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Need for further development in service life modelling of concrete structures in chloride environment

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Abstract

Designing concrete structures for a very long service life may have considerable economic and societal benefits including minimized material consumption over the long term, thus contribute to more sustainable solutions. However, such long service lives require determination and extrapolation of environmental loadings and material durability performance over a long period, as well as reliable and operational models for service life predictions. Codes and standards give deem-to-satisfied recommendations for intended working (service) life up to about 100 years. However, if higher working lives of 200 and 300 years are specified, as for monumental buildings, bridges and other important infrastructures, more in-depth service life predictions are required. This paper focuses on durability and service life predictions for reinforced concrete structures for working (service) life requirements above 100 years.

Keywords: concrete structures; service life; chloride ingress; chloride threshold; probability

1. Introduction

Despite the fact that almost all current concrete structural design codes and standards make no allowance for the effects of deterioration during the life of the structure, premature deterioration of concrete buildings and infrastructure due to corrosion of reinforcement is still a severe challenge, both technically and economically. Moreover, repair-work on the public transportation infrastructure are causing significant inconveniences and delays for both the industry and the general public, and are now recognized as a substantial cost for the society.

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The provisions within codes of practice for concrete structural design and the associated materials standards are typical given in tabulated form relating the provision of resistance (e.g. cement type and quality, maximum water/binder ratio, depth of cover, concrete grade, minimum air content, type of curing, control of early cracking, crack width limitation) to the aggressivity of the environment and the length of the design service life.

In general, Eurocode 2 for concrete structures, an a priori assumption is made that 50-year service life will be achieved for structures designed in accordance with the given requirements and provisions. Other national codes and regulations may adopt higher service lives, like in the Norwegian annex to Eurocode 2 [1], specifying minimum concrete covers for design lives of both 50 and 100 years.

For some important long-life infrastructures and monumental buildings, target service life of 200 and 300 years, or even more, may be specified. Service life modelling, or chloride ingress modelling, based on Fick’s second law of diffusion is becoming the common tool for performance-based specifications of such concrete structures.

An interesting long-life infrastructure in this respect is the design and construction of the Second Gateway Bridge in Australia with a service life requirement of 300 years [2]. Chloride induces corrosion was of particular concern for the durability of the main pier pilecaps. These elements were designed with a concrete cover to the ordinary black steel of 150 mm. To control surface cracking of such large cover gromarkdepth, a mat of LDX 2101 stainless steel reinforcement was specified and places at a distance of 75 mm from the exposed concrete surface. A ternary blend concrete consisting of 30 % fly ash (FA) and 21 % blast furnace slag (BFS) with a water/binder ratio of 0.32 was used in these elements in order to improve concrete durability properties substantially.

Other examples of long service life requirements are the design and construction of concrete foundations for some major residential areas located at the sea front in Norway. In one of those construction projects, the client has specified a target service life (design service life) of 200 years. To meet this design life requirement, a cover of 100 mm to ordinary black steel was specified together with a ternary blend concrete with 6 – 20% FA and 4 % silica fume (SF).

In the above construction projects the concrete cover specifications were verified through probabilistic service life calculations based on Fick’s second law of diffusion. Based on the cover specifications, a conclusion could have been drawn that a cover depth of 100 mm is needed for 200 year design life, whereas 150 mm cover is needed for achieving 300 years. However, this is not the case. This paper discusses the uncertainties associated with the service life model and how the output of the probabilistic model is applied for the prediction and specification of cover depths in the two construction projects

It is worth mentioning that in both projects the service life design included an addition safety margin as electrical continuity was specified for reinforcement in the most aggressive environment, to enable future cathodic protection to be installed.

2. Chloride induced corrosion - Service life modelling

Service life of reinforced concrete is often divided into two distinct time periods – the initiation period and the propagation period, respectively. The initiation period is the time when chlorides penetrate through the concrete towards the reinforcement, with negligible concrete deterioration. The propagation period is the time after corrosion initiation of the reinforcement, including concrete cracking, delamination and reduced reinforcement area.

In the design of new structures the end of service life is often defined at the time when the chloride content at the surface of the reinforcement has exceeded a critical level resulting in depassivation and corrosion initiation of the reinforcement. This critical chloride content, or chloride threshold level, becomes therefore a key parameter in the prediction of the design service life.

For estimation of residual service life and capacity, the corrosion process of the reinforcement (i.e. the propagation period) is important. However, to the authors’ knowledge, such operational service life models are lacking.

2.1. *Initiation period – chloride ingress*

The chloride ingress is commonly modelled by Fick’s 2nd law of diffusion, assuming all transport of chloride ions in an un-cracked concrete medium will occur by ionic diffusion. The chloride concentration at depth x at time t may then be calculated according to equation 1. The time dependency of the diffusion coefficient is further modelled according to equation 2.

$$C(x,t) = C_i + (C_0 - C_i) \cdot erfc\left(\frac{x}{2 \cdot \sqrt{\mathrm{D_a}(t) \cdot t}} \right) \tag{1}$$

$$D_a(t) = D_0 \left(\frac{t_0}{t} \right)^{\alpha} \tag{2}$$

where,

C(x, t): chloride concentration at depth x at time t
C_0: chloride concentration on the exposed concrete surface
C_i: initial chloride concentration in the concrete
t: exposure time
x: cover depth
erfc: the error function complement
$D_a(t)$: time dependent apparent (average) chloride diffusion coefficient at time t
D_0 : chloride diffusion coefficient at the age t_0.
α: age factor
t_0: time at exposure

The chloride diffusion coefficient will typically decrease as time passes since the capillary pore system will be altered as hydration products continue to form. Further, some chloride ions will become chemically or physically bound as they penetrate the pore system. Other pore blocking mechanisms may also take place in the transition zone between concrete and seawater.

The age factor in equation 2 is modelling how fast the diffusion coefficient is improved over time. Several investigations have been conducted worldwide to stipulate the age factor, α, and many different values may be found in the literature. However, most of the values are based on concrete specimens at relative short exposure periods and from different marine structures with different concrete compositions and under varying exposure conditions.

One of very few systematic long term field investigations suitable for determine reliable data for this ageing effect for relevant concrete recipes are those presented in [3,4] on concrete samples exposed to marine environment in Norway. The main observation from the Norwegian marine field studies was that both the calculated surface chloride concentration C_0 and the apparent chloride diffusion coefficient D_a are time dependent variables and seem to reach a constant value after about 10 -15 years of exposure, as illustrated in Figs. 1 and 2. These studies include concrete recipes with CEM I and fly ash content varying from zero to 20 % by weight of cement, and one series of ternary blend concrete with 4 % silica fume (SF) and 20 % fly ash (FA). The water binder ratio was in the order of 0.40 for all concrete samples. Results from the concrete samples tested in the tidal/splash zone are presented in Table 1. As can be seen, the ternary blend concrete with ordinary Portland cement (OPC), 20 % FA and 4 % SF obtained the lowest diffusion coefficient at early age as well as in the long term.

Table 1. Age factors derived from field measurements on concrete samples over 9 years of marine exposure in the tidal zone. Corresponding diffusion coefficients calculated for 28 days of exposure for different blends of concrete, data from [3].

Type of binders:	Age factor		Calculated diffusion coefficient (m^2/s)
	Mean value	Variation (%)	Value at 28 days
Ordinary Portland cement (OPC)	0.19	16	$7{,}9 \cdot 10^{-12}$
OPC with 10-20 % silica fume (SF)	0.43	13	$7{,}2 \cdot 10^{-12}$
OPC with 10- 20% fly ash (FA)	0.40	10	$8{,}7 \cdot 10^{-12}$
OPC with 4% SF and 20 % FA	0.46	17	$4{,}1 \cdot 10^{-12}$

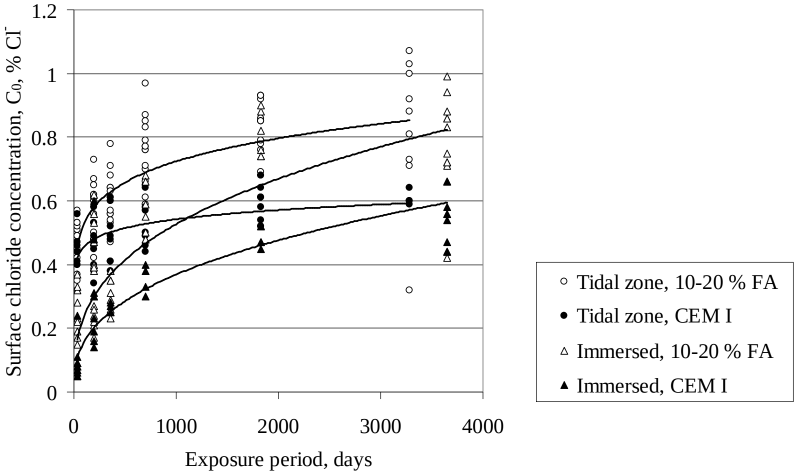

Fig. 1. Surface chloride concentration (C_0) in % of concrete weight for concrete with and without fly ash (FA) [4].

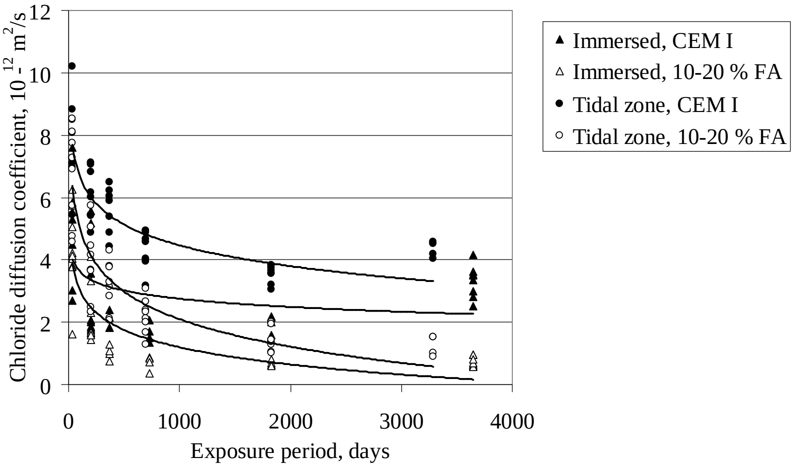

Fig. 2. Apparent diffusion coefficient (D_a) for concrete with and without fly ash (FA) [4].

2.2. *Chloride threshold level – corrosion initiation*

When the chloride threshold level is exceeded in a certain small area (pit) on the reinforcement surface, depassivation occurs and corrosion initiation may start. The corrosion in localized small surface pits continues to grow around and along the reinforcing bars. As this corrosion process is of stochastic nature both in its probability of occurrence and in its geometrical distribution and spatial variation, it is necessary to express the threshold value in statistical terms [5-9].

Reliable data for the chloride threshold level are lacking, especially from field exposure of existing structures. Thus, conservative values as often used in service life calculations. In *fib* “Model Code for Service Life Design” [5] a beta distribution with a mean value of 0.60 by weight of cement is suggested. However, higher mean values have been found by Izquierdo et al [9] based on laboratory tests and by Markeset [6] on a real structure. The model proposed by Markeset [6] is based on corrosion senor measurements on a marine structure in Norway and represented by a lognormal distribution with a mean value for critical chloride content of 0.77 % by weight of cement (or 0.12 % by weight of concrete) and a coefficient of variation of 32%, see Fig. 3.

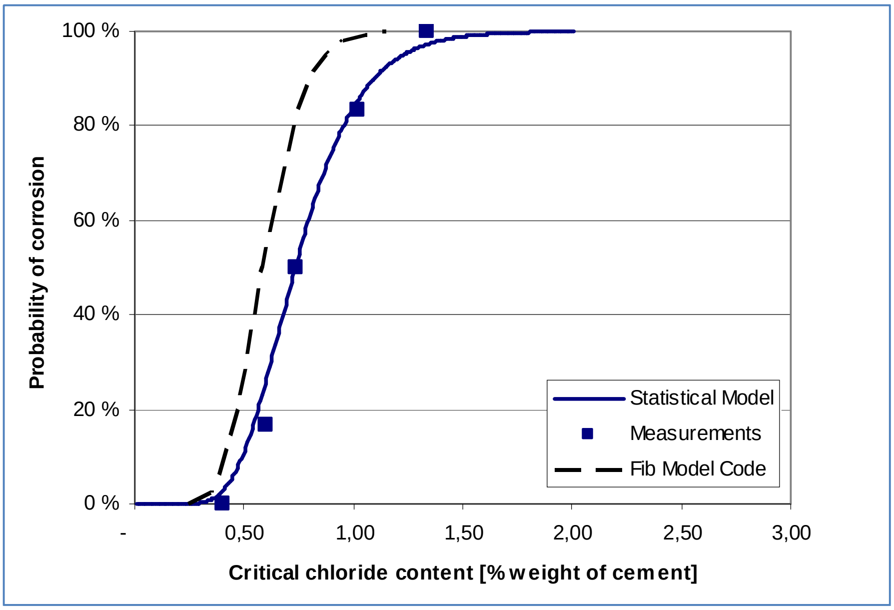

Fig. 3. Probability of corrosion initiation according to Markeset [6] compared to *fib* Model code for service life design [5].

3. Probabilistic service life calculations

In the service life calculations, the input parameters in equation 1 and 2 should be considered as stochastic variables characterized by the distribution type, the mean value and the coefficient of variation (COV). The end of service life is defined as the time to onset of corrosion and the limit state function, $G_{(X)}$, is defined as the difference between the critical chloride concentration, C_{cr} , and the calculated chloride concentration, $C_{(X,t)}$, at the reinforcement:

$$G_{(X)} = C_{cr} - C_{(X,t)} \quad (1)$$

where X is a vector of the statistical parameters as diffusion coefficient, surface chloride concentration, concrete cover, etc.

Introducing onset of corrosion as a failure criterion indicates that this criterion must be dealt with as a Serviceability Limit State (SLS). This means that “failure” only leads to economic consequences and that the effect of deterioration will be observable long before risk of collapse is reached. Treating this as a SLS criterion, the acceptance criterion for corrosion initiation may be set as high as 10 % probability (i.e. reliability index β = 1.28).

3.1. *300 year service life: Pile caps of Second Gateway Bridge*

Probabilistic service life calculations are performed for the pile caps of the Second Gateway Bridge in Australia based on the model input parameters given in [2] and summarized in Table 2. Two sets of simulations are conducted; Model 1 with a diffusion coefficient of 2.0 10^{-12} m^2/s and age factor α=0.56, and Model 2 with a constant diffusion coefficient of 1.1 10^{-13} m^2/s estimated in [2] as the constant value after 30 years of exposure (i.e. α = 0).

Table 2. Input data for the probabilistic time to corrosion initiation predictions, input data from [2].

Variables:	Mean values	Coefficient of variation (COV)	Distributions
Depth of cover (mm):	150	20 %	Normal
Diffusion coefficient, D_0 (m^2/s):			
Model 1:D_0 (for $\alpha = 0.56$)	2.0 10^{-12}	25 %	Lognormal
Model 2: D_0 (for $\alpha = 0$)	1.1 10^{-13}	25 %	Lognormal
Surface chloride content C_s (% by weight of concrete):	0.65	20 %	Normal
Age factors α:			
Model 1	0.56	25 %	Normal
Model 2	0		
Critical chloride content (% by weight of concrete):	0.06	25 %	Lognormal

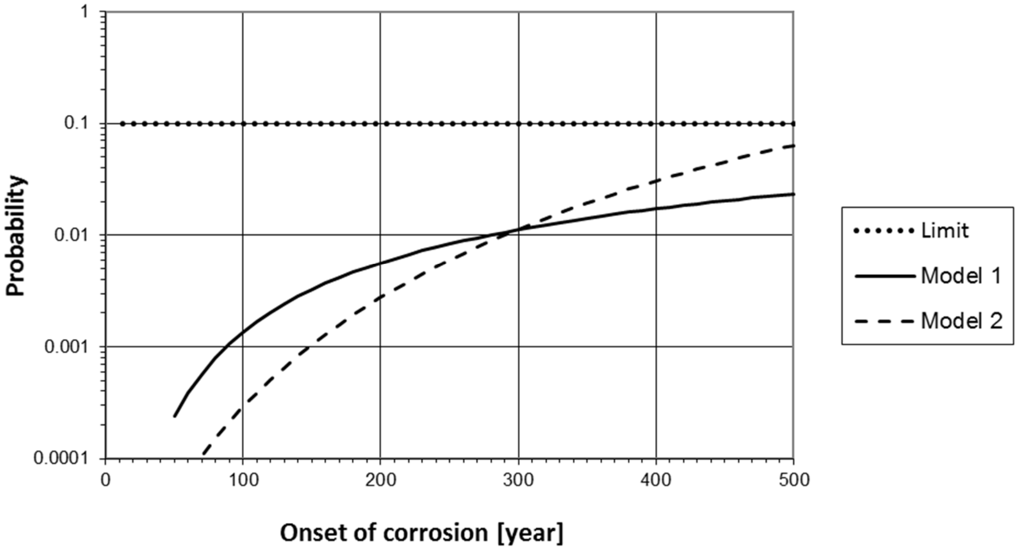

Fig. 4. Probability of corrosion initiation for 150 mm cover depth based on input data given in Table 2.

The probability of corrosion initiation versus service life for the ternary concrete mix and 150 mm depth of cover to the ordinary steel in the pile caps are shown in Fig. 4. As seen, a very low probability of corrosion initiation, about 1 % ($\beta = 2.32$), is obtained for the specified cover of 150 mm. If a probability of 10 % ($\beta = 1.28$) of corrosion initiation is applied, a service life above 500 years may be obtained. The two diffusion models (Model 1 and Model 2) gave about the same result for 300 year of service life.

3.2. *200 year service life: Foundation for residential area at sea front*

The original calculations leading to the specification of the 100 mm cover depth to ordinary steel, was based on probabilistic calculations using a model denoted “Cover specification model”. The statistical input parameters for this model was developed by calibration towards the cover depth provisions given in the Norwegian annex to Eurocode 2 [1] and the recommendation in [10] for 50- and 100-year design life, respectively. For these cover specification calculations, an acceptance criterion for corrosion initiation of 10 % was applied. The modelling and the statistical parameters are further described in [10].

In this paper the effect of applying the specified ternary blend concrete (20 % fly ash and 4 % silica fume), with the diffusion parameters according to Table 1, as well as applying the statistical distribution for the chloride threshold given in Fig. 3 [6], has also been studied. The statistical input parameters applied in the probabilistic calculations for all three variations are listed in Table 3.

The probabilistic calculations for the concrete foundation are presented in Fig. 5. The cover specification model calibrated to the Norwegian annex [1] with 10% probability of corrosion initiation corresponds to a cover depth of 100 mm for the target service life of 200 years. By modelling the ternary blend concrete and applying the statistical distribution for threshold level according to Fig. 3, somewhat lower concrete cover, about 80 mm, is found from the probabilistic analysis for 10 % probability of corrosion initiation.

Table 3. Statistical input parameters for the cover depth predictions for target service life of 200 years.

Variables:	Cover specification model	Ternary blend model 1	Ternary blend model 2	Distributions
	Mean values / COV	Mean values / COV	Mean values / COV	
Design Service life (years)	200	200	200	
Diffusion coefficient, D_0 (m^2/s):	7 10^{-12}/ 40 %	4.1 10^{-12}/ 28 %	4.1 10^{-12}/ 28 %	Lognormal
Age factor α:	0.50 / 15 %	0.46 / 17 %		Normal
Surface chloride concentration C_s (% by weight of concrete)	0.63 / 48 %	0.63 / 48 %	0.63/ 48 %	Normal
Critical chloride content (% by weight of concrete)				
Constant threshold	0.10	0.10	-	Deterministic
Statistical threshold	-	-	0.115 / 32 %	Lognormal

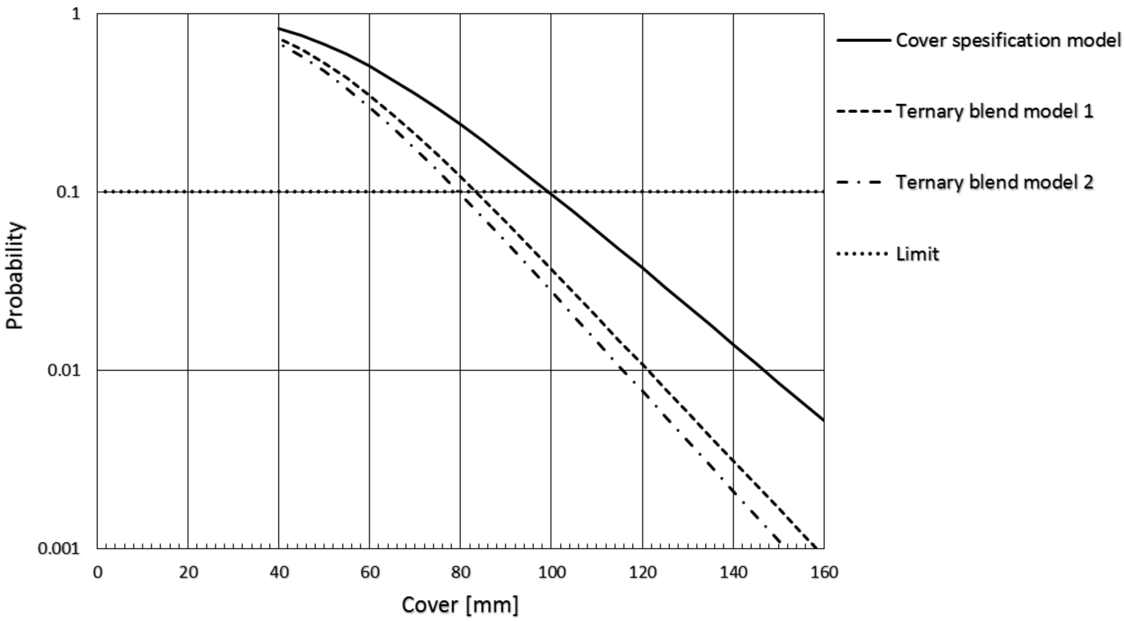

Fig. 5. Probability of corrosion initiation for target service life of 200 years based on input data given in Table 3.

4. Conclusions

The chloride ingress model according to Fick’s second law of diffusion is a pure empirical formula verified through test data over the last 20 years. In particular, the modelling of the time dependent diffusion including the age factor has a major impact on the service life prediction. The critical chloride content (chloride threshold) defining the corrosion initiation is another parameter that influences the results significantly. There is a need for more statistical data for all the model parameters. However, provided good and reliable input parameters the probabilistic approach of service life calculations may be a good decision tool for cover specification for very long service life.

It should also be kept in mind that the model is only applicable for un-cracked concrete. Using very low water binder ratio, i.e. less than 0.4, in order to increase the chloride diffusion coefficient, the concrete becomes more prone to cracking and may thus give increased chloride ingress.

The two construction projects studied have applied different approaches to the probabilistic calculations of Fick’s second law of diffusion as a decision tool for cover specification. Although the statistical input parameters are not identical, the main difference is the definition of end of service life through the actually chosen probability level at corrosion initiation.

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