ECOSMART FOUNDATION INC.
Durability Evaluation of Concrete Mixes with High Volume Fly Ash (HVFA)

Final Report
May 2008
Project No. SIMCORD07014

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April 2008

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THE STADIUM® MODEL IS A HELPFUL TOOL TO PREDICT THE FUTURE CONDITIONS OF CONCRETE MATERIALS. HOWEVER, ALL DURABILITY-MODELING PARAMETERS HAVE A STATISTICAL RANGE OF ACCEPTABLE RESULTS. THE MODELING IN THIS REPORT USES MEAN LABORATORY - OR FIELD-DETERMINED SINGLE VALUES AS INPUT PARAMETERS. THIS PROVIDES A SINGLE RESULT, WHICH PROVIDES A SIMPLE ANALYSIS EVALUATING CORROSION PROTECTION OPTIONS. PREVIOUS CONDITIONS ARE ASSUMED TO CARRY FORWARD IN THE PREDICTION MODEL; THERE ARE NO ASSURANCES THAT THE STRUCTURE WILL BE EXPOSED TO A SIMILAR ENVIRONMENT AS IN THE PAST.

ALL ANALYSES IN THIS REPORT ARE BASED STRICTLY ON THE CORROSION PROTECTION AND CONDITION OF THE REINFORCED CONCRETE MATERIALS. THE CONDITION APPRAISAL AND ANALYSIS BY NO MEANS CONSTITUTE A STRUCTURAL ENGINEERING CONDITION APPRAISAL OR ANALYSIS. ANY AND ALL RECOMMENDATIONS PRESENTED IN THIS REPORT SHOULD BE VERIFIED AND VALIDATED BY A COMPETENT STRUCTURAL ENGINEER.

1 Introduction

SIMCO Technologies Inc. was mandated by **EcoSmart Foundation Inc.** to evaluate the transport properties of concrete mixes containing Fly Ash as a replacement of Portland cement. Concrete cylinders were prepared by Dubai Central Laboratory (DCL), a laboratory facility in United Arab Emirates. They were sent to our laboratory for evaluation of their ionic transport properties. Following the evaluation, different numerical simulations were performed to predict the time to corrosion initiation of rebars for each concrete mix under different exposures.

The identification of the evaluated mixes is:

- EMD-01 (40/20 OPC + 25% Fly Ash)
- EMD-02 (60/20 OPC + 25% Fly Ash)
- EMD-03 (80/20 OPC + 25% Fly Ash + 6% Micro Silica)
- EMD-04 (40/20 OPC + 40% Fly Ash)
- EMD-05 (60/20 OPC + 40% Fly Ash)
- EMD-06 (80/20 OPC + 40% Fly Ash + 6% Micro Silica)

A total of 18 concrete cylinders (3 cylinders (6-in. x 12-in.) per mix) were received in our laboratory on January 28, 2008, wrapped in wet burlaps. At that time, all mixes had been cured for more than 56 days. Following the concrete cylinders reception, concrete samples were prepared. Tests were run after a curing of 70 and 100 days. Based on these two series of testing, it has been possible to determine the 28-day ionic transport properties for each mix considering the evolution of the transport properties with time (from 70 days to 100 days). The following activities were performed during this mandate:

- Determination of ionic diffusion coefficients with STADIUM®, including:
    - porosity and absorption according to ASTM C642
    - chloride migration according to ASTM C1202 (modified)
    - pore solution extraction[1]

- Determination of moisture transport coefficients, including:
    - drying test (performed at 70 days only)

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[1] Barneyback R.S., & Diamond S. (1981). Expression and analysis of pore fluids from hardened cement pastes and mortars. *Cement and Concrete Research 11*, pp. 279-285.

Each mix composition was given by EcoSmart and is presented in Table 1.

Table 1 — Mixes Composition

		Mixture Proportion					
Component	**Units**	***EMD-01***	***EMD-02***	***EMD-03***	***EMD-04***	***EMD-05***	***EMD-06***
Portland Cement	kg/m^3	255	325	360	250	270	280
Fly Ash	kg/m^3	85	110	125	165	185	185
Silica Fume	kg/m^3	0	0	30	0	0	30
Coarse Aggr. -ssd							
20 mm	kg/m^3	715	730	735	720	730	730
10 mm	kg/m^3	355	365	365	360	370	365
Fine Aggr. - ssd							
5 mm	kg/m^3	360	340	295	340	330	305
dune	kg/m^3	420	360	295	370	345	310
Water (net)	l/m^3	166	148	153	152	138	146
Water Reducer							
Type D	l/m^3	-	2.5	3.0	-	2.7	2.9
Type F	l/m^3	-	6.0	10.5	-	6.0	9.0
Type G	l/m^3	4.0	-	-	5.0	-	-
Water/Binder[1] ratio	-	0.49	0.34	0.30	0.37	0.30	0.29

[1] *Binder: all cementitious materials (Portland cement, micro silica and fly ash)*

2 Laboratory Testing

2.1 Concrete Characterization for Service Life Modeling

To generate information on the ionic transport properties of concrete mixes, porosity, pore solution extractions, and ion migration measurements were performed. These tests were performed after a curing of 70 days and 100 days. The moisture transport properties (drying test) were evaluated at 70 days only.

2.1.1 Porosity

Porosity is used as an input data for migration test analyses and service life modeling. Porosity measurements were performed in accordance with ASTM C642 - *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*. A minimal volume of concrete of 350 cm^3 is required to perform this test. Results (porosity and absorption) are presented in Table 2. Each result is the average of 2 individual results.

At 70 days, porosity ranges from 10.8% to 15.0% and the absorption ranges from 4.7% to 6.3%. At 100 days, porosity ranges from 9.8% to 15.6% and the absorption ranges from 4.2% to 6.9%. For a 0.45 concrete batched in the laboratory, the porosity and absorption range from 11% to 12% for the porosity and 5% to 6% for the absorption. EMD-01 mix presents the highest porosity and absorption results. This is explained by the higher water/binder ratio. Neville[2] explains that «*Voids in concrete are in fact either bubbles of entrapped air or spaces left after excess water has been removed. The volume of the latter depends primarily on the water/cement ratio of the mix*». EMD-02 to EMD-06 mixes present good porosity and absorption results.

Table 2 — Absorption and porosity results (ASTM C642)

Mix	*at 70 days*		*at 100 days*	
	Absorption after boiling (%)	**Porosity (%)**	**Absorption after boiling (%)**	**Porosity (%)**
EMD-01	6.3	15.0	6.9	15.6
EMD-02	5.0	11.6	5.0	11.7
EMD-03	5.1	11.9	5.0	11.6
EMD-04	4.7	10.8	4.8	11.0
EMD-05	4.7	10.9	4.2	9.8
EMD-06	5.3	12.1	4.8	11.2

2.1.2 Pore Solution Extraction

Information on pore solution chemistry of concrete is obtained by performing a pore solution extraction based on the procedure described in Barneyback and Diamond[3]. Concrete samples were broken in small pieces and placed in a cell to be subsequently crushed at a pressure of approximately 72,500 psi (500 MPa). The solution "squeezed-out" from the concrete was analyzed to measure the concentration of the various ionic species (i.e. OH^-, Cl^-, Na^+, K^+, Ca^{2+} and $SO4^{2-}$) present in the pore solution. Typically, 2 to 5 ml of pore solution is extracted. The solution was delivered through a drain ring and channel, and recovered with a syringe in order to limit exposure to the atmosphere. Pore solution analyses were carried out shortly after the extraction test by means of atomic adsorption spectroscopy and potentiometric titration.

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[2] A.M. Neville. *Properties of Concrete*, Fourth Edition, p.186

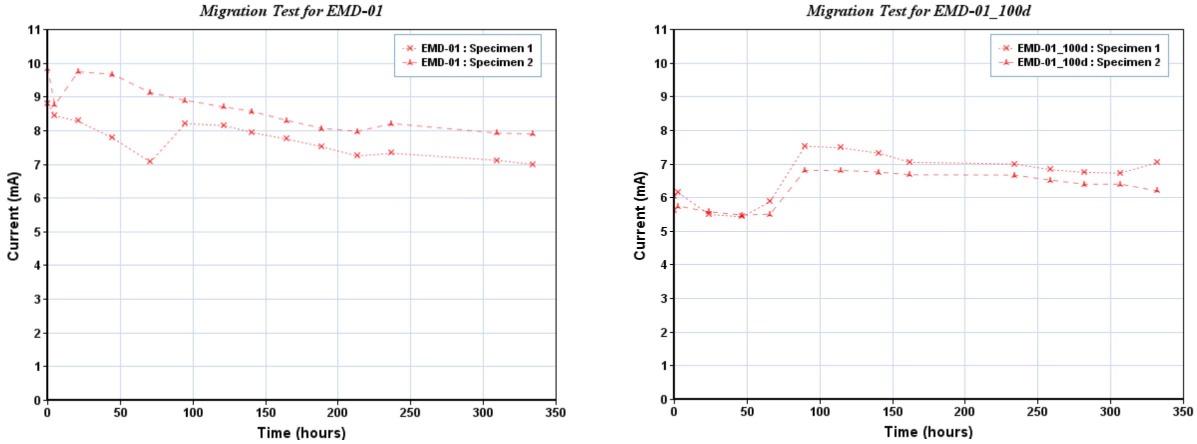
[3] Barneyback R.S., & Diamond S. (1981). Expression and analysis of pore fluids from hardened cement pastes and mortars. *Cement and Concrete Research 11*, pp. 279-285.

Pore solution extractions were performed on a vacuum-saturated sample immersed in a 300 mmol/l NaOH solution, which is similar to the sample preparation for the ion migration test (see section 2.1.3). This pore solution was used for the determination of ionic diffusion coefficients. For each mix, pore solution was also extracted at 70 days from a virgin sample to evaluate the real pore solution of concrete when in service on the field. This pore solution is used for STADIUM® simulations. The pore solutions have been balanced to preserve the electroneutrality of the solution.

2.1.3 Chloride Ion Migration Tests

The ionic diffusion coefficients (D_i) of the main ionic species (Cl^-, K^+, SO_4^{2-}, Ca^{2+}, Na^+, and OH^-) involved in the chemical degradation of concrete were determined using a modified and improved version of the ASTM C1202 – *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* test method. The test consists in measuring the transport of ions through a saturated concrete disk under an external electrical potential applied to the system. The current (electrical charge) passing through the concrete specimen over a given period of time (typically 14 days) is measured periodically. Analysis of the current data with STADIUM®-IDC yields the diffusion coefficients of all ionic species present in the pore solution. The procedure used is described in Samson et al[4].

The raw results of the migration tests are presented in Figures 1 to 6 for both ages tested (70 days and 100 days), and the ionic diffusion coefficients (for OH^- and Cl^- ions) results are summarized in Table 3.



70 days ***100 days***

Figure 1 — EMD-01: Current readings from the migration tests

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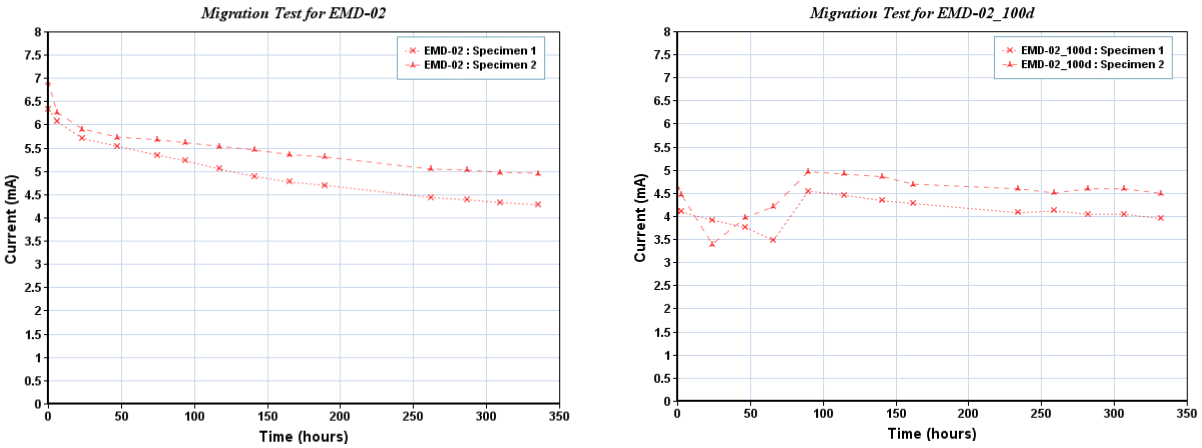
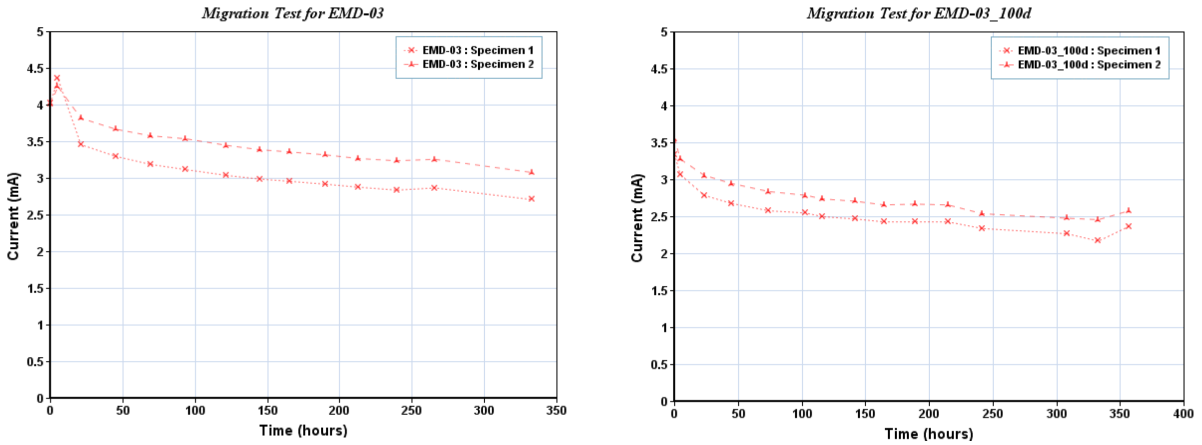
[4] E. Samson, J. Marchand and K.A. Snyder, *Calculation of ionic diffusion coefficients on the basis of migration test results*, Materials and Structures, Vol. 36, April 2003, pp 156-165.



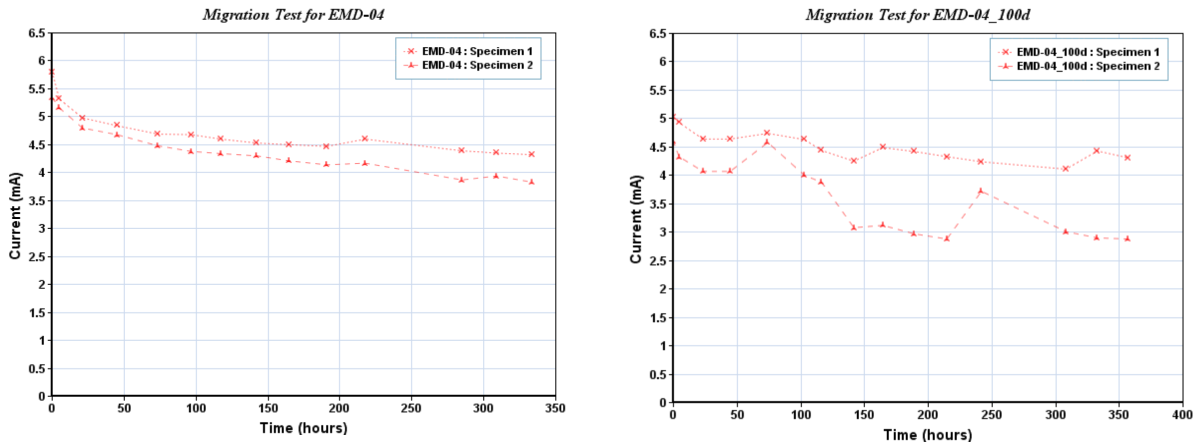
70 days *100 days*

Figure 2 — EMD-02: Current readings from the migration tests



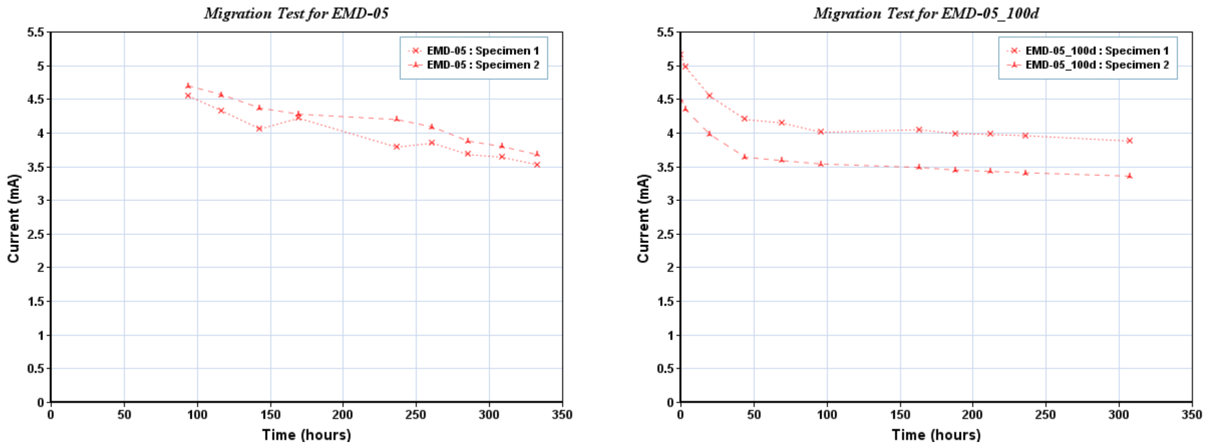
70 days *100 days*

Figure 3 — EMD-03: Current readings from the migration tests



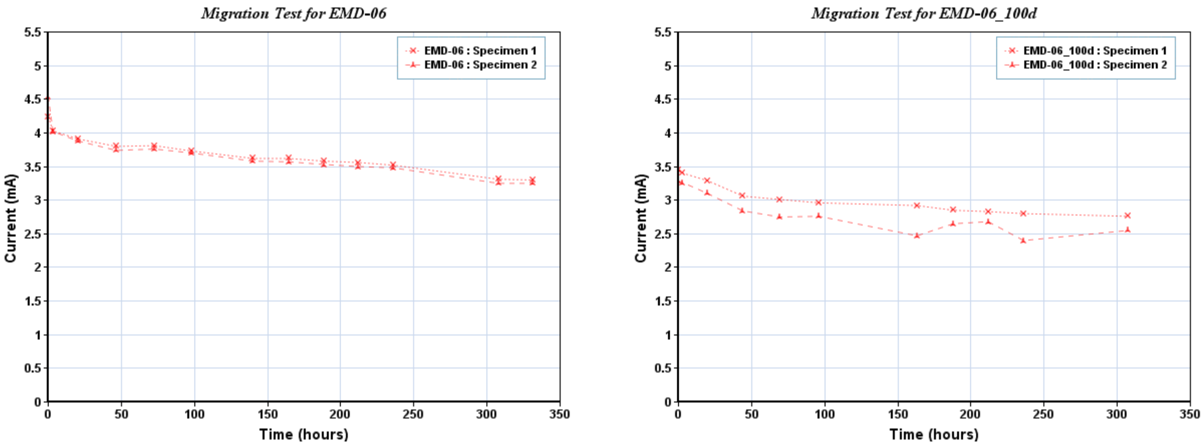
70 days *100 days*

Figure 4 — EMD-04: Current readings from the migration tests



70 days *100 days*

Figure 5 — EMD-05: Current readings from the migration tests



70 days *100 days*

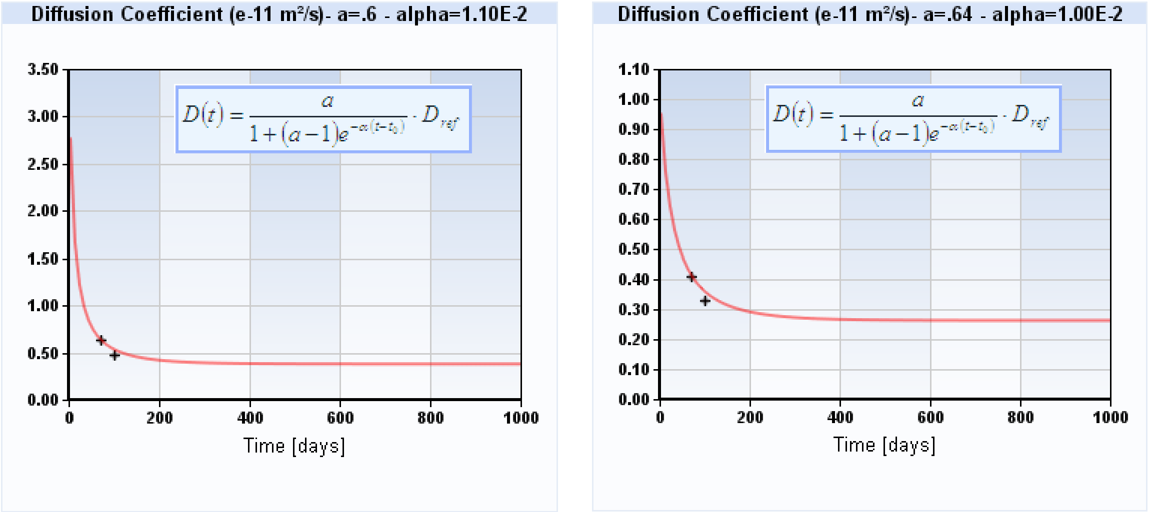
Figure 6 — EMD-06: Current readings from the migration tests

Table 3 — Ionic diffusion coefficients (STADIUM® Modeling)

Mix	*at 70 days*		*at 100 days*	
	OH^- Ions $(x\ 10^{-11}\ m^2/s)$	**Cl^- Ions $(x\ 10^{-11}\ m^2/s)$**	**OH^- Ions $(x\ 10^{-11}\ m^2/s)$**	**Cl^- Ions $(x\ 10^{-11}\ m^2/s)$**
EMD-01	0.63	0.24	0.48	0.19
EMD-02	0.41	0.16	0.33	0.14
EMD-03	0.23	0.09	0.17	0.07
EMD-04	0.32	0.13	0.28	0.11
EMD-05	0.33	0.13	0.26	0.09
EMD-06	0.24	0.09	0.18	0.07

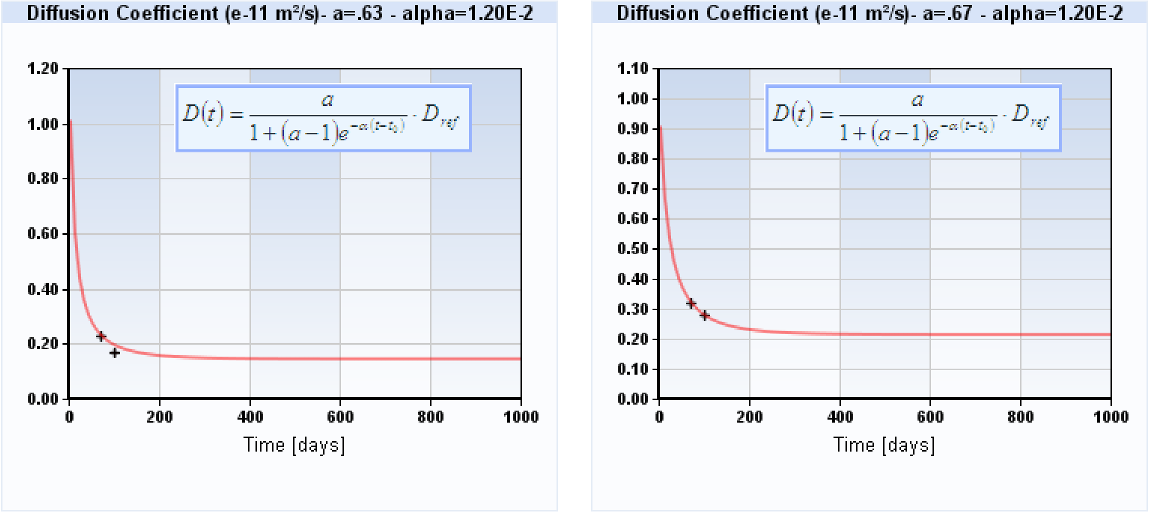
Based on the results presented in Table 3, the concrete produced in this project is of good quality. The ionic diffusion coefficient for OH^- ions ranges from 0.23 to 0.63 x 10^{-11} m^2/s at 70 days and from 0.17 to 0.48 x 10^{-11} m^2/s at 100 days. The EMD-03 mix, containing 25% fly ash and 6% micro silica, presents the lowest diffusion coefficients while EMD-01 has the highest. This is in correlation with the water/binder ratios and the porosity results measured (see Tables 1 and 2).

Figures 7 to 9 show OH^- diffusion coefficient evolution curves. These curves were established using the 70 and 100 days results with our past experiences with these types of mixes. The points on the graph are the results measured at 70 and 100 days. Using these graphs it is possible to estimate the ionic diffusion coefficients at 28 days. Table 4 presents the 28-day diffusion coefficients for each mix estimated using these graphs.



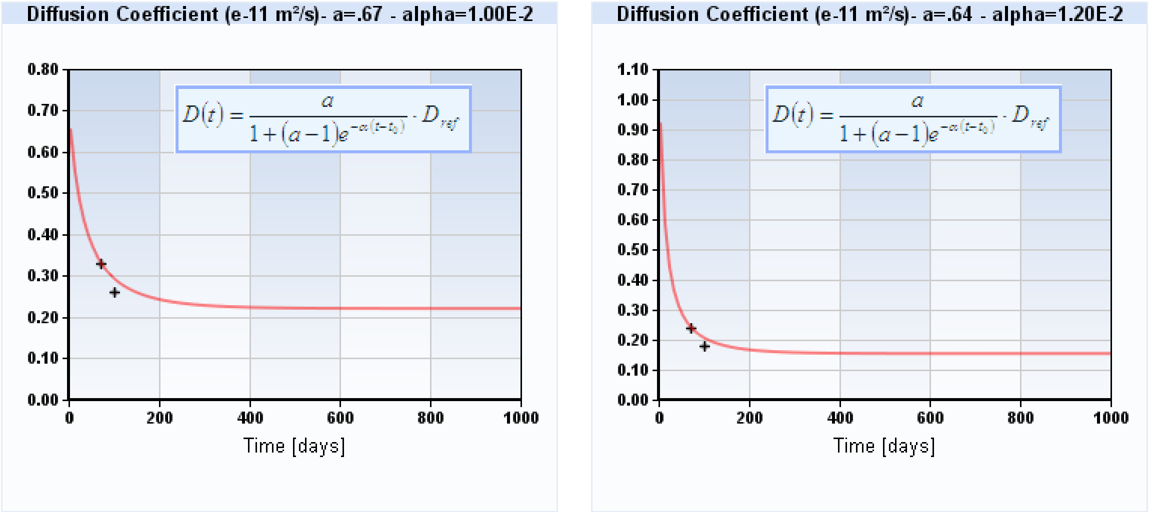
EMD-01 EMD-02

Figure 7 – Ionic diffusion coefficient evolution curves for EMD-01 and EMD-02



EMD-03 EMD-04

Figure 8 – Ionic diffusion coefficient evolution curves for EMD-03 and EMD-04



EMD-05 EMD-06

Figure 9 – Ionic diffusion coefficient evolution curves for EMD-05 and EMD-06

From the results in Table 4, the estimated OH$^-$ ions diffusion coefficient at 28 days ranges from 0.37 to 1.03 x 10^{-11} m^2/s at 28 days. The EMD-03 mix, containing 25% fly ash and 6% micro silica, presents the lowest diffusion coefficients while EMD-01 has the highest. A higher diffusion coefficient indicates that ions will diffuse faster through concrete. The ionic diffusion coefficients correlate with the porosity results. For high porosity, usually the diffusion coefficient is high. For a 0.45 concrete without supplementary cementitious materials batched in the laboratory, the ionic diffusion coefficient, at 28 days, for OH$^-$ ions ranges from 1 to 2 x 10^{-11} m^2/s.

Table 4 — Estimated ionic diffusion coefficients at 28 days

Mix	OH$^-$ Ions (x 10^{-11} m^2/s)	Cl$^-$ Ions (x 10^{-11} m^2/s)
EMD-01	1.03	0.40
EMD-02	0.58	0.22
EMD-03	0.37	0.14
EMD-04	0.48	0.19
EMD-05	0.44	0.17
EMD-06	0.38	0.15

2.1.4 Drying Tests

Moisture transport properties were evaluated using the mass loss from drying tests. With this information, it is possible to perform unsaturated concrete simulations. These values are used in STADIUM® for the service life simulations performed in section 3.

All drying tests were performed on concrete cured at 100% relative humidity for 70 days. The test consists in measuring the mass losses of concrete disks exposed to a controlled relative humidity of 50% and a temperature of 23°C. Two different series of 3 concrete discs, having a different thickness, are used. The 1 cm and 5 cm disks are waxed on the lateral surface only, and both concrete faces (top and bottom) are exposed to the drying environment. The mass losses of concrete specimens over a given period of time (2 to 3 months) are measured periodically. The mass losses were then simulated using the STADIUM®-MTC module for water transport properties evaluation. Simulation results using the parameters presented in Table 5 adequately reproduce the experimental drying results.

Using the evaluated parameters, the moisture diffusion coefficient of each concrete mix was calculated for a saturated concrete ($D_{100\%\ RH}$). A higher $D_{100\%\ RH}$ moisture diffusion coefficient indicates that water will move faster through concrete. Based on the results presented in Table 5, the concrete produced in this project has good moisture transport properties with $D_{100\%\ RH}$ ranging from 1.58 to 10.98 x 10^{-10} m^2/s. The EMD-03 mix, containing 25% fly ash and 6% micro silica, presents the lowest $D_{100\%\ RH}$ while EMD-01 has the highest. This is in correlation with the water/binder ratios, the porosity results, and the ionic diffusion coefficients (see Tables 1, 2, 3 and 4).

Table 5 — Moisture diffusion coefficients – drying phase

Parameter	**Mixture**					
	EMD-01	***EMD-02***	***EMD-03***	***EMD-04***	***EMD-05***	***EMD-06***
A (x 10^{-14} m^2/s)	0.68	2.33	1.20	6.12	4.07	1.40
B	80	80	80	80	80	80
$D_{100\%\ R.H.}$ (x 10^{-10} m^2/s)	**10.98**	**2.56**	**1.58**	**3.52**	**2.45**	**2.19**

3 Service Life Modeling – Time to Corrosion

3.1 Numerical simulations with STADIUM®

Numerical simulations were carried out to predict ingress of chlorides and sulfates associated with the penetration of seawater under saturated and unsaturated conditions. The concrete element used for the numerical simulations was a concrete cope wall 600 mm thick, and different concrete covers were evaluated. The chloride content from 25 mm to 275 mm (at every 25 mm) from the exposed surface was simulated.

The seawater composition of the Arabian Gulf is given in Table 6 and it was the seawater to which the concrete structure was exposed in the simulations. The seawater composition was kept constant during the entire simulations, and the salinity was fixed at 38.9 ‰ (based on concentrations of Table 6). All parameters presented in Tables 1 to 5 were used as input parameters for the numerical simulations with STADIUM®.

Table 6 — Seawater composition – Arabian Gulf

Ionic Species	Concentration (ppm)
Na^+	12,400
K^+	450
SO_4^{2-}	2,720
Ca^{2+}	430
Cl^-	21,450
Mg^{2+}	1,460

All numerical simulations were run to evaluate the time needed to initiate steel corrosion in a concrete element. In this study, the critical chloride concentration is 0.3% of cementitious materials content[5]. For the analysis purpose, the threshold used in this report was estimated at **565 ppm**, calculated from the average cementitious materials content of the 6 mixes (see Table 1).

3.1.1 Submerged simulations

The concrete element used for this series of numerical simulations was a concrete cope wall of 300 mm thick exposed all year to seawater (365 days per year). Numerical simulations were performed assuming that the relative humidity, at the exposed surface, was 100%. The temperature varied during the year and the values used are based on

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[5] Rosenberg, A. et al. (1989) Mechanisms of Corrosion of Steel in Concrete, *Materials Science of Concrete*, Vol. 1, J. Skalny ed., American Ceramic Society, Westerville (USA), p. 285-313.

information recorded by weather agencies (source: www.weatherbase.com). The temperature cycle was kept constant for the entire duration of the simulation (Figure 10).

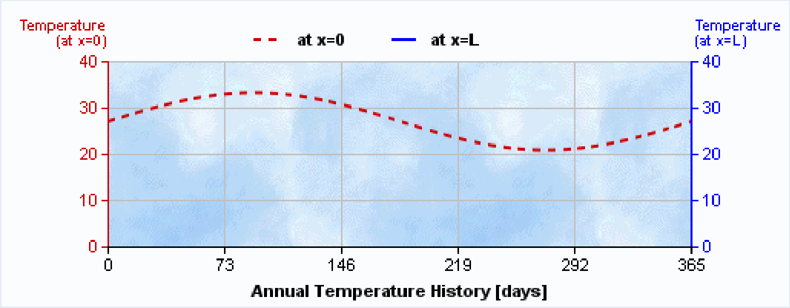

Figure 10 – Cyclic temperature used in the submerged simulations

Figures 11 and 12 present chloride content evolution curves for concrete covers of 75 mm and 100 mm respectively. Time to initiate corrosion for each mix is resumed in Table 7.

In Figure 11, for a cover of 75 mm, the numerical simulations show that the chloride content reaches the corrosion threshold after approximately 14 years if the EMD-01 mix is used. For the same cover but with mix EMD-03, it will take 39 years before initiation of steel corrosion begins. In Figure 12, for a cover of 100 mm, the numerical simulations show that the chloride content reaches the corrosion threshold at approximately 24 years if the EMD-01 mix is used. Mixes EMD-03, EMD-05 and EMD-06 will protect the steel for more than 50 years.

It is important to mention that even though the chloride content threshold is reached for the submerged concrete, it is possible that no corrosion is active due to the lack of oxygen. These values are still applicable for the concrete that is near the lowest low tide level where the oxygen is more accessible and the level of chloride contamination is high.

Table 7 — Time to Corrosion – Submerged

Mix ID	**Time to Corrosion[1], years**	
	at 75 mm	*at 100 mm*
EMD-01	14	24
EMD-02	26	47
EMD-03	39	more than 50
EMD-04	25	45
EMD-05	31	more than 50
EMD-06	32	more than 50

[1]: based on a chloride content threshold of 565 ppm.

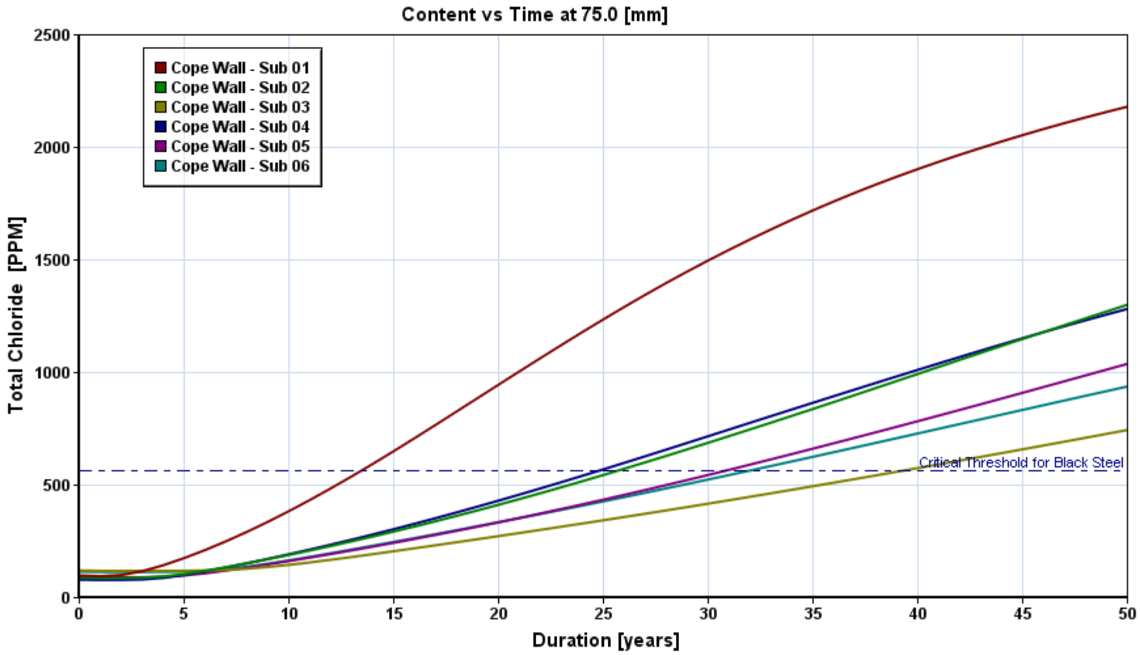

Figure 11 – STADIUM® Time to Corrosion for Rebar at 75 mm - Submerged

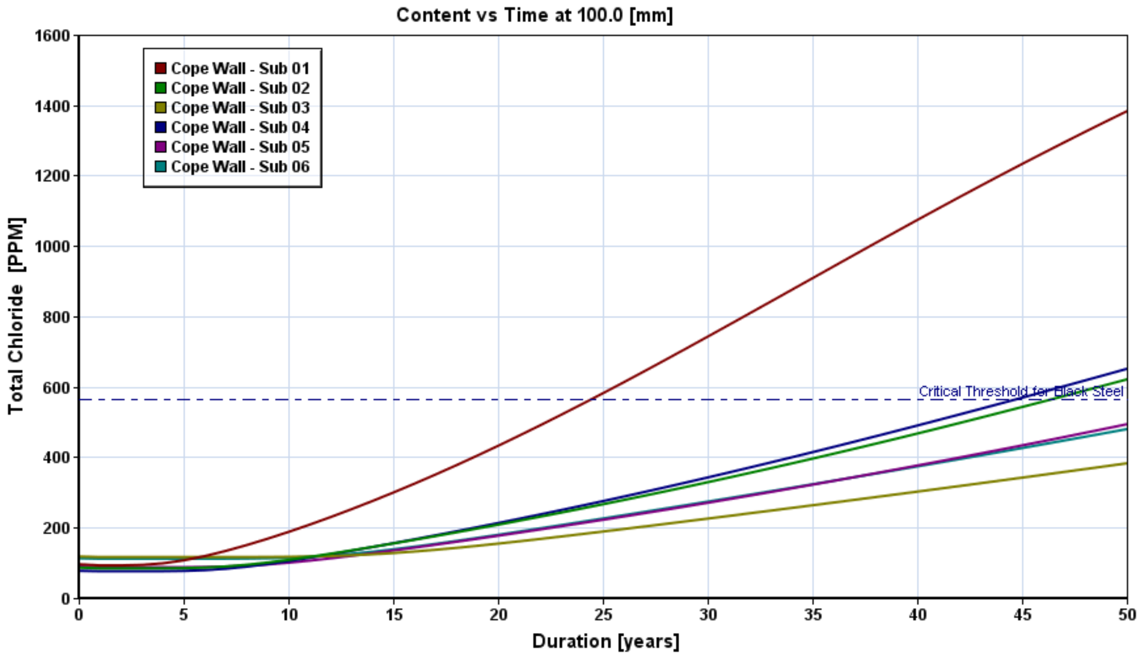

Figure 12 – STADIUM® Time to Corrosion for Rebar at 100 mm – Submerged

3.1.2 Tidal zone simulations

The concrete element used for this series of numerical simulations was a concrete cope wall of 600 mm thick exposed to cyclic exposure to seawater (tidal zone). To represent a tidal zone, numerical simulations were performed assuming that relative humidity, at the exposed surface, was 80% during the drying period. When exposed to seawater, the relative humidity was kept at 100%. Due to software limitations, for this type of simulations (tidal simulation), the temperature during the simulations was fixed to the average temperature of Abu Dhabi (27°C), based on information recorded in 2007 by weather agencies (source: www.weatherbase.com). The temperature was kept constant for the entire duration of the simulations. Figure 13 present cyclic relative humidity used in this series of numerical simulations.

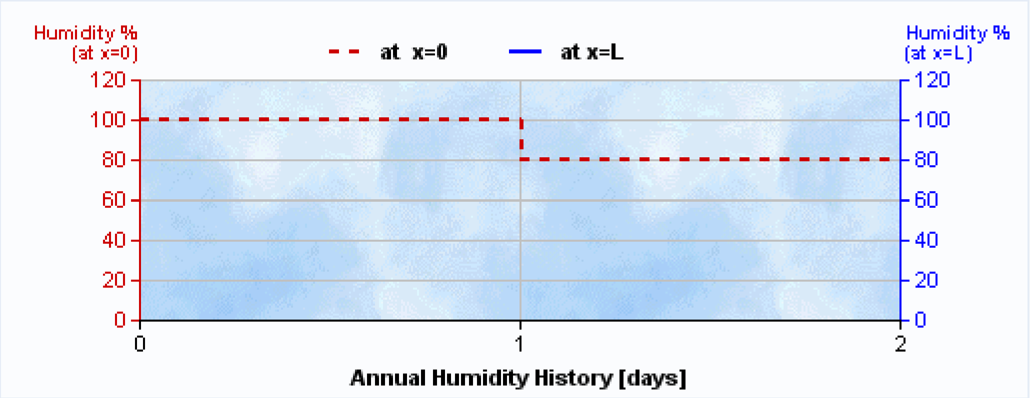

Figure 13 – Constant humidity used in the tidal zone simulations

Figures 14 and 15 present chloride content evolution curves for a rebar with a concrete cover of 75 mm and 100 mm respectively. Time to initiate corrosion for each mix is given in Table 8.

In Figure 14, the numerical simulations show that the chloride content reaches the corrosion threshold of 565 ppm after approximately 28 years if the EMD-01 mix is used and the concrete cover is 75 mm. With the same concrete cover, only EMD-03 mix resists to the 50-year exposure. In Figure 15, for a concrete cover of 100 mm, the numerical simulations show that the chloride content reaches the corrosion threshold after approximately 49 years if the EMD-01 mix is used. All other mixes will protect the steel for more than 50 years. The good performance of these concrete, when exposed to drying and wetting cycles, is due to the good moisture transport properties (low moisture movement) which slows down the ingress of water when compared to a poor concrete (high water diffusion properties).

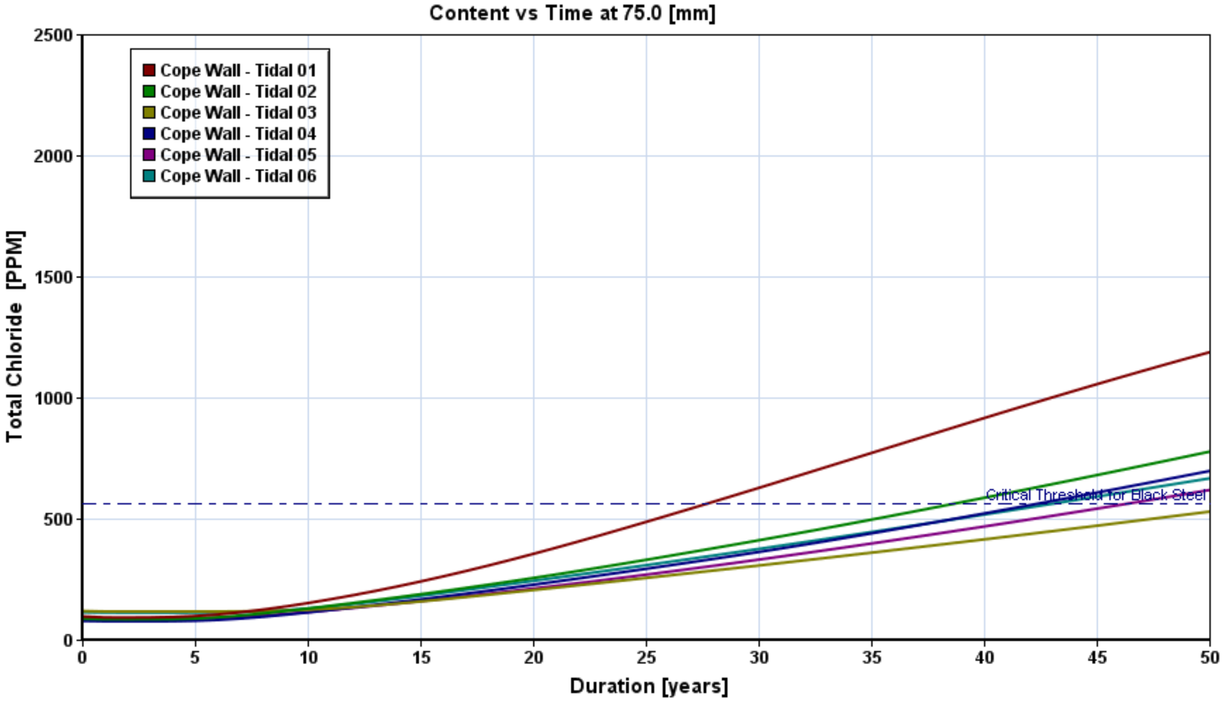

Figure 14 – STADIUM® Time to Corrosion for Rebar at 75 mm – Tidal zone

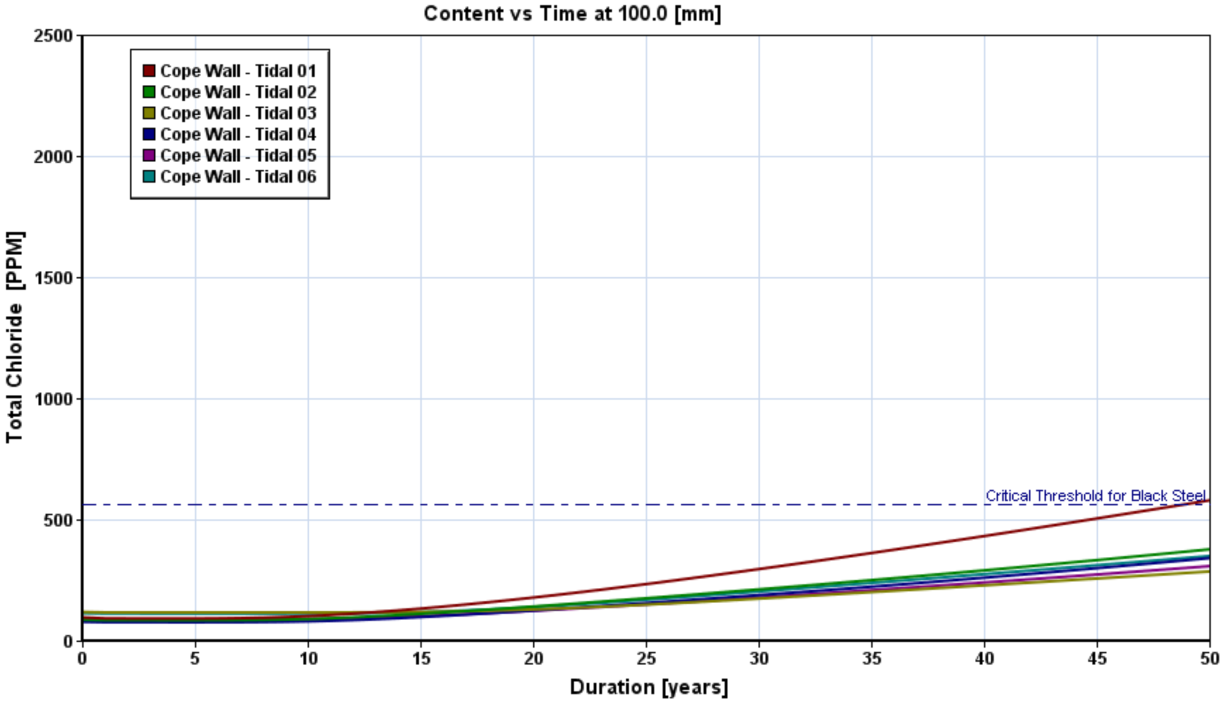

Figure 15 – STADIUM® Time to Corrosion for Rebar at 100 mm – Tidal zone

Table 8 — Time to Corrosion – Tidal Zone

Mix ID	Time to Corrosion^1, years	
	at 75 mm	*at 100 mm*
EMD-01	28	49
EMD-02	39	more than 50
EMD-03	more than 50	more than 50
EMD-04	43	more than 50
EMD-05	47	more than 50
EMD-06	44	more than 50

[1]: based on a chloride content threshold of 565 ppm.

3.1.3 Parking in contact with groundwater simulations

The concrete element used for this series of numerical simulations was a concrete wall of 600 mm thick. The numerical simulations were performed assuming that relative humidity, at the exposed surfaces, were 65% in the parking environment and 95% for the groundwater. A salinity of 2 times the one in seawater was used to represent concentration found in groundwater. This was observed in a past project in Abu Dhabi where the salinity of the ground water had reached, at a depth of more than 25 foot, 3 times the salinity of seawater. The temperature varied during the year, and the values used are based on information recorded by weather agencies (source: www.weatherbase.com). The temperature cycle was kept constant for the entire duration of the simulations. Figures 16 and 17 present the cyclic temperature and constant relative humidity used in this series of numerical simulations. In both Figures, position x = 0 represents the surface exposed to the groundwater and x = l the surface exposed to the parking environment.

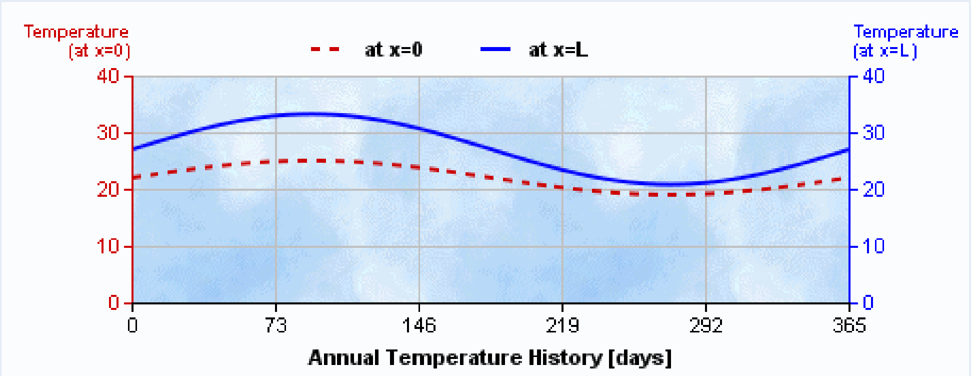

Figure 16 – Cyclic temperature used in the parking and soil simulations

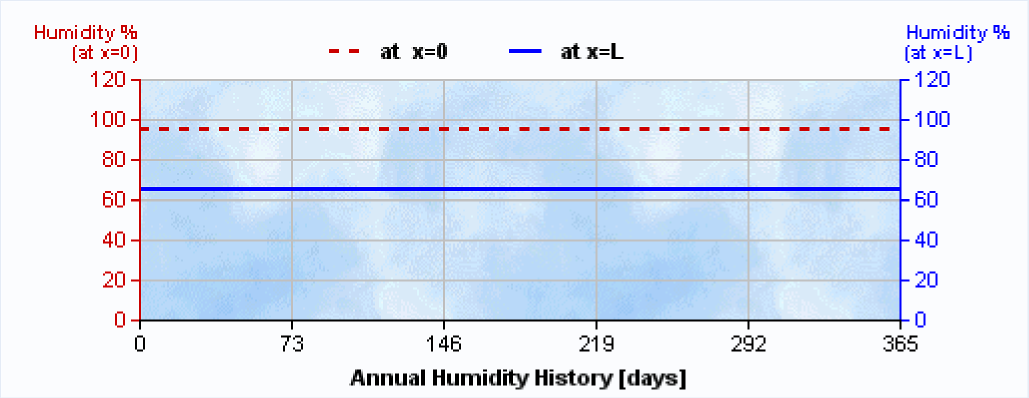

Figure 17 – Constant humidity used in the parking and soil simulations

Figures 18 and 19 present chloride content evolution curves for a concrete cover of 75 mm and 100 mm from the exposed surface respectively. Time to initiate corrosion for each mix is given in Table 9.

In Figure 18, numerical simulations show that, from the groundwater exposed surface, the chloride content reaches the corrosion threshold of 565 ppm after approximately 12 years if the EMD-01 mix is used with a concrete cover of 75 mm. Mix EMD-03 resists 23 years before initiation of steel corrosion. In Figure 19, for a rebar with a concrete cover of 100 mm, numerical simulations show that chloride content reaches the corrosion threshold after approximately 20 years if the EMD-01 mix is used. Mix EMD-03 resists 39 years before it initiates steel corrosion.

Table 9 — Time to Corrosion – Parking and Groundwater

Mix ID	Time to Corrosion[1], years	
	at 75 mm	*at 100 mm*
EMD-01	12	20
EMD-02	15	20
EMD-03	23	39
EMD-04	15	27
EMD-05	19	32
EMD-06	18	30

[1]: based on a chloride content threshold of 565 ppm.

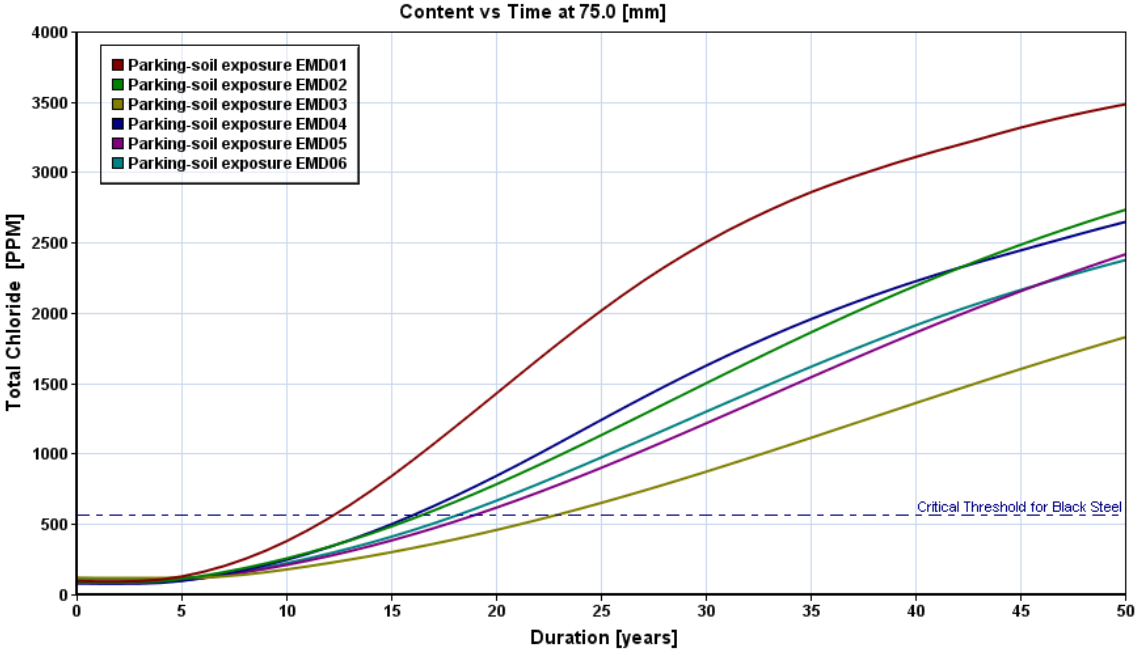

Figure 18 – STADIUM® Time to Corrosion for Rebar at 75 mm – Parking & Groundwater

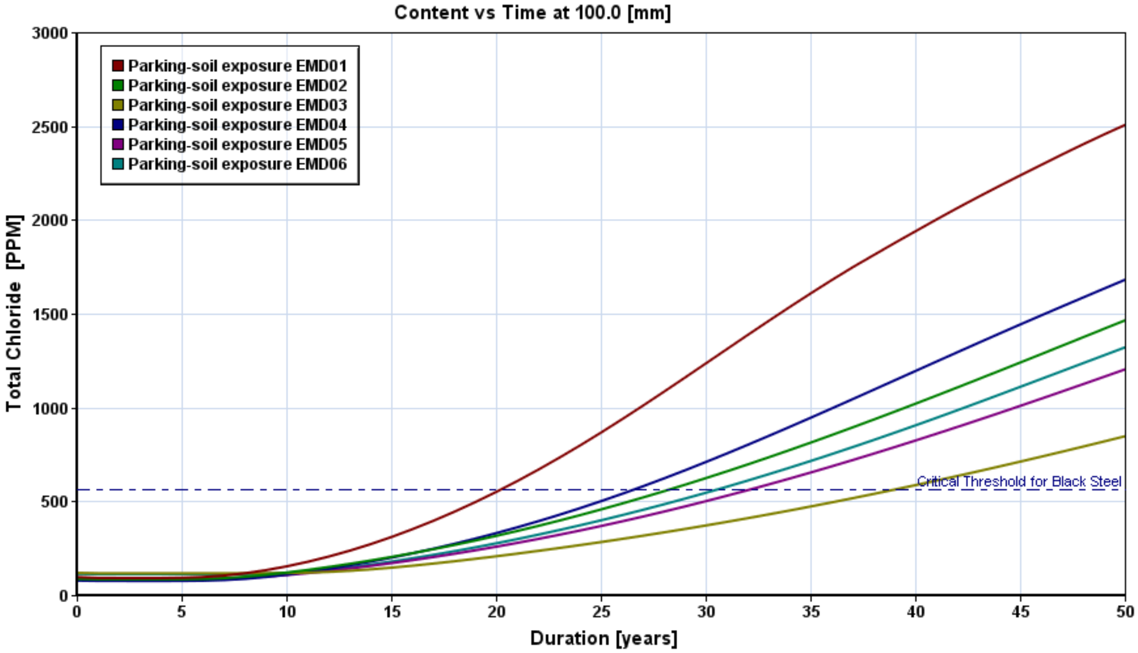

Figure 19 – STADIUM® Time to Corrosion for Rebar at 100 mm – Parking & Groundwater

4 Conclusion

Transport properties were evaluated for concrete cylinders from the EcoSmart project in Abu Dhabi, United Arab Emirates. A total of 6 concrete mixes with high volume fly ash were tested to evaluate their ionic transport properties. All concrete mixes were produced in Abu Dhabi. 3 cylinders per mix were sent to our laboratory for characterization of their transport properties (ionic and moisture transport properties). Numerical simulations using STADIUM® software were then performed to predict time to corrosion initiation for each concrete mix exposed to 3 different exposures for a period of 50 years.

The porosity results were found to be good, particularly for 5 mixes (EMD-02 to EMD-06). EMD-01 mix had a higher porosity which is explained by the higher water-binder ratio. The ionic diffusion coefficients and moisture diffusion coefficients of EMD-01 mix are the highest while EMD-03 has the lowest. These results correlate the findings observed with the porosity results.

In a submerged condition, the numerical simulations indicate that for a rebar covered with 75 mm of concrete, there will be no mixture capable to give a 50-year resistance against corrosion initiation when exposed to the Arabian Gulf seawater. A 100 mm concrete cover is needed and only mixes EMD-03, EMD-05 and EMD-06 will give a 50-year resistance before the corrosion is initiated. As explained earlier, for the submerged simulations, these times are the time to reach the chloride content threshold. It is possible that the corrosion will initiate at a later time since the corrosion activity will be low due to the lack of oxygen. It is known in the literature that the oxygen availability is low in the submerged zones. Although for concrete near the lowest low tidal level (LLTL), this concrete is exposed to oxygen and high chloride contamination.

In a tidal zone condition, the numerical simulations indicate that EMD-03 mix will give a protection of 50 years against corrosion initiation, while for the other mixes; the corrosion initiation will be earlier. With a concrete cover of 100 mm, the time to initiate corrosion will be higher than 50 years for all mixes except EMD-01 mix.

When the concrete is exposed to a contaminated soil (groundwater), the numerical simulations indicate that neither a 75 mm nor 100 mm concrete cover with any of the mixes will protect the steel during 50 years. The time to initiate corrosion will be lower than 50 years in all cases.

Based on the results obtained in this study, EMD-03 mix containing 25% fly ash and 6% micro silica in replacement of Portland cement is the mix that showed better ionic transport properties and corrosion initiation resistances. This mix is also the one with the highest Portland cement proportion. However, high volume fly ash could influence the long term properties. For example, if all tests were performed after 1 year, results could be better.

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