.

The barrier wall, shown in Figure 1, was constructed to a height of 1100mm with an overhang of 180mm to cover the transverse post-tensioning anchorheads. The concrete cover for the inner and outer faces is 75mm and 60mm, respectively. The cover was increased from the original design of 50mm for both the front and back sides of the barrier wall. During the summer months both sides are exposed to spray from the Northumberland Strait while the front side of the wall is exposed to de-icing salts during the winter months. Due to the severity of the de-icing salts the front cover is greater than the back. Each spring, the front face is flushed with fresh water to remove the accumulated road salt residue.

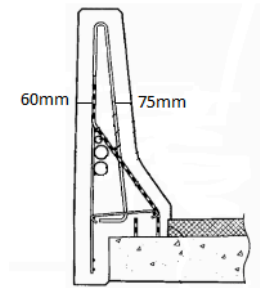


Figure 1: Barrier Wall cross-section

Table 1 summarizes the concrete mixture proportions used to construct the barrier walls. A minimum compressive strength of 45 MPa and a maximum water-to-cementitious-material ratio of $W/CM = 0.40$ was specified. The cement used was designated Type LASF and is a low-alkali blended portland cement containing approximately 8 to 9 % silica fume.

Table 1: Barrier Wall Mix Design

Material	Quantity (kg/m^3)
Cement (LASF)	360
Water	138
W/CM	0.38
Sand	782
Stone	1080
Air %	6
Water Reducer	1.44 (L/m^3)

Following the completion of the barrier wall, a coating was applied to the front face of the barrier. An acrylic coating was selected to protect the barrier wall from marine spray and de-icing salts. This product was sprayed on the surface of the barrier wall using a compressed air spray gun. Acrylic coatings have

shown impressive results in protecting concrete exposed to chlorides (Almusallam et al, 2003).

Two test blocks were cast on Prince Edward Island near the approach of the bridge to allow assessment of the coating on chloride penetration. The blocks were cast using the same materials and mixture proportions as the barrier wall, but were cast in wooden forms rather than being slip-formed. The acrylic coating was hand applied to one of the test blocks.

3. Results and Discussion

3.1 Chloride Ingress

In order to gain an understanding of how the coating is performing over time, concrete cores were taken from both the barrier wall and the two test blocks at regular intervals. Cores were taken from test blocks in 2003, 2008 and 2012 and from the barrier wall in 2004, 2008 and 2012. Cores from the barrier wall were taken from five locations along the inside of the barrier wall (N37, N78, N132, S37, S78), where N and S designate North and South sides of the bridge. Only one core was taken from each of the test blocks (96 and 97) at each interval; the acrylic coating was applied to block 96 only.

Cores at each interval were used to determine the chloride profile and to determine the depth to which chlorides had penetrated relative to time. All cores were profile ground in 1-mm increments for the first 10 mm and then 2-mm increments to a total depth of 25mm. The chloride content for each increment was determined by digesting the powder samples gained from profile grinding in nitric acid and performing potentiometric titration with silver nitrate. The chloride content was determined on the basis of total chloride percent by mass of concrete, and was then converted to units of mass percent of cement assuming a cementitious material content and concrete density from the mixture proportions.

Figure 2 is an average chloride penetration profile of the five cores taken along the barrier wall in 2004, 2008 and 2012 (five cores taken each year). Assuming a chloride threshold value of 0.4% by mass of cement for the initiation of corrosion (a commonly accepted value), it can be seen that the threshold value has penetrated by approximately 13 to 15 mm in cores extracted during 2008 and 2012. It is evident that very little change in the chloride profile occurred between 2008 and 2012. This is possibly the result of the relatively short time interval between measurements, but may also be an indication that the rate of ingress is decreasing with time; perhaps due to the concrete ability to bind chlorides. The shallow depth data in Figure 2 indicates that the surface concentration is increasing with time as can be expected for a concrete exposed to deicing salts on a seasonal basis.

Figure 3 shows the chloride profiles of cores taken from both the coated block (block 96) and the uncoated block (block 97) in 2003, 2008 and 2012. At each time interval there are significant differences in the surface concentration comparing the coated and uncoated blocks with the coating being effective in reducing the surface chloride content. The chloride content is also lower in the coated block at depth (e.g. 10 mm) when comparing cores extracted in 2003. However, the differences in the chloride content at depth for uncoated and coated blocks is not that marked at later ages and for the cores taken in 2012 it would appear the threshold concentration (0.4% chloride by mass of cement) has penetrated approximately the same distance in both blocks.

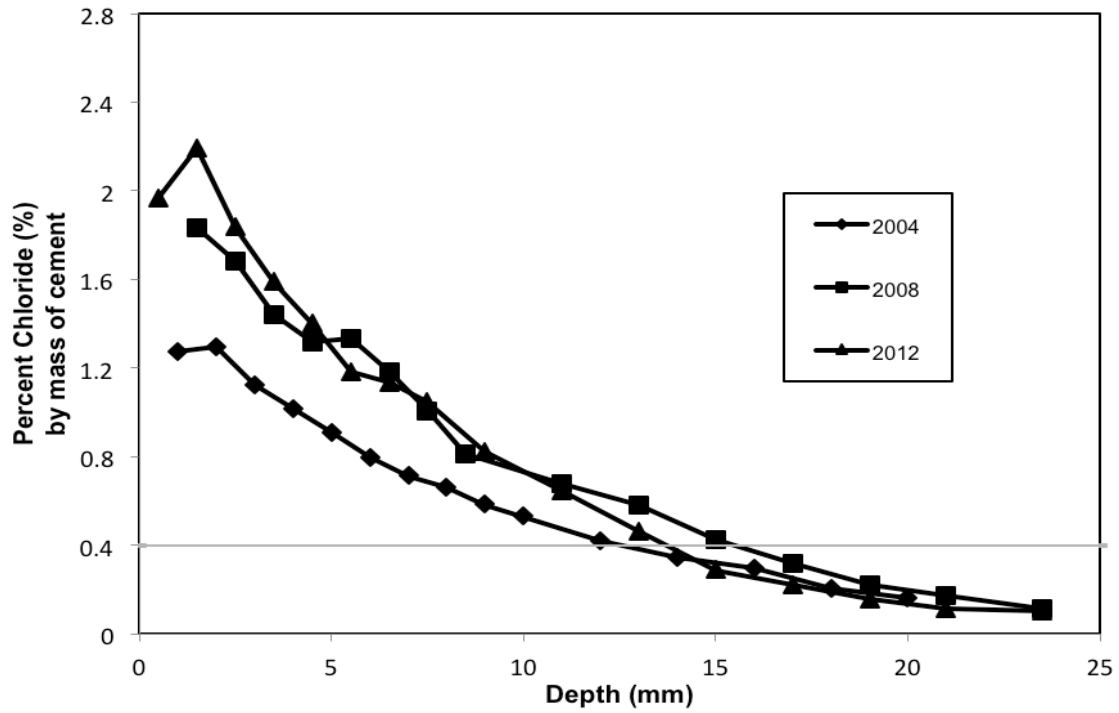


Figure 2- Barrier Wall Chloride Penetration (each profile is an average for 5 cores)

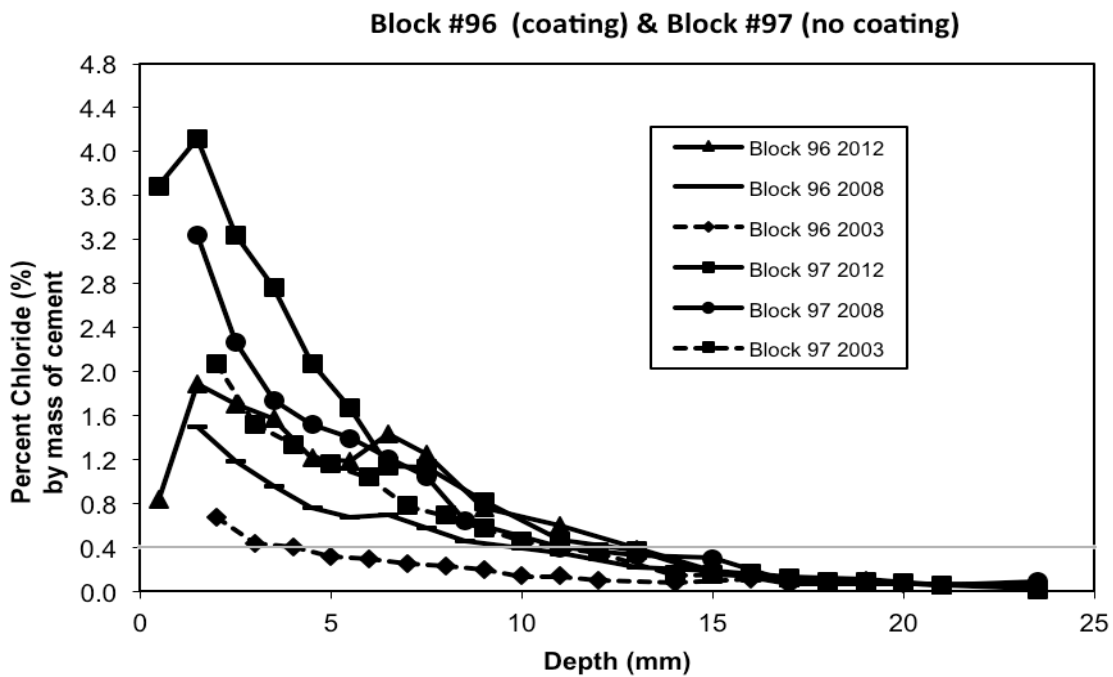


Figure 3 – Test Block Chloride Penetration

Figure 4 compares the chloride profiles for the barrier wall and the test blocks for cores taken in 2012. Despite differences in the methods of forming and coating application the profiles for the barrier wall and the coated block are remarkably similar at depths greater than 7mm. However uncoated block shows much higher chloride concentrations closer to the surface compared with the coated concretes, but the concentration profiles below 7 mm are surprisingly similar, and the chloride threshold concentration (0.4% chloride by mass of cement) appears to have penetrated to approximately the same depth (~ 13 mm) in all three cases.

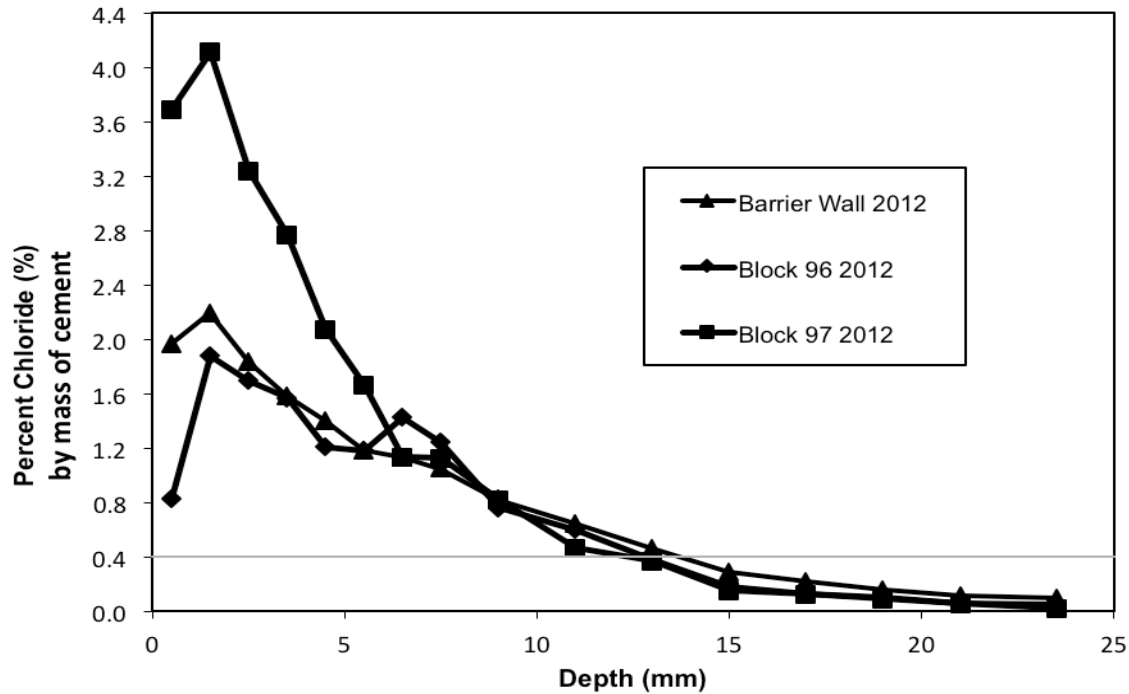


Figure 4 – Comparison between Barrier Wall and Test Block

Figure 5 shows the change in the surface concentration, C_s , with time for the coated and uncoated concretes. The surface concentration was calculated by fitting Equation 1 to the experimental profiles and using regression analysis to determine the best-fit values of C_s and D_c for each age.

$$[1] \quad \frac{C_x}{C_s} = 1 - \operatorname{erf}\left(\frac{x}{2\sqrt{D_c t}}\right)$$

where C_s is the chloride concentration at the surface (%), C_x is the chloride concentration (%) at depth x (m) and time t (s), and D_c is the effective chloride diffusion coefficient (m^2/s). Equation 1 assumes the surface concentration and diffusion coefficient are constant with time.

In all cases the surface concentration appears to be increasing linearly with time. The coating appears to have been effective in reducing the rate of increase of the surface concentration by half. Also shown in Figure 5 is a typical loading used for concrete exposed to deicing salts in predictive models such as Life-365 (Ehlen et al. 2009). The surface concentration is normally assumed to increase linearly with time until a maximum value is reached beyond which the concentration remains constant. The rate of buildup and the magnitude of the maximum value depend on the exposure conditions particularly the deicing salt

application rates. It is too early to determine at what point the surface concentrations in the barrier walls and blocks will reach a threshold.

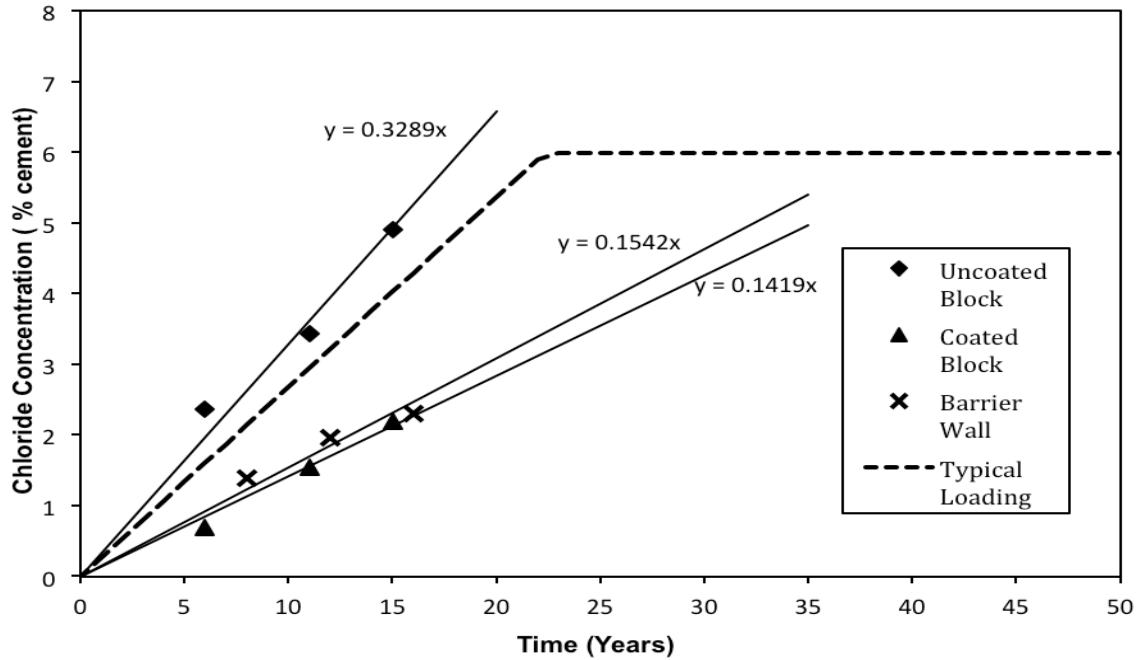


Figure 5 – Surface Concentration Comparison at a depth of 2mm.

3.2 Service-Life Prediction

A simple methodology that could be used to determine the residual service life (or time-to-corrosion) of the barrier wall would be to calculate D_c for the various chloride concentration profiles by fitting Eqn.1 to the profiles, and then using the same equation to predict the time at which the chloride concentration at the depth of the reinforcing steel reaches the chloride threshold value. Such an approach has frequently been used in similar studies reported in the literature. This approach is less accurate when both the diffusion coefficient, D_c , and the surface concentration, C_s , vary significantly with time.

Ideally the service-life prediction should account for the time-dependent changes of D_c and C_s , and also for the effect of temperature on diffusion. The previously mentioned model Life-365 accounts for the change in surface chloride concentration as discussed above and accounts for the effect of time and temperature through Eqn. 2 as follows:

$$[2] \quad D(t, T) = D_{ref} \cdot \left(\frac{t_{ref}}{t} \right)^m \cdot \exp \left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$$

where: $D(t, T)$ is the diffusion coefficient (m^2/s) at time t (s) and temperature T (K), D_{ref} is the diffusion coefficient measured at some reference time t_{ref} and temperature T_{ref} , m is a constant, U is the activation energy (taken as 35000 J/mol) and R is the universal gas constant (8.3144 J/mol/K). In Life-365 D_{ref} is the diffusion coefficient at a reference time of 28 days and temperature of 20°C (293K).

For the purpose of this study Life-365 was used by setting the following parameters:

- temperature history (monthly average) selected for Charlottetown, PEI (database incorporated in Life-365)
- $m = 0.2$ (default value in Life-365 for concrete with silica fume)
- surface concentration allowed to increase linearly with time up to a maximum value of 6% (by mass of cement) at 40 years

The reference diffusion coefficient, D_{ref} , was then selected to provide a fit to the data for all five cores extracted from the coated barrier wall in 2012 and to pass through the threshold concentration of 0.4% (by mass of cement) at a depth of 15 mm. The profile at 15 years using Life-365 with the values selected is shown Figure 6. The value of the reference diffusion coefficient used is $D_{ref} = 8.5 \times 10^{-13} \text{ m}^2/\text{s}$.

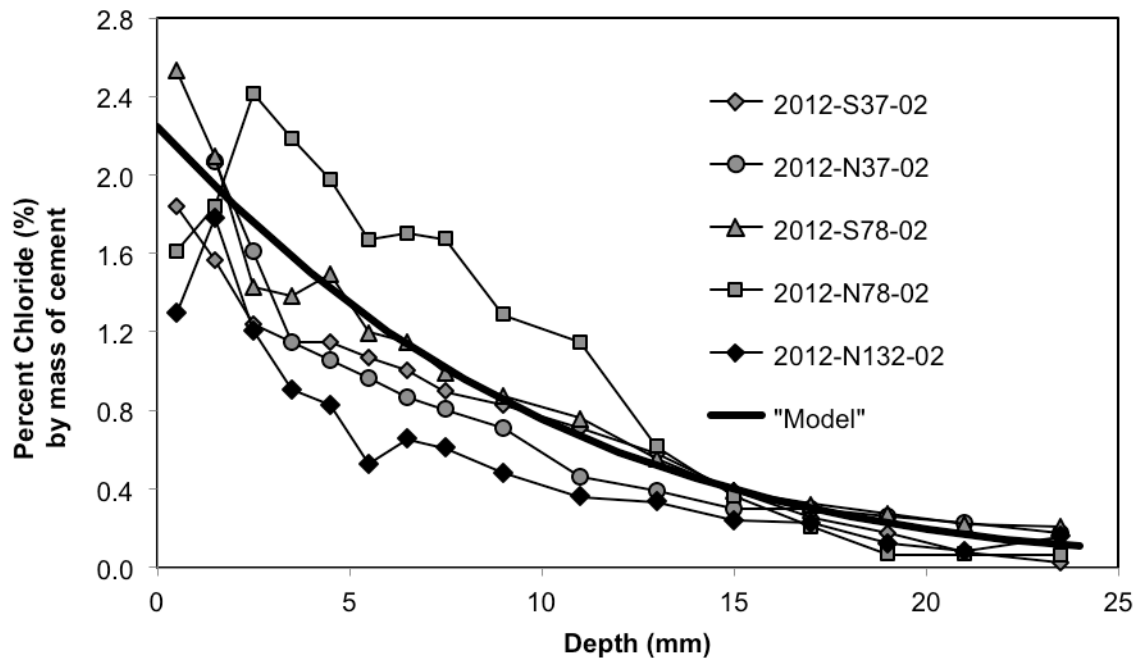


Figure 6 - Profile Determined by Life-365 for the Coated Barrier Wall (using $D_{ref} = 8.5 \times 10^{-13} \text{ m}^2/\text{s}$, $m = 0.2$, maximum surface concentration of 6% by mass of cement at 40 years and average monthly temperatures for Charlottetown, PEI).

Assuming that surface chloride concentration will continue to increase beyond 15 years to a maximum of 6% (by mass of cement) at 40 years and that the diffusion coefficient continues to decrease as per Eqn. 2 with $m = 0.20$ ¹, the predicted time for the threshold concentration of 0.4% (by mass of cement) to reach the steel at a depth of 75 mm is 119 years.

A similar analysis was performed using the single profile available for the uncoated block in 2012 (see Figure 7). The same inputs were used for temperature history and the m -value but the rate of increase of the surface chloride concentration was increased so that the maximum value of 6% (by mass of cement) was reached in 20 years. This yields a calculated diffusion coefficient of $D_{ref} = 3.2 \times 10^{-13} \text{ m}^2/\text{s}$ and a calculated time-to-corrosion of 273 years.

¹ Note that Life-365 assumes that the diffusion coefficient, D_t , will decrease with time in accordance with Eqn. 2 until the concrete reaches an age of 25 years after which the value of D_t remains constant with time.

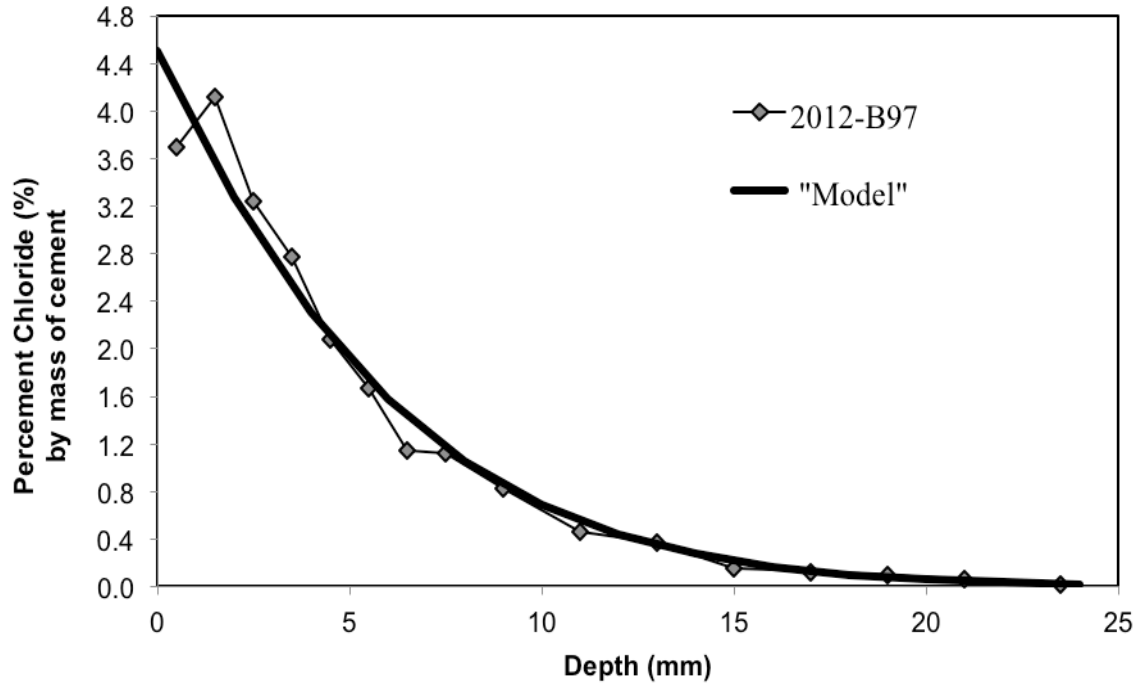


Figure 7 - Profile determined by Life-365 for the Uncoated Block (using $D_{ref} = 3.2 \times 10^{-13} \text{ m}^2/\text{s}$, $m = 0.2$, maximum surface concentration 6% by mass of cement at 20 years and average monthly temperatures for Charlottetown, PEI).

4. Discussion

The predicted time-to-corrosion of the steel reinforcement in the coated barrier is 119 years. A number of assumptions were necessary to enable the prediction to be made including the value of $m = 0.2$ (default value in Life-365). Inspection of the data shows that the profiles at the three ages tested are comparatively close indicating a decrease in the rate of chloride penetration with time. It is difficult to calculate a more realistic m -value with the data available at this time but this may be possible when further data are collected at later ages.

A similar analysis for the uncoated block resulted in a lower diffusion coefficient and a significantly longer predicted service life. At first sight this appears unexpected because the chloride concentrations are elevated close to the surface on the uncoated block compared with the coated block. However, the chloride contents at depths below about 5 mm are generally similar for the coated and uncoated blocks. Having an increased surface concentration but similar concentration at depth leads to a lower diffusion coefficient being calculated for the uncoated concrete. This could be a result of the method of determining the diffusion coefficient, it may be an indication that diffusion is not the primary mechanism of transport in this exposure environment or it may actually be that a lower diffusion rate occurs in the uncoated block. One possible explanation for a lower diffusion coefficient is that the uncoated block might have greater exposure to moisture in service (assuming the coating inhibits moisture transfer) leading to an increase in the degree of hydration and concomitant reductions in diffusivity with time (Scott et. al., 2005). This requires further testing is required to understand the different behaviour of the coated and uncoated specimens.

Given the comparative performance of the coated and uncoated specimens the reapplication of the coating to the barrier wall does not seem warranted at this time. It appears that the barrier wall will achieve its required service (100 years) with no further intervention. Continued monitoring is

recommended to better understand how the chloride ingress progresses with time and how the ingress is influenced by the coating.

5. Conclusion

The chloride ingress in concretes exposed to deicing salts and marine salt spray was investigated for a barrier wall coated with an acrylic compound and two test blocks of the same concrete composition one of which was coated with the same material. The chloride profiles established at various ages up to 15 years were very similar for the coated barrier wall and block, and the depth of penetration of the threshold chloride content (0.4% by mass of cement) was approximately 15 mm at 15 years. The uncoated block had significantly higher chloride concentrations at the surface. For all three concretes it appears that the surface chloride concentration is increasing linearly with time, the rate of increase being approximately twice as fast in the uncoated block. Despite increases in the surface concentration in the coated block, the chloride profiles were almost identical at depths below approximately 5 mm in all three concretes and there was little observable difference in the depth of penetration of the chloride threshold. This leads to a lower calculated diffusion coefficient for the uncoated block and a longer predicted time-to-corrosion. Consequently, the beneficial ability of a coating to inhibit chloride ingress appears to be uncertain. Additional longer-term data is required to determine whether recoating the barrier wall is likely to have a positive effect in extending its life.

6.0 References

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