CHLORIDE PENETRATION AFTER FIELD EXPOSURE COMPARED WITH ESTIMATES FROM SERVICE LIFE PREDICTION MODELS

James M Aldred [1, 2] and Arnaud Castel [1]

(1) AECOM Sydney, Australia.

(2) Centre for Infrastructure Engineering & Safety, School of Civil and Environmental Engineering, The University of New South Wales, Australia

Abstract

In 1982, reinforced concrete test beams were suspended in a temperate marine splash zone beneath a berth in Fremantle, Western Australia. The concretes used in these specimens included Ordinary Portland cement alone or with silica fume or ground granulated blast-furnace slag (GGBS) replacement. During 2001 the test beams were subjected to resistivity, half-cell potential and LPR corrosion rate measurements. Samples of concrete were removed to determine the depth of chloride penetration. The chloride diffusion coefficient and sorptivity of uncontaminated concrete were also measured. Some data on chloride penetration had been previously obtained after two and six years exposure. The measured chloride penetration profiles are compared with some commonly used service life prediction models to assess the validity of their predictions based on the initial information that would have been available at the time the specimens were cast.

Keywords: marine exposure, Corrosion, Silica fume, GGBS, Sorptivity, Chloride, Diffusion, Life 365, Concrete Society, Stadium

1. INTRODUCTION

Premature deterioration of reinforced concrete due to chloride-induced corrosion of reinforcement is a global problem that costs billions of dollars annually. In severe maritime environments, concrete structures have often failed to achieve their required service life without major maintenance. Chlorides penetrate concrete through capillary absorption into unsaturated concrete, wick action and diffusion through water filled pathways within the matrix driven by a concentration gradient.

Codes may specify minimum compressive strength/cementitious content, maximum w/cm ratio and cover thickness requirements to improve chloride resistance. Some codes recognise that replacement of Portland cement with supplementary cementitious materials such as ground granulated blast furnace slag (GGBS), fly ash or silica fume can increase the time to corrosion. However, many designers are concerned that the code requirements may not achieve a 100 year design life. Service life prediction models have been developed to help determine the time to corrosion of embedded reinforcement. Most models are based on Fick's Laws with assumptions regarding expected surface chloride levels and long-term aging effects.

This paper compares the results obtained by three commonly used service life prediction models with chloride profiles from concrete specimens exposed to a marine environment for 2, 6 and 19 years. A range of concretes with cementitious contents of 400 kg/m3 and nominal w/cm ratios of 0.4 were exposed to a splash zone beneath Berth 8 in Fremantle [1]. Fremantle is the main port facility in Western Australia, it is located approximately 20 km south west from the centre of Perth. The weather is best characterised as a temperate Mediterranean climate with an annual average daily temperature of 18°C, consisting of a hot summer and a cool winter. Berth 8 in the Inner Harbour was constructed in 1972 using a nominal 28 MPa (4000 psi) concrete. Within 10 years, the soffit of the slab and beams were badly deteriorated in a strip above a sheet-piled retaining wall which caused incoming waves from passing vessels to be splashed upwards. The area concerned was repaired in 1981/82. It was decided to suspend reinforced concrete specimens of various compositions below the repaired section to be monitored over time and establish their relative performance in a location of known severity to reinforced concrete.

2. SERVICE LIFE PREDICTION MODELS

2.1 Concrete Society Model

Concrete Society TR 61 Enhancing reinforced concrete durability (2004) includes a spreadsheet model based on an understanding of the processes involved and the principal influencing factors. This model was validated against the consensus view of current behaviour (and of course specific examples where available). Service life predictions can be made using either details of the concrete mix (i.e. water/cementitiuos ratio, binder type and content) or measurements from tests or exposure trials on structures (i.e. apparent diffusion coefficient at a defined age).The transport of chloride ions is modelled using Fick’s second law of diffusion.

The input parameters include strength grade, cementitious content and type, temperature, surface chloride level, exposure condition and bar diameter. The spreadsheet allows assessment of the use of different admixtures, steel types, coatings and other measures. The CSM does not use an arbitrary default chloride threshold value for the assessment of corrosion initiation but varies the threshold level based on the temperature as well as cementitious content and type. The spreadsheet not only estimates the time to initiation of corrosion but also the time to cracking.

As the CSM is an excel spreadsheet, it is easy to interrogate and manipulate. Accordingly it is easy to graphically present the output.

3.2 Life 365 Model

According to Violetta (2002), “Life-365 is used to predict the time to the onset of corrosion, and the time for corrosion to reach a level requiring repair. Life-365 can then estimate costs over the entire design life of a structure, including initial construction costs and predicted repair costs.

Life-365 requires the following general user inputs for each project:

- Geographic location;
- Type of structure and nature of exposure, one dimensional (parking or bridge deck) or two dimensional (marine pile) model;
- Depth of clear concrete cover to the reinforcing steel; and

- Details of each corrosion protection strategy scenario such as water-cementitious material ratio (w/cm); type and quantity of fly ash, GGBS, silica fume, or corrosion inhibitors; type of steel, uncoated or coated; and presence of membranes or sealers.”

The transport of chloride ions is also modelled using Fick’s second law of diffusion. Life 365 is freely available online and therefore has become a very popular tool for service life prediction. Life 365 has a default chloride threshold level of 0.05% by mass of concrete and a propagation phase of 6 years. However it does allow the user to modify the various parameters.

Life 365 is a proprietary software intended for a specific purpose with standardised outputs so that interrogating the predictions as intended in this study is understandably more difficult. For example the model also places limits on key parameters such as cover depth so that estimating time to corrosion initiation at early ages is not possible. However, we would agree that in severe environments covers less than 30 mm are not a good idea.

3.3 Stadium Model

STADIUM® uses time-step finite element analysis to simulate the progress of harmful ions (including chloride and sulphate) into and through concrete, by considering the chemical and physical properties of the concrete being analysed. According to the Cementitious Barriers Partnership, “the calculations in the STADIUM® model are divided into two primary modules. The first module accounts for coupled transport of ions and water without considering chemical reactions (e.g., dissolution, precipitation, etc.). Transport is modeled with a volume-averaged version of the extended Nernst-Planck equation, which accounts for the electrical coupling between the ions as well as for the chemical activity of the species in solution. Terms are added to consider the impact of fluid flow and temperature gradients on ionic fluxes. The transport equations are coupled to Poisson’s equation, which gives the electrical potential in the material as a function of the ionic profiles distribution. Coupling with moisture conservation and heat conduction equations is also taken into account.

The second STADIUM® module is a chemical equilibrium code. After each transport step, this module equilibrates the concentrations at each node of the finite element mesh with the phases of the hydrated cement paste. Solid phases can also be formed as a result of the penetration of aggressive species into the porous network of the material. The variation of solid phases will lead to local variations in porosity. These variations will likely affect the transport properties of the material locally. STADIUM® takes this locally varying phenomenon into account in the transport module described above.**”**

STADIUM® includes default values for materials and exposure (salinity needs to be inputed) but, unlike the other models, allows detailed input of materials compositon and expected exposure. The default uses a default chloride threshold value of 0.05% by mass of concrete for black steel. STADIUM® does not estimate time to propagation. STADIUM® provides a plethora of graphical outputs and also allows site data to be uploaded. The resultant graphs generated provide an excellent way of comparing predicted and actual penetration. These graphs are copyright and therefore they cannot be included in the paper.

3. CONCRETE SPECIMENS AND INITIAL ASSESSMENT

The mix proportions of the concretes with nominal w/cm ratio of 0.4 and the key properties of the binders are shown in Table 1. The concretes were considered to have a characteristic cylinder compressive strength of 50 MPa. The exposure programme included concretes with w/c ratio of 0.6 which was indicative of the concrete used in original construction as well as other admixtures and replacement combinations. The present study was limited to these 4 mixtures to enable assessment of the default values used in the models.

The beam specimens, which had nominal dimensions as shown in Figure 1, were reportedly water cured for 28 days then left covered and stored in the laboratory for approximately 9 months before exposure. The specimens were suspended beneath Berth 8 in September 1982 in an environment where there would have been as many as 600 cycles of wetting per year. Waves impacting the retaining wall would splash the specimens which were suspended from the soffit of the slab.

50 mm diameter cores were taken from selected beam specimens in 1984 and 1988 after approximately 2 and 6 years field exposure. The cores taken in 1984 were sliced into 0-5mm, 7-15mm, 17-25mm and 27-50mm increments. The cores taken in 1988 were sliced into 0-5mm, 7-15mm, 17-30mm and 32-53mm increments. These slices were pulverised and the acid soluble chloride contents were measured in accordance with BS 1881 : Pt 124. After 19 years exposure, tests on the penetrability and corrosion of the reinforcement were conducted upon removal of the beam specimens from under the berth are discussed in Ref [2]. The half-cell potential and corrosion current measurements indicated that the OPC mix was corroding but there was no visible cracking or rust staining. The values for the other mixes suggested a low probability of corrosion. The beams were cored with a 75mm diameter coring bit to the depth of the reinforcement and then cut into the following depth increments: 0 – 9 mm, 11 – 24 mm, 26 – 49 mm, 51 -60 mm for acid soluble chloride measurements.

Table 1: Mix design characteristics for Berth 8 specimens (kg/m^3).

Designation	OPC	SF 10	GGBS 30	GGBS 65
OPC[1]	400	360	280	140
GGBS[2]	-	-	120	260
Silica fume[3]	-	40	-	-
20 mm granite	860	860	860	860
10 mm granite	310	310	310	310
7 mm granite	200	200	200	200
Dune sand	520	520	520	520

1. AS 1315 Type A – Cockburn Cement Ltd (Hypothetical C_3A 7.8%)
2. GGBS – Cockburn Cement Ltd (Al_2O_3 . 14.4%)
3. Silica fume – Proprietary silica fume additive including dry lignin superplasticiser (SiO_2 - 91.4%)

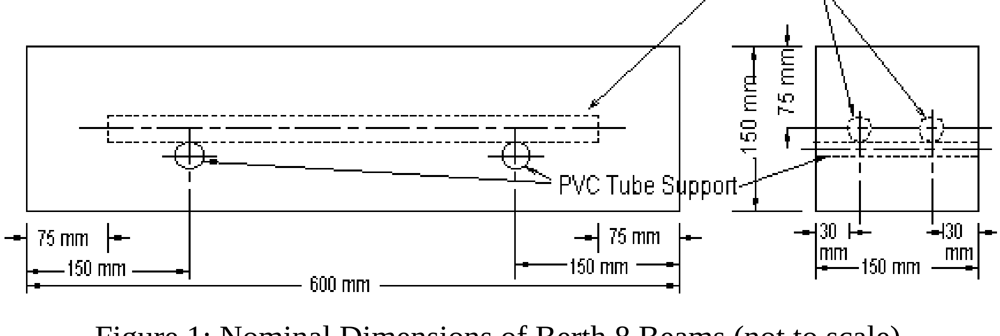

Figure 1: Nominal Dimensions of Berth 8 Beams (not to scale).

The chloride profile was measured on slices taken from cores and the uncontaminated section of the specimen was tested for sorptivity using a Taywood procedure and bulk diffusion using the NT Build 443 procedure. The sorptivity for the GGBS mixes were higher than the OPC mix and the silica fume mix nominally lower. The effective diffusion coefficients based on chloride profiles after field exposure were significantly lower than for the Nordtest procedure

4. COMPARATIVE RESULTS FROM MODELLING

The intention of this study is to compare the predicted chloride penetration that would have occurred at the exposure site using the three models. The modelling was based on default values (or interpolated values where necessary) as would be used by a designer specifying a project before any validation or compliance testing or even the specific materials. As Life 365 and STADIUM® use a default chloride threshold level of 0.05%, this was the value used for the CSM.

The default exposure condition was taken as marine splash zone for the Concrete Society and Life 365 models and UFGS Moderate for STADIUM®. The suggested characteristic values of 0.75% and 0.90% by weight of concrete for portland and blended cement respectively for the CSM. The default surface chloride level of 1.0% by weight of concrete was used for Life 365 which includes a build-up period of 10 years. The temperature was set as 18°C for the CSM and STADIUM®. For Life 365, the default temperature values for San Diego were used.

STADIUM® has inputs based on predefined concrete mixes with w/cm ratios of 0.35 and 0.45. The cementitious binder options include OPC with 8% silica fume, 35% GGBS and 70% GGBS replacement. The transport properties used in the STADIUM® modelling in this study were based on linearly interpolating between the values for w/cm ratios without adjusting for the nominal changes in the percentage replacement levels between the exposed specimens and the model. However the composition of the cementitious materials were changed based the actual materials used. We accept that these modifications would have influenced the results to some extent but such modifications would have been necessary for a designer well before construction. It also highlights one of the difficulties in using STADIUM® without site specific data. The same difficulty actually exists for the other models but the models do the interpolation or extrapolation for you!

4.1 Concrete Society Model

Figure 2 shows the predicted chloride penetration after two years exposure (dotted lines) compared with the values obtained from cores (solid lines). The chloride levels in the surface layer are similar but the levels at greater depths are significantly underestimated by the CSM. This suggests that effects such as sorptivity played a dominant role in initial chloride penetration overwhelming any differences in diffusivity. As the cover to the reinforcement at the side of the beam specimens was only 30 mm, the acid soluble chloride content had already exceeded the default threshold level for the three mixes tested. Figure 3 shows the predicted chloride penetration after 19 years exposure (dotted lines) compared with the values obtained from cores (solid lines). The chloride profile for the OPC mix could not be determines because the specimen was fully contaminated. Indeed it had been contaminated after 6 years exposure. Therefore the predicted chloride penetration for the OPC mix had significantly underestimated the actual chloride penetration. The CSM had also underestimated chloride penetration into the GGBS 30 mix. The prediction was similar to the core result for the GGBS 65 mix but significantly overestimated chloride penetration into the SF 10 mix.

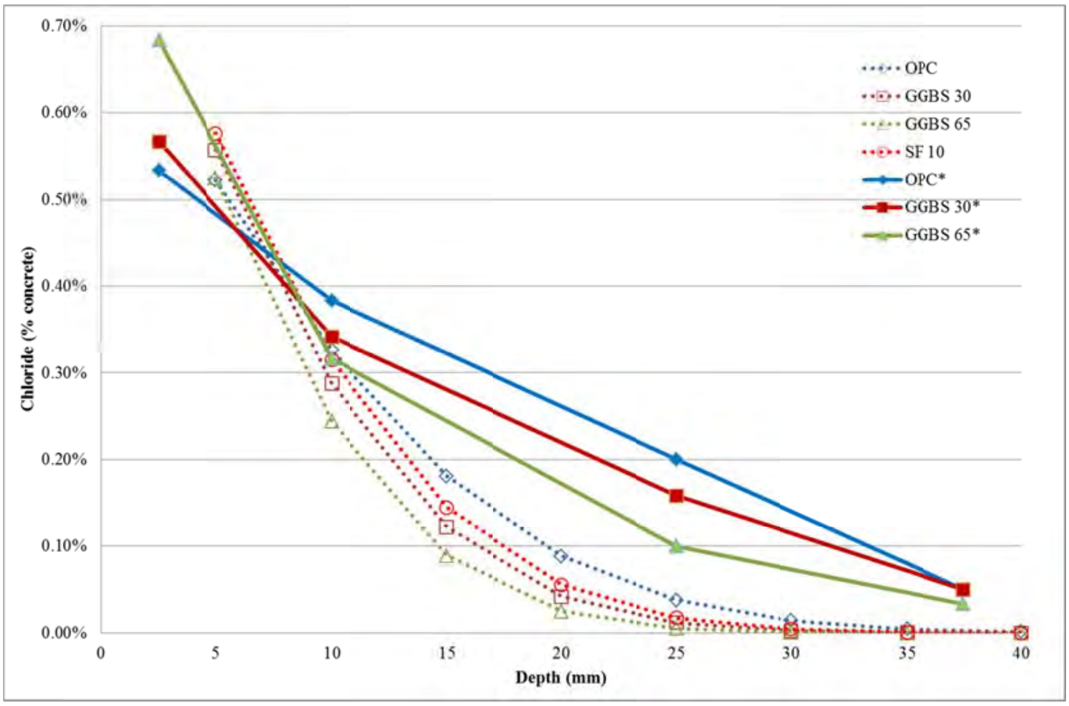

Figure 2: Predicted and measured chloride penetration after 2 years using CSM.

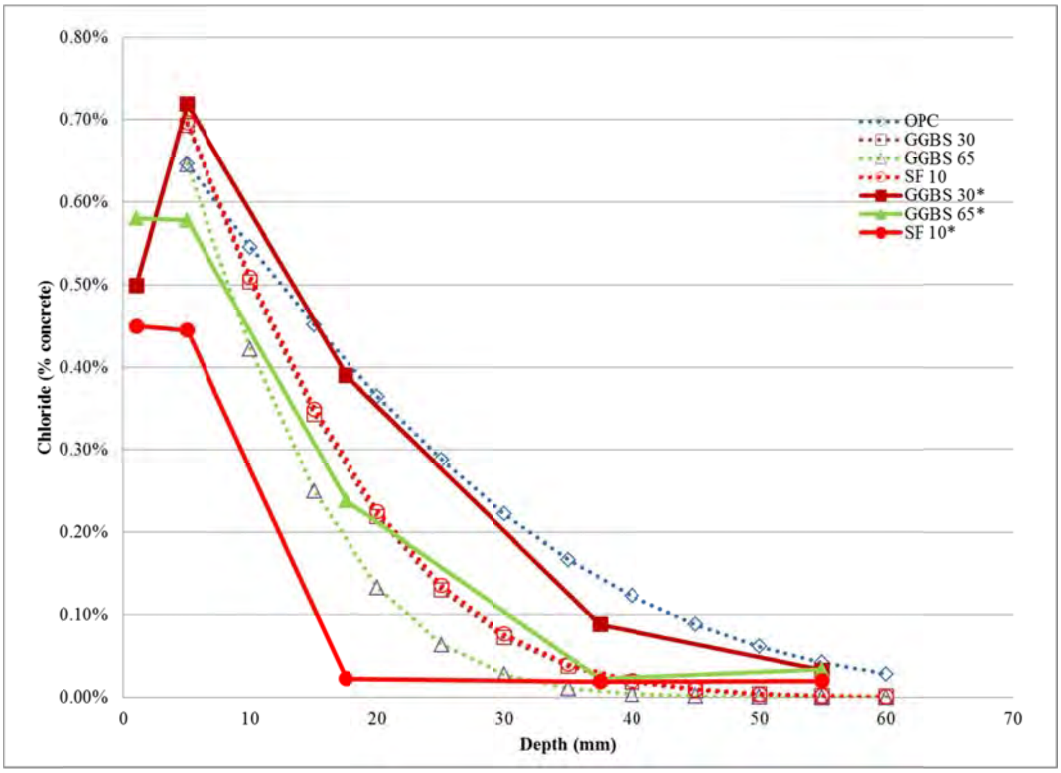

Figure 3: Predicted and measured chloride penetration after 19 years using CSM.

4.2 Life 365 Model

Life 365 appeared to profoundly underestimate the rate of initial chloride penetration. We would expect this to be due to the combined effect of not considering sorptivity effects as well as the default duration to build up significant surface chloride levels.

Life 365 appeared to give estimates of chloride penetration after 19 years for the OPC and GGBS 65 mixes broadly similar to the core result but overestimated chloride penetration in the GGBS 30 and SF 10.

4.3 STADIUM® Model

The STADIUM® modelling underestimated the depth of chloride penetration after 2 years compared with the result from cores in spite of mass transport due to sorptivity being considered in the model. This is possibly due to the prolonged drying of the specimens before exposure. The predicted surface chloride level was also significantly lower than measured from the cores.

After 19 years, the STADIUM® modelling tended to significantly underestimate the surface chloride level compared with the results from cores. At greater depths, the predicted chloride profile for the GGBS 30 concrete was similar to that measured but significantly overestimated the depth of chloride penetration for the GGBS 65 mix and particularly the SF 10 mix. It was interesting to note that the transport properties of the higher GGBS replacement mix were lower and the predicted surface chloride level lower but STADIUM® predicted a slightly higher chloride penetration depth than for the lower GGBS replacement mix.

5. DISCUSSION

Table 3 summarises the approximate depth to which chloride is predicted or measured to have reached the default threshold level of 0.05% by weight of concrete. After 2 and 6 years, the measured values are generally greater than the predicted depth suggesting a non-conservative prediction. After 19 years, the predictions vary depending on the model used.

Within this study, the measured chloride penetration of the silica fume mixture was consistently significantly less than predicted. Chloride penetration in the three models is strongly influenced by diffusivity. Calculations of the effective chloride diffusion coefficient based on profiles from cores compared with a bulk diffusion test after 19 years are given in Table 4. While the bulk diffusion for the GGBS mixtures was approximately 9 times that from field exposure, the differential was 48 times for the silica fume mix. Perhaps this may help explain the overestimation of the predicted chloride penetration depth for this mix.

The significant difference between the calculated field and laboratory chloride diffusivity highlights the importance of other ion in the transport process. This suggests that models such as STADIUM® which consider multi-ion transport and chemical interactions should provide a better predictions than those based on chloride movement alone.

Table 3: Predicted and measured depth of chloride threshold level after 2, 6 and 19 years exposure in the splash zone.

	OPC	GGBS 30%	GGBS 65%	SF 10%
2 year				
Concrete Society	23	19	17	20
Life 365	<30	<30	<30	<<30
Stadium	31	20	19	15
Core	37	37	34	nt
6 year				
Concrete Society	35	25	22	26
Life 365	45	35	<30	<30
Stadium	53	31	31	26
Core	75	nt	35	15
19 year				
Concrete Society	54	34	27	34
Life 365	>>75	67	40	45
Stadium	89	51	52	43
Core	>>75	50	35	13

Table 4: Effective chloride diffusion data from Berth 8 specimens

	Dce (based on Cl profile)			Dc (Nordtest 443)	Ratio Dc/Dce
Age (yrs)	2	6	19	20	
OPC	5.10E-12	1.09E-11	n/a	n/a	n/a
GGBS 30	2.28E-12	4.30E-13	4.05E-13	3.72E-12	9.19
GGBS 65	1.10E-12	1.34E-12	2.30E-13	2.04E-12	8.87
SF 10	n/a	1.45E-13	5.30E-14	2.54E-12	47.92

6. CONCLUSIONS

Chloride penetration data obtained from a field exposure programme in Australia was compared with the predictions from CSM, Life 365 and STADIUM® using their default values. This study has shown a significant underestimation of early chloride penetration by all three models. The predictions at later ages were more varied; sometimes similar to the field data but sometimes underestimating or overestimating penetration. This study highlights the complexity of service life prediction modelling and the potential for non-conservative or overly conservative predictions when using default values in certain microclimates.

REFERENCES

[1] Vallini, D. and Aldred, J.M. (2003) "Durability assessment of concrete specimens in the tidal and splash zones in Fremantle port." Coasts & Ports Australasian Conference, Auckland, New Zealand.

[2] Aldred, J.M. and Buenfeld, N.R. (2006) "Durability assessment of concrete specimens after 19 years in the splash zone" *8th International Conference on Concrete in Hot and Aggressive Environments* Bahrain, 27-29 Nov, 2006