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Methodology for Designing Structures to Withstand Extreme Environments: Performance Based Specifications

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METHODOLOGY FOR DESIGNING STRUCTURES TO WITHSTAND EXTREME ENVIRONMENTS: PERFORMANCE-BASED SPECIFICATIONS

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Abstract
Existing guidelines in BS 8500 allow the selection of concrete mix based on variables such as compressive strength, maximum water to binder ratio, minimum cement content and minimum cover thickness. This approach does not guarantee the durability and expected performance of the concrete structure in a given environment. One alternative is to develop performance- based specifications that supplement the existing guidelines in BS 8500, by specifying the required performance of concrete in terms of measurable properties such as resistance to environmental penetrations. This paper demonstrates one of such methodology for developing performance-based specifications for concretes exposed to marine environments. Chloride ingress related durability problem being critical in a marine environment, the reliability and repeatability of the different test methods for assessing the rate of chloride ingress is discussed first. Furthermore, a numerical simulation model is used to explore the test data to obtain long-term chloride ingress trends. Based on this, guidelines for selecting appropriate concrete mixes for a marine exposure is presented and discussed.

Keywords: Chloride Diffusivity, Chloride Ingress, Concrete Testing, Electrical Resistivity, Modelling, Permit Ion Migration Test, Performance-based Specification

1. General

A significant part of the construction budget is spent for repair and rehabilitation of concrete structures that deteriorates prematurely. As a direct consequence of this, asset owners are often forced to take decisions to repair and maintain an existing ailing infrastructure as opposed to investing in new ones. An effective decision making in this regard requires systematic information about the state of health of an asset (or expected performance), an acceptable level of variance in the ascertained information, an effective maintenance strategy that is linked to its whole life value. In the case of concrete infrastructure, factors such as materials used, design and type of loading on the structure, its location, severity of the exposure condition, etc., all will influence the decision making process due to calculated state of health of the structure. Therefore, it is important to specify the expected performance of a structure in addition to guidelines given in standards, such as BS 8500, which cover the factors defined earlier. At present, there are no performance specifications available for new concrete structures that will ensure the expected state of health of an asset. This paper outlines one of the approaches for developing performance-based specifications for concrete structures exposed to marine environments.

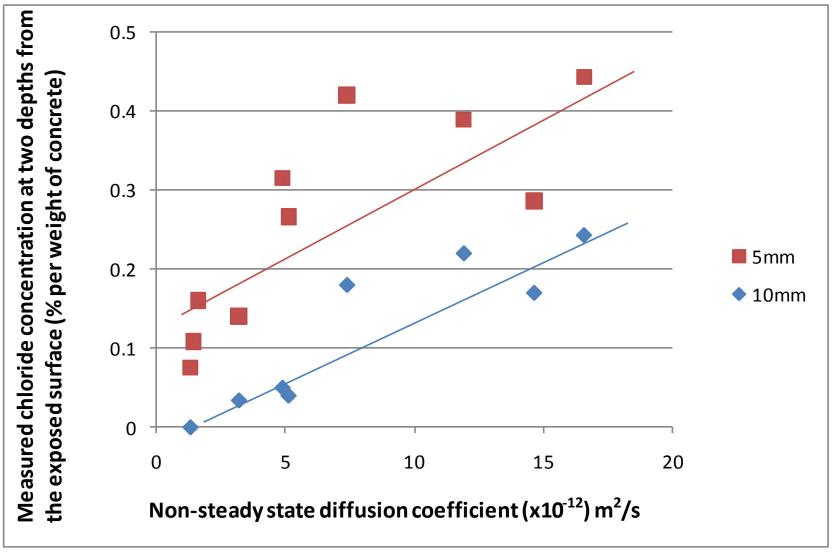
The main objective of this paper is to summarise developments in testing and modelling concrete for chloride ingress and illustrate how progress could be made in developing performance-based specifications with the help of these techniques.

2. Measurement of resistance to chloride ingress in concrete

Although the primary mechanism of chloride transport through unsaturated concrete cover is absorption, the accumulation of chlorides in this layer leads to further penetration of chlorides into concrete by diffusion (Nilsson *et al.*, 1996). As a consequence, diffusion becomes the most dominant mechanism of chloride transport at greater depths, which can be measured in terms of the coefficient of chloride ion diffusion. Different test methods are available to determine the chloride ion diffusion coefficient, e.g. steady-state and non-steady-state chloride diffusion and migration tests.

2.1 Relationship between chloride penetration and concrete diffusivity assessed using different lab based test methods

Figures 1 to 3 show the diffusivity of concrete (assessed using different lab based tests) plotted against the quantity of chloride ions measured at 5 and 10 mm depths from the exposed surface. The chloride ion concentration at these depths was determined by analysing powder samples which were collected from concrete samples immersed in 2.8M NaCl solution for 35days using potentiometric titration method. Data points in the graphs represent ten different concrete mixes. Further details regarding the mixes are available in Table. Results presented in Figures 1 to 3 show that the diffusivity assessed by the different test methods can be used with varying degree of accuracy to predict the quantity of chloride ions at a particular depth.

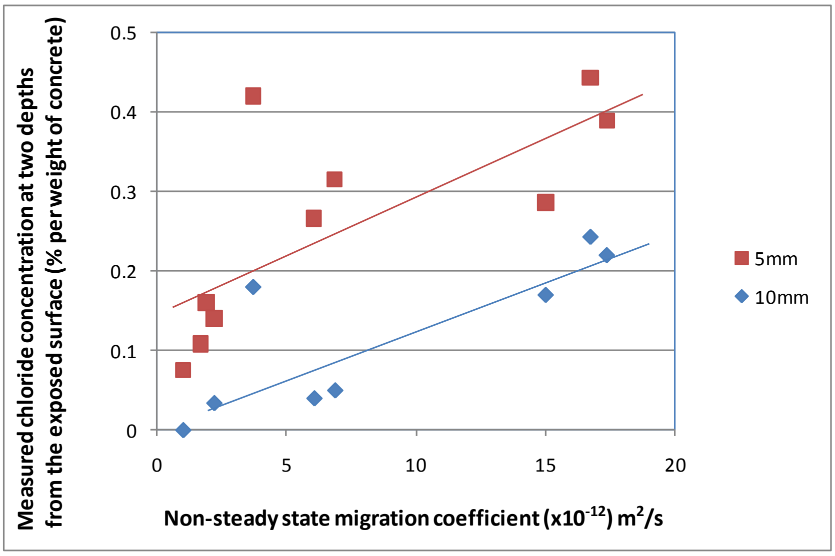


w/cm	Mix detail
0.50	opc
0.45	opc
0.35	opc
0.40	opc + ms
0.42	opc + ms
0.42	opc + pfa
0.45	opc + pfa
0.42	opc + ggbs
0.45	opc + ggbs

Figure 1 – Chloride concentration versus non-steady state diffusion coefficient for 5mm and 10mm depths from the exposed face of concrete specimens (Mix details in Table 1)

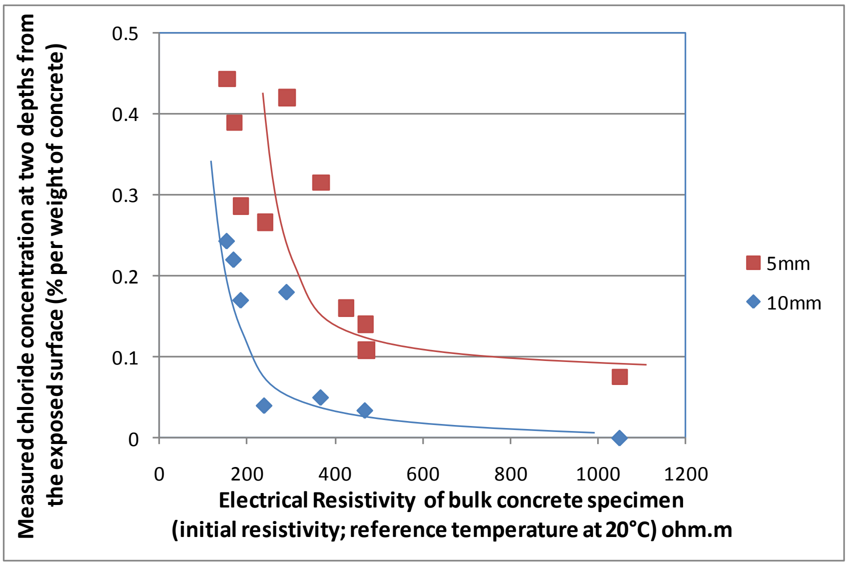
Figures 2 and 3 suggest that useful information about penetration of chloride ions can be obtained using rapid test methods. Nordic Test Build 492 (1999) requires on average 24 hours for assessing the diffusivity of concrete whereas electrical resistivity can be measured instantaneously. It is also worth noting that the electrical resistivity in this case was obtained from concrete specimens saturated with calcium hydroxide

($Ca(OH)_2$) solution. However, all these tests require concrete cores with a minimum thickness 50mm to be extracted from the structure. This will considerably limit the number of test that can be performed and frequent testing can leave the structure badly disfigured. It is also worth noting that there are test methods such as Permit Ion Migration test, that can be used on site for assessing the rate of chloride ingress through concrete and eliminates extraction of cores (Nanukuttan, *et.al*, 2006).



w/cm	Mix detail
0.50	opc
0.45	opc
0.35	opc
0.40	opc + ms
0.42	opc + ms
0.42	opc + pfa
0.45	opc + pfa
0.42	opc + ggbs
0.45	opc + ggbs

Figure 2 – Chloride concentration versus non-steady state migration coefficient (Nordic Test Build 492) for depths 5mm and 10mm from the exposed face of concrete specimens



w/cm	Mix detail
0.50	opc
0.45	opc
0.35	opc
0.40	opc + ms
0.42	opc + ms
0.42	opc + pfa
0.45	opc + pfa
0.42	opc + ggbs
0.45	opc + ggbs

Figure 3 – Chloride concentration versus electrical resistivity of bulk concrete for 5mm and 10mm depths from the exposed face of concrete specimens (Mix details in Table 1)

2. Effect of concrete mix properties on long term performance

Three test methods that can assess the chloride ingress resistance of concrete were identified in the previous section. It is vital to understand the repeatability and scope of the results in order for the test to be used for qualifying concrete. Table 1 shows mix details of 9 different concretes used in constructions across Europe and data on the chloride diffusivity (or chloride ingress resistance of concrete). The results in Table 1 identify the beneficial effects of using supplementary materials, such as pfa, ggbs and ms, and the influence of w/b on chloride ingress resistance. Most of the results are on average ±20% from the median. The results presented in Table 1 is in agreement with that reported by 11 other participating institutions who compared the repeatability and reproducibility of the test methods as part of an EU funded project (Chlortest, 2006). Hence it can be concluded that the tests are repeatable with 20% variability. To study the scope of these results it is necessary either to study the long-term behaviour of these concrete mixes in a field exposure environment or to simulate the behaviour in a given environment. The former would require long-term study with considerable investment and resources, whereas the latter would depend heavily on the accuracy of the numerical model used for predicting the behaviour. The approach used in this paper is to consider both the aspects. The long-term performance data from a structure exposed to a marine environment (North Sea) is used to validate the numerical models used for prediction. The second aspect is to use the test results along with the validated numerical model to predict the behaviour of different concrete mixes in the same environment.

Figure 4 - Shows the location of the pier stem (right hand side of the picture) near the Dornoch bridge, Scotland

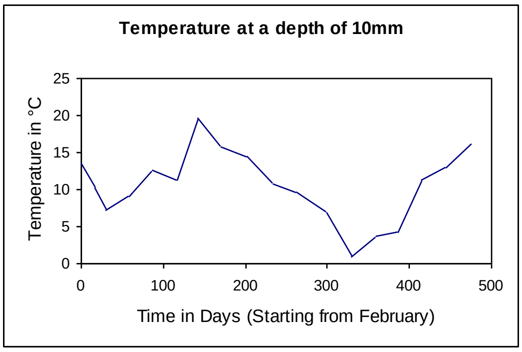


Figure 5 - Temperature of concrete at 10mm depth recorded for 16 months.

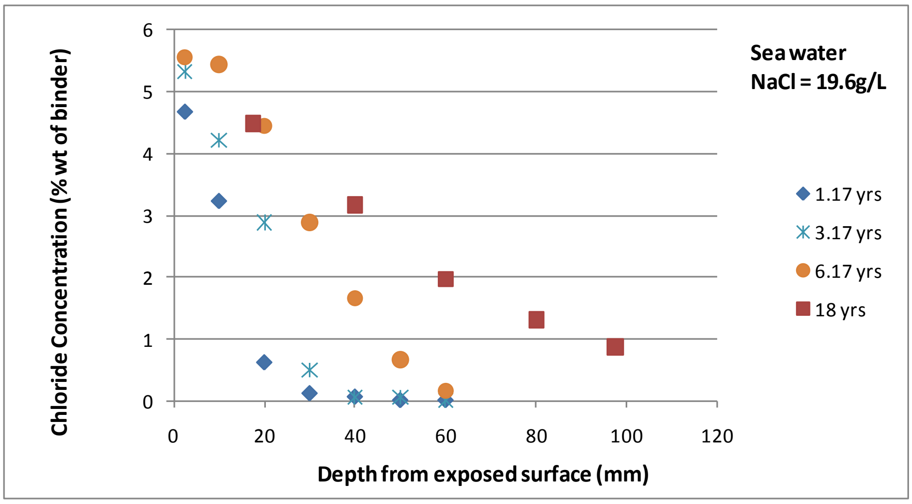


Figure 6 - The chloride profiles from OPC pier stems exposed to tidal low level

Table 1 Details of concrete mixes (Quantities reported in kg/m^3) and their chloride ingress resistance as measured by different test methods

Mix designation	**opc 0.35**	**opc 0.45**	**opc 0.50**	**ms 0.40**	**ms 0.42**	**pfa 0.42**	**pfa 0.45**	**ggbs 0.42**	**ggbs 0.45**
Country of Origin	Sweden	Spain	Sweden			Norway	Portugal	Netherlands	
Cement type (BS EN 197-1, 2000)	CEM I 42.5 N	CEM I-42.5 N	CEM I 42.5 N			(18% PFA) CEM II/A-V 42.5 R	(39% PFA) CEM IV/B 32.5R	(~70% Slag) CEM III/B 42.5 LH HS	
Cement content	450	400	400	399	389.5	410	340	410	350
Microsilica				21	20.5				
Water	157.5	180	200	168	172.2	172.2	153	172.2	157.5
Fine Aggregate (Min size 75µm)	904 (≤8mm)	742 (≤6mm)	920 (≤8mm)	842.5 (≤8mm)	897 (≤8mm)	901 (≤8mm)	62 (≤2mm) 603 (2-4mm)	901 (≤8mm)	70 (≤1mm) 790 (1-4mm)
Coarse Aggregate	904 (5-10mm)	1030 (6-16mm)	816 (5-10mm)	842.5 (8-16mm)	897 (10-15mm)	901 (10-15mm)	619 (4-12mm) 555 (12-25mm)	901 (5-10mm)	1040 (4-16mm)
Superplasticiser % of cement	CemFlux Bro 1.0	Melcret 222 4.8	-	Cementa 92M 3.4	CemFlux Bro 0.5	CemFlux Bro 0.5	Rheobuild 1000 4.1	CemFlux Bro 0.5	Cretoplast 3.9
water/binder (w/b)	**0.35**	**0.45**	**0.5**	**0.4**	**0.42**	**0.42**	**0.45**	**0.42**	**0.45**
Age at test (years)	~0.5	~1.0	~0.5	>1.0	~0.5	~0.5	<1.0	~0.5	<1.0

Measurable performance indicators (chloride diffusivity/bulk electrical resistivity results)

Mix designation	**opc 0.35**	**opc 0.45**	**opc 0.50**	**ms 0.40**	**ms 0.42**	**pfa 0.42**	**pfa 0.45**	**ggbs 0.42**	**ggbs 0.45**
D_{nssd} x 10^{-12} m^2/s (standard error)	5.11 (±0.56)	14.63 (±3.74)	16.56 (±1.82)	1.61 (±0.62)	4.88 (±0.58)	1.44 (±0.27)	7.38 (±2.43)	1.31 (±0.16)	3.19 (±1.35)
D_{nssm} x 10^{-12} m^2/s (standard error)	6.00 (±1.24)	15.00 (±3.02)	16.70 (±0.99)	1.90 (±0.07)	6.90 (±0.50)	1.70 (±0.13)	3.70 (±0.54)	1.00 (±0.05)	2.20 (±0.25)
ρ_{bulk} (ohm.m) (standard error)	175.70 (±16.5)	187.00 (±22.19)	56.00 (±12.77)	426.80 (±21.25)	236.30 (±31.00)	323.70 (±40.07)	291.40 (±4.61)	838.30 (±160.32)	469.80 (±17.25)
$D_{in\ situ}$ x 10^{-12} m^2/s (from Permit Ion Migration Test based on $D_{in\ situ}$ = 0.11 D_{nssm})	0.66	1.65	1.84	0.21	0.76	0.19	0.41	0.11	0.24
Predicted Chloride concentration at 50mm depth (% wt of binder as in Fig. 10)	For North-Sea tidal low level exposure (constant wetting and drying condition) using ClinConc Service Life Prediction Model [ref]								
	2.56	4.42	4.75	0.77	2.89	0.86	2.37	0.31	1.15

CemFlux Bro is polycarboxylether based superplasticiser; Melcret 222 and Rheobuild 1000 are both napthalene based superplasticisers; Cretoplast is a water reducing superplasticiser; Cementa 92M is melamine formaldehyde based superplasticiser; D_{nssd} is the coefficient from non-steady diffusion test; D_{nssm} is the coefficient from non-steady migration test; $D_{in\ situ}$ is the coefficient from Permit ion migration test; ρ_{bulk} is the saturated bulk electrical resistivity

Long-term performance study on concrete specimens exposed to North Sea

Data from a long-term study conducted on three ordinary Portland cement concrete pier stems exposed to tidal, splash and atmospheric conditions in North Sea are presented below (Nanukuttan *et al.* 2008). The concrete mix details are reported in Table 2. Chloride concentrations from various depths (termed as chloride profile) were determined continuously for a period up to 7 years and then after 18 years. General location of the piers and annual temperature variation at the site is as shown in Figures 4 and 5 respectively. Chloride profiles determined at 1.17, 3.17, 6.17 and 18 years from tidal low level (immersed continuously and rarely dry) are presented in Figure 6.

Table 2. Mix details for OPC pier stems exposed to North Sea

Mix	Cement kg/m^3	20mm kg/m^3	10mm kg/m^3	Fines kg/m^3	w/b	F_{28} MPa	D_{nssm} (10^{-12}m^2/s)
Plain	460	700	350	700	0.4	66	15 (± 3.5)

Several service life prediction models were considered as part of the wider study. However, only data from numerical simulations made using ClinConc service life model (Tang, 2006) is reported in this paper. In any case, this model was selected based on the recommendations by an EU FP5 Growth Programme project (ChlorTest, 2006) which reviewed different test methods and service life models.

The real and numerically simulated chloride profiles are presented in Figures 7-9. The top and bottom lines indicate the level of variation due to the disparity in input parameters including D_{nssm}. Figures 7 and 8 show that numerical simulation can predict the chloride profile with a high degree of accuracy. However, at the age of 18 years (Fig. 9), the simulation has underestimated the chloride ion content at depths greater than 50mm. The cause of this disparity, whether experimental error or error in the simulation, needs to be studied further.

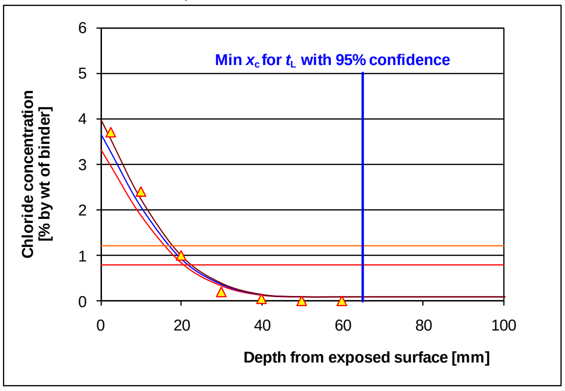


Figure 7 - The real and predicted chloride concentration after 1.17 years of exposure.

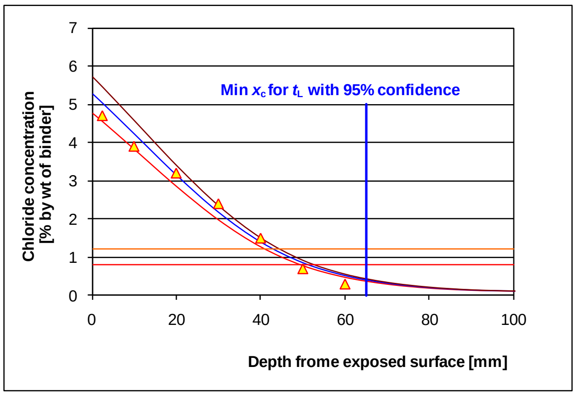


Figure 8 - The real and predicted chloride concentration after 7.17 years of exposure.

Guidelines for selecting concrete mixes for marine exposures

Based on the non-steady state migration coefficient (D_{nssm}) in Table 1, chloride profiles were simulated for the different concrete mixes exposed to the North Sea environment. Figure 10 shows the chloride profiles after 50 years of exposure to tidal low level exposure zone in North Sea. Such information will allow users to select a suitable concrete mix for their exposure condition. Furthermore, the test results such as D_{nssm} identified in Table 1 can be used for defining performance-based specifications for concretes. As an example, in order to keep the chloride concentration at the level of reinforcement that is at a depth of 50mm from the exposure surface to a value below 0.5 % by wt of binder, one should use 0.42 ggbs or any concrete which has a diffusivity D_{nssm} less than 1 x 10^{-12} m^2/s.

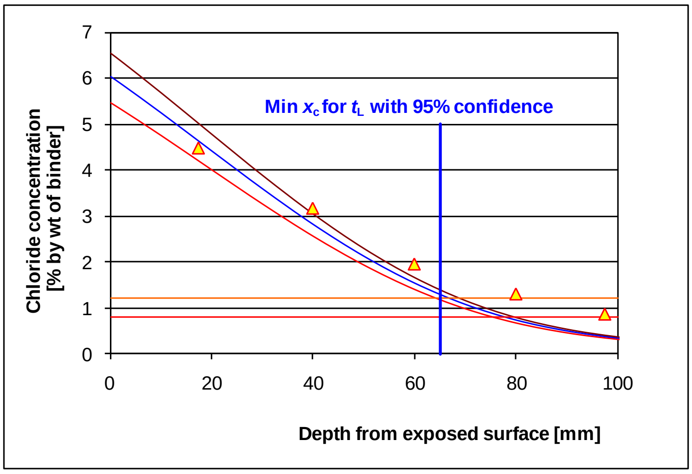


Figure 9 - The real and predicted chloride concentration after 18 years of exposure. [Data points indicate real data collected from the North Sea exposure site]

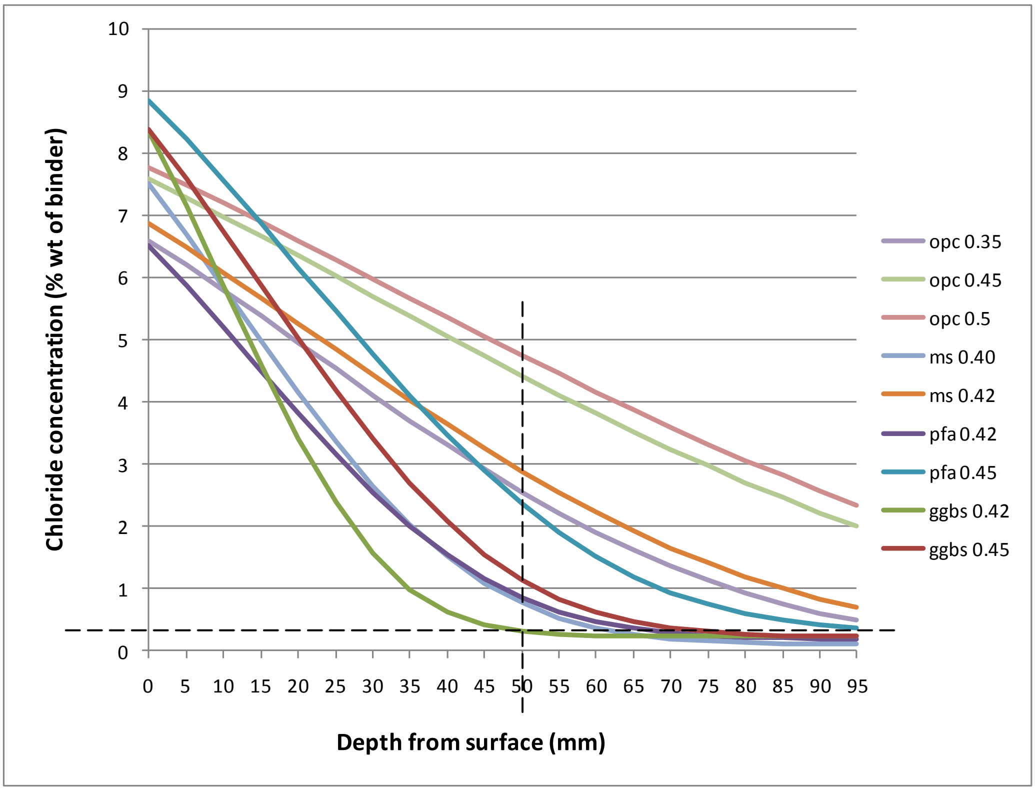


Figure 10 - Numerically simulated chloride profiles for various concretes listed in Table 1

CONCLUDING REMARKS

The usefulness, scope and repeatability of various lab based test methods for assessing the chloride penetration resistance were demonstrated. Data from one of the test method was further exploited to predict the chloride concentration versus depth at different service life of a structure. The accuracy of the prediction was also verified by comparing the predicted data against the field data from a long-term study. It was found that up to 7 years the predictions were accurate, but there was an underestimation of chloride content beyond 50mm depth at 18 years. This means that further refinements of the model are necessary.

The paper shows that a combined use of testing and modelling can be employed to develop performance-based specification for a marine environment. Such an approach can be adopted for any extreme exposure condition provided reliable test methods and numerical models are developed.

Acknowledgements

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