Service Life of Chloride-Contaminated Concrete Structures

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Abstract

Corrosion of reinforcement is the most significant cause of premature deterioration of reinforced concrete structures. The problem is particularly acute where corrosion is initiated by chloride ingress, for example in coastal environments and in highway structures subjected to the application of de-icing salts. Concern has been expressed in technical journals at the apparent inability of Portland cement concretes to protect embedded reinforcement in concrete infrastructure over a required service life of 100 years where chloride-rich environments are experienced. The use of secondary cementitious materials in concrete, including the waste materials Pulverised Fuel Ash (pfa) and Ground Granulated Blastfurnace Slag (ggbs), may enhance the resistance of the concrete to the chloride ingress. The use of pfa and ggbs is not yet a common feature of Irish concrete practice, in part because of a lack of research in this country on the topic. Indigenous sources of pfa and ggbs are now available in this country. This project researched the chloride-diffusivity of Irish Portland cement concretes in chloride environments to verify the adequacy of National Provisions for Portland cement concretes in the context of the recently published standard I.S./EN 206-1. The potential influence of secondary cementitious materials was also investigated.

It was found that the advice in respect of Portland cement concretes, for a 50-year service life in Exposure Classes XD1, XD2 and XD3 is satisfactory. A definitive comment cannot be made on Exposure Classes XS1, XS2 and XS3 due to lack of data but there are indications that XS3 is satisfactory. The relative merits of pfa and ggbs were clearly demonstrated and in comparison to similar Portland cement concretes mixes would convey enhanced service lives. Service life duration could be extended by a factor of up to three, providing a good margin of safety in satisfactory service life prediction.

Keywords: Chloride, ggbs, pfa, Portland cement, service life

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INTRODUCTION

The transport of chloride ions into concrete can take place by several different methods. The major transport mechanisms are capillary absorption, diffusion and, where relevant, flow under hydrostatic pressure. Capillary absorption is driven by moisture gradients in the concrete and significantly influences the extent of chloride ion take-up. It therefore influences the concentration gradient within the concrete. Diffusion processes then encourage the ingress of chloride ions through the cover, as long as there is a continuous liquid phase in the concrete. Permeation occurs through hydrostatic pressure if a solution containing chloride ions is present under an applied hydraulic head on at least one face of the concrete. There is evidence that mathematical models based on diffusion alone can provide useful predictions for engineering judgement of service life potential.

The author's study, and that of Dr. T. Callanan, were presented as a 'work in progress' report to the CRI03 colloquium in Belfast [1]. This paper presents an update on the findings based on the experiments described in the earlier paper and reference to findings by Dr. Callanan.

SERVICE LIFE MODELLING

Mathematical Model

There are several different mathematical models described in the literature (Richardson [2]) to simulate the ingress and migration of chloride ions into concrete. There are models available that incorporate all three mechanics of chloride ingress but these tend to be too complicated for development as performance-based specification tools due to the number of variables and difficulties in characterising inherent uncertainties associated with each variable. The matter is greatly simplified by consideration of diffusion only and there is evidence to show the validity of this approach. Bamforth [3] stated that while it is recognised that the ingress of chlorides into concrete is a complex interaction of physical and chemical processes, it is generally accepted that the diffusion of chloride ions is the main mechanism of chloride ingress beyond the 10mm near-surface zone.

Collepardi et al [4] demonstrated that chloride diffusion into concrete can usefully be modelled by the error function solution to Fick's second law of diffusion by Crank [5]. Equation (1) mathematically expresses Fick's second law of diffusion for the non-steady state condition, where the concentration *C* of the medium is changing with time *t*.

$$\frac{\partial C}{\partial t} = D_{ca} \frac{\partial^2 C}{\partial x^2} \qquad (1)$$

It is only applicable to one-dimensional flow with the space co-ordinate *x*, measured normal to the section. The parameter D_{ca} is the apparent diffusion coefficient. The equation may be solved for a semi-infinite medium using the Laplace transformation, assuming that the surface concentration is constant (C_0), the initial concentration in the concrete is zero and the infinite point condition $C_{(x=\infty,\ t>0)}$ is also zero since it is far enough away from the surface. The error function solution as applied by Crank is based on these assumptions, and may be stated as Equation 2.

$$C = C_0 \left\{ 1 - erf\left(\frac{x}{2\sqrt{(D_{ca} t)}} \right) \right\} \tag{2}$$

where *erf* is the error function. The error function as defined in Equation 3 is a standard mathematical function, which occurs in statistics and various studies in physics and heat conduction equations to which Fick's laws of diffusion are closely related.

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{3}$$

It is accepted that diffusion theory alone may not fully describe the relevant transport mechanisms and therefore coefficients D_{ca} derived from Crank's application of the error function solution are best characterised as empirical values, and are sometimes referred to as 'apparent diffusion coefficients', based on a best fit curve between theoretical and actual performance. The concrete is sampled at various depth intervals and analysed for chloride content to establish a chloride profile. Samples may be obtained by the collection of dust drillings at specified depth intervals or by profile grinding of a concrete core. The established profile is then compared with a predetermined profile or analysed by producing a best-fit least squares curve using the error function solution to Fick's second law of diffusion. This will produce an apparent diffusion coefficient D_{ca} and a notional surface concentration C_{sn}. The surface chloride concentration cannot be determined accurately and so a notional surface concentration is estimated by continuing the determined concentration profile using the error function equation until it intersects the Y-axis. The point at which the profile intersects the Y-axis is then known as the notional surface concentration C_{sn} and Equation 2 become the modified form of the error function equation shown in Equation 4.

$$C = C_{sn} \left\{ 1 - erf\left(\frac{x}{2\sqrt{(D_{ca} t)}} \right) \right\} \tag{4}$$

The method used to produce the best fit least squares curve using the modified form of the error function equation is well suited to statistical based computer packages. One such statistical package is 'Microsoft Excel' which includes the 'Solver' analysis tool as part of its analysis toolpack. 'Microsoft Excel Solver' is based on well-established numerical analysis and is used for equation solving and optimisation by iterative procedure.

Bamforth [3] noted that there was very little time-dependent change in D_{ca} for Portland cement concrete but there were significant reductions for PFA and GGBS mixes over the period of exposure. Using both his work and other published results, Bamforth expressed the relationship between the decreasing apparent chloride diffusion coefficient *Dca* value and the exposure time for PFA and GGBS concretes as Equation 2.16.

$$D_{ca} = a \bullet t^n \tag{5}$$

where

- t exposure time
- a value of *Dca* at time t = 1 year
- n slope of the line relating log D_{ca} and log t

The coefficients a and n are derived from regression analysis of the data, which was collected by Bamforth. This further refinement has not been included in the judgements made in this paper, thus erring on the conservative side.

DETERMINATION OF PARAMETERS IN IRISH PRACTICE

The application of the error function solution to Fick's second law of diffusion as a chloride ingress model requires the determination of a number of variables. These variables include apparent chloride diffusion coefficients, service life, concrete cover, corrosion threshold values and notional surface chloride concentrations. The values used in application of error function solution model are outlined as follows:

Apparent Chloride Diffusion Coefficients (Dca values)

A number of laboratory test methods (rapid, medium and long term) were employed to establish apparent chloride diffusion coefficients for the concrete mixes used in this study. The long-term immersion tests were found to provide the most consistent results due to care taken to ensure that diffusion was the dominant transport process. The medium-term ponding tests were found to be a useful technique for the rapid ingress of chloride into concrete samples to accelerate the initiation of corrosion. However it can be a poor indicator of chloride ingress rate due to the significant effect of absorption in the intentionally reduced cover depth. The rapid migration tests were found to produce good results for the NPC and ggbs concretes, which suggest that further research may be worthwhile considering the efficiency of the test. The most striking aspect of the rapid migration test was the poor performance of the pfa concretes. It is considered that this was due to the increased time required for pfa concretes to fully hydrate. It is likely though that extending the concrete age will promote further hydration and give improved results for all samples tested.

Since diffusion was the dominant transport process in the long-term immersion tests, a higher degree of confidence can be taken in the diffusion coefficients produced from this test. It is on this basis that it was decided to use these values in the chloride ingress model. Table 1 shows the set of D_{ca} values that were inputted into the model.

Table 1 Apparent Diffusion Coefficients Values

Apparent Chloride Diffusion Coefficients (x 10^{-12} m^2/s)		
	320 XD1 XS1	400 XD3 XS3
NPC	6.91	6.62
GGBS 30%	2.50	1.80
GGBS 50%	2.43	2.16
PFA 15%	2.94	2.52
PFA 30%	2.33	2.16

Concrete Cover

The values for the recommended concrete covers were adopted from Table 4.4N Eurocode 2 (EN 1992-1-1:2004). The concrete covers for a 50-year and 100-year design working life and exposure classes XD1 / XS1 and XD3 / XS3 are outlined in Table 2.

Table 2 Concrete covers

Design Working Life	**XD1 / XS1**	**XD3 / XS3**
50 year life	35	45
100 year life	45	55

Corrosion Threshold Values

It was not possible to establish, to a sufficient degree of accuracy, corrosion threshold values for the concrete samples used as previously explained. A corrosion threshold value of 0.4 % is often used in research and practice and this carries a risk of corrosion of approximately 25%. Callanan [6] suggested that based on the limited observations in Ireland and the uncertainty that exists in research that an appropriate value of 1.0% by mass of cement, which carries a risk of corrosion of approximately 35% should be taken.

Notional Surface Chloride Concentration

A large range of notional surface chloride concentration values has been found in reported results. Varying environmental conditions from country to country may be responsible for the large range. Based on a study carried out by Callanan [6] on a number of Irish highway structures a notional surface chloride concentration of 1.2% by mass of cement was identified as an appropriate value for Irish concretes in the ‘XD’ series of exposure classes. No field data is currently available in Ireland for the ‘XS’ series.

SERVICE LIFE PREDICTION

Concern has been expressed in a number of technical journals at the apparent inability of normal Portland cement (NPC) concretes to protect embedded reinforcement in concrete infrastructure over a required service life of 100 years in locations where they are exposed to chloride-rich environments. The objective of this work was to expand on the limited research that has been previously carried out on the performance of Irish Portland cement concretes with or without secondary cementitious materials. Studies were made of relevance to the XS and XD range of Exposure classes. Two sets of calculations were carried out using the error function solution to Fick’s second law and the value outlined in the previous section. The first set of calculations were carried out for the concretes with a binder content of 320 kg/m^3 and exposure class XD1 and the second set of calculations were carried out for the concretes with a binder content of 400 kg/m^3 and exposure class XD3.

The results are shown graphically in Figure 1 and 2. Both sets of results indicate that with a corrosion threshold value of 1.0% by mass of cement, covers equal to that recommended in EN 1992-1-1:2004 and a surface concentration of 1.2%, the required service life can be achieved with NPC concretes.

The graphs also show predictions for secondary cementitious products that were used: ground granulated blastfurnace slag (ggbs) and pulverised fuel ash (pfa). The replacement levels used were 30% ggbs, 50% ggbs, 15% pfa and 30% pfa. It may be seen that there are significant benefits to be achieved from the use of secondary cementitious materials. The use of ggbs and pfa can increase the service life by a factor of three.

It would appear therefore that the advice in respect of Portland cement concretes, for a 50-year service life, in Exposure Classes XD1, XD2 and XD3 is satisfactory. Extension of this to 100 years by the recommended additional cover also seems to be achieveable. A definitive comment cannot be made on Exposure Classes XS1, XS2 and XS3 due to lack of data but there are indications that XS3 is satisfactory. The relative merits of pfa and ggbs were clearly demonstrated and in comparison to similar Portland cement concretes mixes would convey enhanced service lives. Service life duration could be extended by a factor of up to three, providing a good margin of safety in satisfactory service life prediction.

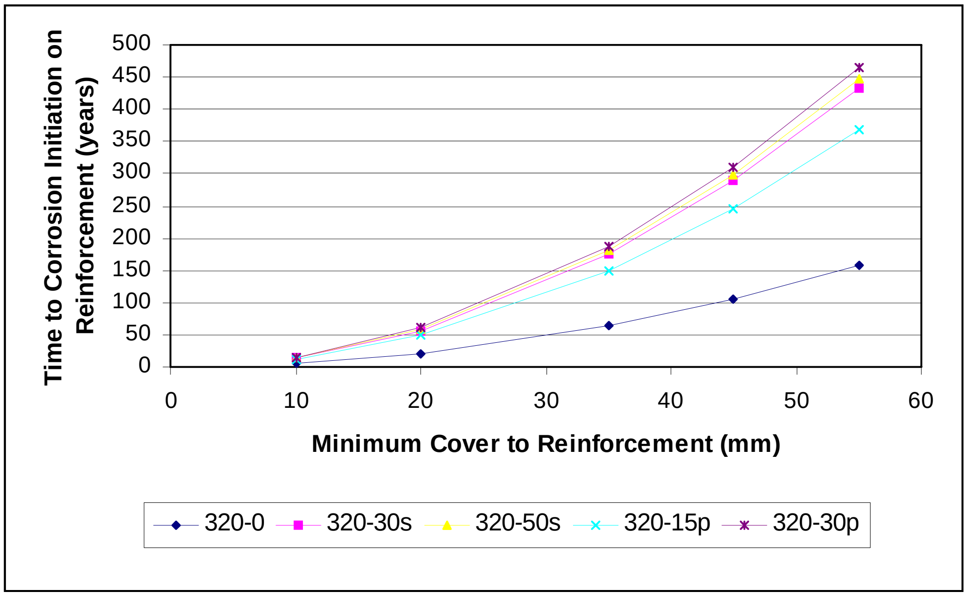

Figure 1 Time to corrosion initiation for a given cover, concrete with 320 kg/m^3 binder content, notional surface concentration of 1.2% and chloride threshold value of 1.0%

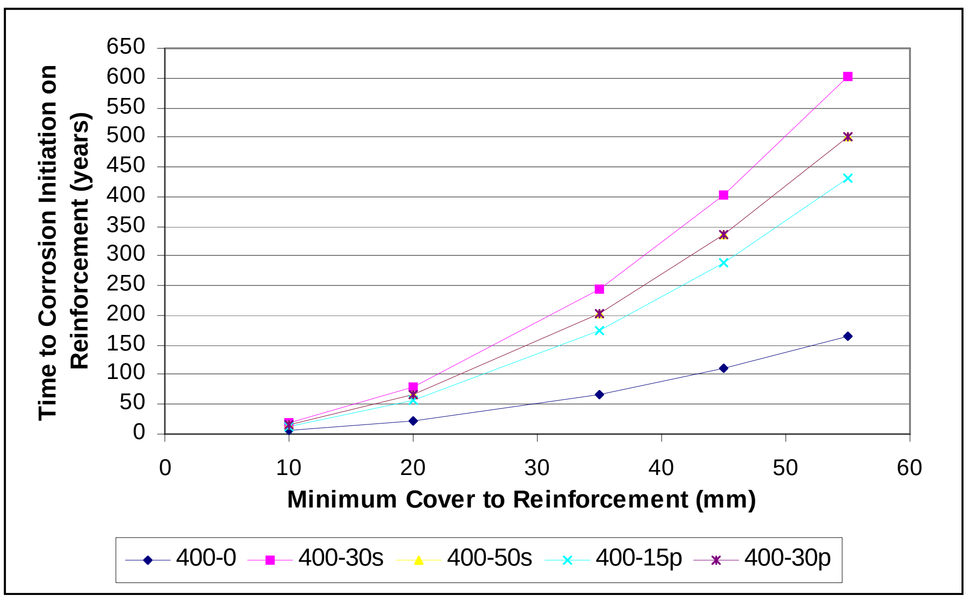

Figure 2 Time to corrosion initiation for a given cover, concrete with 400 kg/m^3 binder content, notional surface concentration of 1.2% and chloride threshold value of 1.0%

CONCLUSIONS

The results from the laboratory testing program showed the NPC concretes had apparent chloride diffusion coefficients of the order of 7 x $10^{-12}m^2/s$. The range of apparent chloride diffusion coefficients for the concretes with the secondary cementitious materials was substantially lower. For ggbs it was of the order of 2 to 2.5 x $10^{-12}m^2/s$ while for pfa the values were about 0.5 x $10^{-12}m^2/s$ higher. Values for the corrosion threshold value and the notional surface chloride level were taken from a study carried out by Callanan [6] on a number of highway structures in service in Ireland - a corrosion threshold value of 1% by mass of cement and a notional surface chloride level of 1.2% by weight of cement. The recommended covers to the reinforcement were taken from Eurocode 2 EN 1992-1-1:2004. Using the error function solution to Fick's second law of diffusion as a service life model, while the benefits of using ggbs and pfa were clearly demonstrated, it was established that NPC concretes could achieve the required service life under conditions assumed for current service in Ireland for the 'XD' series of exposure classes. A definitive comment cannot be made on the 'XS' series of exposure classes due to lack of data but there are indications that XS3 is satisfactory.

The benefits of pfa and ggbs inclusion were clearly demonstrated and could provide a good margin of safety in satisfactory service life prediction across both 'XD' and 'XS' classes.

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