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SERVICE LIFE PREDICTION MODELS FOR CHLORIDE-LADEN CONCRETE STRUCTURES: A REVIEW AND NOMOGRAPHS

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ABSTRACT

Several models are available for predicting the service life of concrete structures exposed to chloride environments. However, all the models are not suitable for use in all the cases, especially for the advanced concrete systems exposed to complex environmental conditions. In addition, all the models do not yield similar results, due to the differences in their technical and mathematical approaches. In this paper, a brief discussion on the merits and demerits of four existing service life prediction models (i.e., Life-365™, CHLODIF, ClinConc and DuraCrete) is presented. The critical parameters that are typically used in the service life prediction models are identified and the variations that exist in the published data on these parameters are reviewed. Then, a comparative study on the above-mentioned four reviewed models is presented. The comparison is based on the predicted corrosion initiation time (t_i) for various conditions. The sensitivity of these models to various input parameters in predicting t_i is then presented. In addition, a probabilistic service life prediction based on the DuraCrete model and incorporating the large scatter that exists in the various critical parameters is presented. Finally, a framework for determining t_i, using nomographs is proposed. These simplified nomographs may be of immense help to the practicing design engineers and contractors, who are not accustomed to and find it difficult to use software programs.

Keywords

Service life, Concrete, Corrosion initiation, Chlorides, Diffusion, Threshold, Sensitivity, Nomograph

1.0 INTRODUCTION

Today's structures are exposed to severe environmental and structural loading conditions, yet expected to last for long periods of time (say, several decades) with very little repair and maintenance. In general, concrete structures have the ability to resist deterioration for long periods of time. However, premature corrosion and the resulting reduction in the strength and serviceability of concrete structures have been reported worldwide. The worldwide annual cost of corrosion is estimated to be US $2.2 trillion, which is over 3% of world's Gross Domestic Product (GDP). In the United States (US), the total cost of corrosion (both direct and indirect costs) for the year 2011 has crossed US $1 trillion, accounting to 6.38% of its GDP [1]. India loses a staggering amount of over INR 2 trillion (US $45 billion approx.) per year, which is over 2.4% of India's GDP [2]. Lieser and Xu [3] reported that the cost of corrosion in China is more than 5.2% of its GDP. In addition, the use of poor quality materials and poor construction practices can accelerate and aggravate the problem of corrosion. Lieser and Xu [3] also concluded that "… rapidly developing nations can avoid repeating the costly infrastructure repair and replacement cycle of industrialized nations by adopting advanced materials and construction methods…". The corrosion-induced degradation of concrete structures and hence, the costs due to corrosion can be minimized by adopting durable materials and systems during construction. However, the engineers and designers should be able to predict the durability of various materials and structural systems and then select them. Service life prediction models can be used for this purpose during the design stage itself.

Chloride-induced corrosion is one of the most significant deterioration processes in reinforced concrete structures. It occurs in two stages: (1) Initiation and (2) Propagation. As shown in Figure 1, the initiation phase is much longer than the propagation phase. This emphasizes the importance of predicting the duration of the initiation phase in the overall scheme of predicting the service life of a concrete structure. In this paper, the service life is considered to be equal to corrosion initiation time (t_i) [i.e., corrosion propagation time is not considered]. During the initiation phase, the chloride ions in the surrounding environment penetrate through the cover concrete and reach the reinforcement. The reinforcement corrosion is initiated as the concentration of chlorides accumulated at the surface of the reinforcement reaches a particular level (defined as the chloride threshold level or C_{th}). Diffusion, capillary absorption and permeation are some of the mechanisms through which chlorides can penetrate into the porous materials. However, diffusion is considered as the dominant mechanism in the case of uncracked concrete structures. The chloride ingress into concrete is generally predicted using Fick's 2nd law of diffusion as follows [4].

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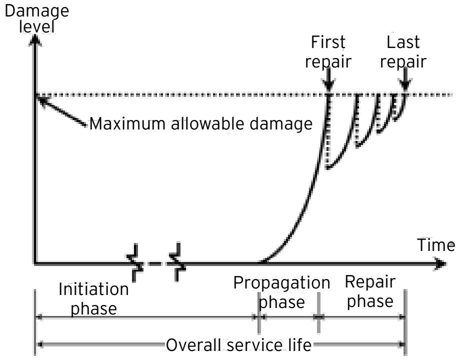


Figure 1. Time to first repair and service life as function of maximum allowable damage (adapted from Trejo and Pillai [25]).

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \text{ ---------------------------(Eq. 1)}$$

where, C is the chloride concentration, D is the diffusion coefficient of chlorides in concrete, x is the depth of penetration, and t is the exposure time or age of the structure. For predicting the chloride ingress into concrete structures, Carslaw and Jaeger [5] have provided the closed–form solutions for the Eq. (1) with the following set of assumptions.

- Concrete is a semi–infinite, porous, homogeneous and isotropic material.
- No reactions (e.g., chloride binding) occur between the concrete and diffusing species (i.e., chlorides).
- $C(x,t) = 0$ when $t = 0$ and $x > 0$
- $C(x,t) = f(t)$ when $x = 0$ and $t > 0$

Carslaw and Jaeger [5] provided solutions, as given in Eqs. (2), (3), and (4), based on the following three different boundary conditions:

- When surface chloride concentration is continuous and constant, i.e., $f(t) = C_0$;
- When surface chloride concentration is a linear function of time, i.e., $f(t) = k\,t$;
- When surface chloride concentration is a square–root function of time, i.e., $f(t) = k\sqrt{t}$.

If $f(t) = C_0$, $C(x, t) = C(x,t) = C_i + (C_s - C_i)\cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right)$------------(Eq. 2)

If $f(t) = kt$, $C(x,t) = kt\left\{\left(1+\frac{x^2}{2Dt}\right)\cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right) - \frac{x}{\sqrt{\pi Dt}}\cdot \exp\left(-\frac{x^2}{4Dt}\right)\right\}$----------(Eq. 3)

If $f(t) = k\sqrt{t}$, $C(x,t) = k\sqrt{t}\left\{\exp\left(-\frac{x^2}{4Dt}\right) - \frac{x\sqrt{\pi}}{\sqrt{4Dt}}\cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right)\right\}$ --------(Eq. 4)

where, $C(x,t)$ is the chloride concentration at depth, x, at exposure time, t; C_i is the initial chloride concentration at depth x ($t = 0$); C_S is the surface chloride concentration ($t \geq 0$); erfc is the complementary error function; and k is a constant. Based on the Fick's 2nd law of diffusion, finite element approach, and experimental results, several models have been developed over the past few decades for predicting the spatial and temporal variations of chloride ingress into and the service life of concrete structures exposed to chloride environments.

This paper presents a review of four service life prediction models such as (1) Life–365™, (2) CHLODIF, (3) ClinConc, and (4) DuraCrete. The critical parameters that significantly affect the service life of concrete structures have been identified. Then the randomness on these critical parameters is reviewed (based on the values reported in literature). Need for the probabilistic service life prediction is then discussed. Next presented is the sensitivity of these four service life models to various critical parameters, along with the probabilistic service life prediction based on the DuraCrete model. Finally, two nomographs (developed based on Eq. (2) and Life–365™) for predicting the service life of concrete structures are presented.

2.0 RESEARCH SIGNIFICANCE

Design (or service) life of a concrete structure is a very important parameter that significantly affects the cost of construction. Pre-mature corrosion of concrete structures is a major problem impacting the durability and service life of concrete structures. Various mathematical models and software programs are available for calculating the service life of concrete structures. This paper reviews four service life prediction models that are currently in use and closely examines the critical parameters affecting the service life. The observed scatter in the critical parameters (as reported in the literature) is reviewed. At the end, simple tools (i.e., two nomographs) for direct use by the engineers, without the hassle of learning a software program is suggested. These nomographs can greatly aid (at the design stage itself) the engineers and contractors in selecting durable materials and systems, optimizing design parameters and for adopting quality construction practices.

3.0 SERVICE LIFE MODELS

3.1 Review of Models

In this section, a comparative study of four service life prediction models, namely Life–365™, CHLODIF, ClinConc and DuraCrete, is presented. The working philosophy of these prediction models can be outlined as follows:

- Model the chloride ingress, by taking into account the estimated or known values of C_S, D, and x.
- Define the initiation of corrosion, usually by limiting the value of C, i.e., the chloride concentration at the reinforcement level. In other words, corrosion is deemed to have initiated if $C \geq C_{th}$.
- Compute the time required for the chlorides to ingress through the cover concrete and attain $C = C_{th}$.

Although these four models closely follow Eq. (1) for the modeling chloride ingress, they use different input variables, as shown in Table 1. Consequently, there can be significant variations in the values of t_i predicted using different models. According to Oslakovic et al. [6], CHLODIF gives greater differences in the results and an unrealistically large range of t_i; Life–365™ gives results that are in reasonably good agreement with the real life situations; and DuraCrete also gives reasonable results, provided that the materials/

parameters used are modeled with accuracy. The prediction models for the chloride ingress in concrete can be categorized in two ways [7]:

- Empirical models and physical models, based on the differences in which deterioration processes are modeled. Empirical models perform well, only under conditions similar to those for which the experimental data is available. Physical models, on the other hand, are based on current knowledge on the specific process occurring (in this case, chloride ingress and binding) and do not introduce a lot of parameters that cannot be measured. Also, independently determined parameters are used as input data. In physical models, for example, the available experimental data is used only for model validation and improvisation. Compared to empirical models, extrapolation using physical models is relatively safer.
- Probabilistic models and deterministic models, based on the mathematical approaches adopted for predicting service life of a concrete structures. While the former utilizes probabilistic approach for calculating t_i at an 'acceptable' safety level, the latter utilizes various numerical approaches to solve the mathematical iterations involved. The deterioration modeling in both the probabilistic and deterministic models can be either empirical or physical.

Table 1. Different variables considered and the variation in the approaches adopted by various service life prediction models.

Variable / Approach	Life-365™	CHLODIF	ClinConc	Dura-Crete
Chloride binding coefficient			√	
Temperature	√	√	√	√
Relative humidity		√		√
Corrosion inhibitor content	√			
Type of steel /chloride threshold	√			
Admixtures in concrete	√	√	√	√
Porosity			√	
Effect of co-existing ions			√	
Modeling approach	Empirical	Empirical	Physical	Empirical
Computational approach	Deterministic / probabilistic	Deter ministic	Deter ministic	Deter ministic

3.1.1 Life 365™

Life-365™ [8], developed by Strategic Development Council of American Concrete Institute, is one of the most commonly used service life prediction models [8]. It is user-friendly and freely available as a complete software package. Originally developed in 2000 through a consensus approach by concrete industry, it can be used as a "standard model" for predicting t_i of concrete structures exposed to different environments. In Life-365™, t_i is predicted using finite difference approach to Fick's 2nd law with the total chloride content as the driving force. Life-365™ considers the diffusion coefficient to be time- and temperature-dependent (based on Arrhenius equation), and is given by [8],

$$D(t,T) = D_{ref} \times f(t) \times f(T) = D_{ref} \times \left(\frac{t_{ref}}{t}\right)^{m} \times \ e^{\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \quad \text{---------------------(Eq. 5)}$$

where, $D(t,T)$ is diffusion coefficient at time t and temperature T; m is diffusion decay or age factor ($m = 0.2 + 0.4\left(\frac{\%FA}{50} + \frac{\%SG}{70}\right)$, whose value is limited to 0.6); %FA and %SG are percentages of fly-ash (≤ 50%) and slag (≤ 70%) in the cement, respectively; D_{ref} (= D_{28}) is the apparent chloride diffusion coefficient at time t_{ref} (= 28 days) and temperature T_{ref} (= 293 K); U is activation energy of the chloride diffusion process (35000 $J \cdot mol^{-1}$); and R is universal gas constant (8.31 $J \cdot mol^{-1} K^{-1}$), respectively. For practical considerations, the value of diffusion coefficient is assumed to be constant after 25 years. The D_{28} is theoretically computed based on the water-cement ratio (w/c) ($D_{28} = 10^{-12.06+2.4(w/c)}$). Model also accounts for the presence of silica fume (%SF ≤ 15%) through the relation, $D_{SF} = D_{PC} \cdot e^{-0.165 \cdot SF}$, where D_{SF} and D_{PC} are diffusion coefficients for Ordinary Portland Cement concrete with and without silica fume. The use of corrosion inhibitors (calcium nitrite inhibitor and Rheocrete 222+), membranes, sealers and various steel types have also been accounted for [8].

Default values are assumed for most parameters required in the analysis. However, there are provisions to define parameters that are specific to the project. For predicting the service life of a concrete structure, the details on the geographic location (for *T* profile), dimensions of structure, nature of exposure, concrete-mixture proportion, type of reinforcement used, depth of clear concrete cover to the reinforcement provided (or achieved, if possible), and corrosion protection strategies employed must be provided. It should be noted that Life-365™ is limited by the assumptions or simplifications made in order to deal with the complex phenomena (such as chloride ingress, loss of passivity on embedded steel, corrosion of steel and subsequent damage of the surrounding concrete), where the lack of sufficient knowledge restricts a rigorous and accurate analysis. The model is based on a database that is typically collected from the North American continent [8].

3.1.2 CHLODIF

CHLODIF [6,9] is meant for the durability design of 'new' structures for which the data on initial chloride concentration and diffusion coefficient are not available. In this model, the chloride diffusion into concrete is described by [6],

$$C(x,t)=\left\{\left[C_o+k(t-1)\right]\cdot erfc\left(\frac{x}{2\sqrt{\tau}}\right)\right\}+k\left\{\left(1+\frac{x^2}{2\tau}\right)\cdot erfc\left(\frac{x}{2\sqrt{\tau}}\right)-\frac{x}{\sqrt{\pi\tau}}e^{-\frac{x^2}{4\tau}}\right\}$$

----------------(Eq. 6)

where, C_O is the initial surface chloride concentration (Eq. 6), k is the coefficient of linear increase in C_O, t is the time, *erfc* is the complimentary error function, x is the clear cover depth and τ is a factor that accounts for the temporal variation of the apparent chloride diffusion coefficient (D). If, the surface chloride concentration (C_S) is assumed to be a constant, i.e., $k = 0$ and $C_S = C_O$, Eq.(6) transforms into the following.

$$C(x,t)=C_s\cdot erfc\left(\frac{x}{2\sqrt{\tau}}\right)$$

----------------(Eq. 7)

where, $d\tau = D(t)\,dt$ thus $\tau = \int_0^t D(s)\,ds$

CHLODIF takes into account the effect of various parameters, such as w/c, the concentration of chemical and mineral admixtures (silica fume (SF), slag (SG), fly-ash (FA) and superplasticizers (SP) in the cement and concrete, relative humidity (RH), age of the structure (t), temperature (T), wing influence (W_S) and the details on curing as well as cracking on the prediction of t_i. W_S accounts for the effect of wind on the acceleration of chlorides into concrete. Consequently, the chloride diffusion coefficient is described as follows [9].

$$D = D_{W/C} \times f_{int}(SF, SG, FA, SP, Curing, Crack) \times f_{ext}(t, T, RH, W_S, C_S)$$

----------------(Eq. 8)

where, $D_{w/c}$ is the chloride diffusion coefficient depending on w/c ratio ; $D_{w/c} = 5\text{x}10^{-13} \text{ x } e^{4.8708(w/c)}$ -----------(Eq. 9)

Combination of all these parameters transform the chloride diffusion coefficient in Eq.(8) to the following.

$$D(t)=5\times10^{-13}\times e^{4.8708(w/c)}\times f_{\text{int}}\times\left[1+256\left(1-\frac{RH}{100}\right)^4\right]^{-1}\times t^{-m}=\text{Constant}\times t^{-m}$$

----------------(Eq. 10)

where f_{int} is a coefficient accounting for the chemical and mineral admixtures in the concrete and the curing as well as cracking of concrete, t is the actual age of concrete (years) and m is the age factor (typically taken as 0.10). For example, respective f_{int}'s for the use of slag, superplasticizer, and for using fabric framework are 0.3, 0.8, and 0.04, respectively. Also, if the concrete is cracked a value in the range of 1 – 1.3 is used as f_{int} [9].

3.1.3 ClinConc

ClinConc [10,11] is one of the most advanced models for predicting the chloride ingress [10]. ClinConc has been modified in the recent years to be more "engineer-friendly" [11]. ClinConc is based on the finite-difference approach and uses the data that can be independently measured (without relying on any curve-fitting procedures) and used as input. ClinConc takes into account the convection, multi-ionic characteristics, etc., in addition to the diffusion phenomenon. As mentioned previously, most empirical models consider that all the chlorides (bound and free chlorides) diffuse into the concrete. Strictly speaking, this is incorrect because only the free chlorides diffuse and bound chlorides do not diffuse as they are chemically bound with other complexes. ClinConc considers that only free chlorides diffuse. ClinConc consists of two major steps in predicting the service life: (1) Simulating the ingress of free chlorides through the pore solution of concrete using a flux equation based on Fick's 2nd law; (2) Calculating the distribution ('free' and 'bound' part) of total chloride content in concrete using the mass balance equations combined with non-linear chloride binding. The free chloride concentration at depth x is determined using Eq. (11).

$$\frac{c-c_i}{c_s-c_i}=erfc\left(\frac{x}{2\sqrt{\frac{k_D D_0}{1-n}\cdot\left[\left(1+\frac{t'_{ex}}{t}\right)^{1-n}-\left(\frac{t'_{ex}}{t}\right)^{1-n}\right]\cdot\left(\frac{t'_{6m}}{t}\right)^{n}\cdot t}}\right)$$

----------------(Eq. 11)

Where,

$$D_0=\frac{\left(0.8a_t^2-2a_t+2.5\right)\left(1+0.59K_{b6m}\right)\cdot k_{TD}}{1+k_{OH6m}\cdot K_{b6m}\cdot k_{Tb}\cdot f_b\cdot\beta_b\left(\frac{c_s}{35.45}\right)^{\beta_b-1}}\cdot D_{6m}$$ ---------(Eq. 12)

$$n=-0.45a_t^2+0.66a_t+0.02$$ ---------------------------(Eq. 13)

where, D_O is the initial apparent diffusion coefficient; t_{6m} is the age of concrete at the start of exposure; t is the duration of the exposure; n is the age factor to account for the decrease in the diffusivity with time; α_t is the time-dependent factor for chloride binding; D_{6m} is the diffusion coefficient from laboratory tests at the start of exposure (t'_{6m}); K_b is the binding factor; k_{TD} and k_{Tb} are the temperature factors for diffusion coefficient and chloride binding; k_{OH} is the factor describing the effect of alkalinity; f_b and β_b are chloride binding constants; c, c_S and c_i are the free chloride concentrations in the concrete pore solution at depth x, in seawater (or surrounding environment) and initially in concrete at x (when $t = 0$), respectively; k_D is the extension coefficient linking D_{6m} to the initial apparent diffusion coefficient of the actual environment ('6m' = 6 months). The factors k_D and n are determined based on concrete properties, such as cement hydration, hydroxide content, water accessible porosity, time-dependent chloride binding and the environmental parameters such as chloride concentration and temperature. The total chloride content (i.e., the sum of the bound and free chlorides) can be calculated based on the relationship between the free and total chloride content, i.e., a chloride binding isotherm [11].

Among the models considered in this paper, only ClinConc treats the material properties and the exposure environment separately. Despite its merits, ClinConc also has some limitations. For example, it was primarily developed for submerged structures, where the concrete surface is in constant contact with the seawater and models only the pure diffusion. This model needs certain modifications when applied to other scenarios such as air-borne chlorides. The ability of the model to accurately describe the future ingress in not very clear, as it excludes the effects of all the other ions on the chloride transport process. The most significant advantage is that only one of the input parameters, *D*, needs to be measured. Another advantage is that the effect of temperature variations and leaching can be considered in a physical way. Refer publication of Tang [11] for further details.

3.1.4 DuraCrete

DuraCrete [12] (a probabilistic performance-based durability design of concrete structures) is not only a t_i prediction model, but also a complete alternative approach for the design of concrete structures. Conventional design methods are based on deem-to-satisfy criteria/rules, such as minimum cover, minimum w/c ratio, or limitation on the crack width [12]. If these criteria/rules are met, then the structure is deemed "safe" and expected to satisfy design life requirements. In conventional designs, the insight on t_i, necessary maintenance, and probability of failure are considered in an indirect manner. DuraCrete overcomes this limitation by explicitly using performance requirements, reliability index, and desired t_i. Although the framework is available, significant challenges lie in reliably modeling the input parameters and using DuraCrete.

While Life-365™, CHLODIF and ClinConc models try to compute a definite value for t_i (when $C = C_{th}$), DuraCrete defines a serviceability limit state (SLS) by determining the probability of corrosion initiation. By defining the acceptance criteria, it is possible to predict serviceability for a pre-determined design t_i with a selected level of reliability. Alternatively, the t_i can be calculated by defining the acceptance criteria in terms of reliability. Assuming the initial chloride concentration in concrete to be zero, the design function for SLS is given by [12],

$$g = C_{cr}^{d} - C^{d}\left(x,t\right) = C_{cr}^{d} - C_{s,cl}^{d} \cdot erfc\left(\frac{x^{d}}{2\sqrt{\dfrac{t}{R_{cl}^{d}\left(t\right)}}}\right) \qquad \text{----------------(Eq. 14)}$$

such that g ≤ 0 indicates the initiation of corrosion. Here C_{cr}^{d} and $C_{s,cl}^{d}$ are design chloride concentration in concrete and at the surface, x^d is design cover thickness,

Table 2. Governing equations of the service life models in consideration

Models	**Governing equations**
Closed-form solutions [5]	If $f(t) = C_0$; $C\left(x,t\right) = C_i + \left(C_s - C_i\right) \cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right)$; If $f(t) = k \cdot t$; $C\left(x,t\right) = kt\left\{\left(1+\frac{x^2}{2Dt}\right) \cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right) - \frac{x}{\sqrt{\pi Dt}} \cdot \exp\left(-\frac{x^2}{4Dt}\right)\right\}$ If $f(t) = k \cdot \sqrt{t}$; $C\left(x,t\right) = k\sqrt{t}\left\{\exp\left(-\frac{x^2}{4Dt}\right) - \frac{x\sqrt{\pi}}{\sqrt{4Dt}} \cdot erfc\left(\frac{x}{\sqrt{4Dt}}\right)\right\}$
Life-365™ [8]	$D\left(t,T\right) = D_{ref}\left(\frac{t_{ref}}{t}\right)^{m} e^{\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}$ where $m = 0.2 + 0.4\left(\frac{\%FA}{50} + \frac{\%SG}{70}\right) \leq 0.6$ $D_{ref} = 10^{-12.06+2.4(w/c)} \cdot e^{-0.165 \cdot SF}$; $FA \leq 50\%$; $SG \leq 70\%$; $SF \leq 15\%$
CHLODIF [6]	$C\left(x,t\right) = \left\{\left[C_o + k\left(t-1\right)\right] \cdot erfc\left(\frac{x}{2\sqrt{\tau}}\right)\right\} + k\left\{\left(1+\frac{x^2}{2\tau}\right) \cdot erfc\left(\frac{x}{2\sqrt{\tau}}\right) - \frac{x}{\sqrt{\pi\tau}} e^{-\frac{x^2}{4\tau}}\right\}$ where $d\tau = D(t)\,dt$; $\tau = \int_0^t D(s)ds$; $D\left(t\right) = \text{Constant} \times t^{-m}$
ClinConc [11]	$\frac{c - c_i}{c_s - c_i} = erfc\left(\frac{x}{2\sqrt{\frac{k_D D_0}{1-n} \cdot \left[\left(1+\frac{t'_{ex}}{t}\right)^{1-n} - \left(\frac{t'_{ex}}{t}\right)^{1-n}\right] \cdot \left(\frac{t'_{6m}}{t}\right)^{n} \cdot t}}\right)$ $D_o = \frac{\left(0.8a_t^2 - 2a_t + 2.5\right)\left(1 + 0.59K_{b6m}\right) \cdot k_{TD}}{1 + k_{OH6m} \cdot K_{b6m} \cdot k_{Tb} \cdot f_b \cdot \beta_b\left(\frac{c_s}{35.45}\right)^{\beta_b - 1}} \cdot D_{6m}$ and $n = -0.45a_t^2 + 0.66a_t + 0.02$
DuraCrete [12]	$g = C_{cr}^{d} - C^{d}\left(x,t\right) = C_{cr}^{d} - C_{s,cl}^{d} \cdot erfc\left(\frac{x^{d}}{2\sqrt{\frac{t}{R_{cl}^{d}\left(t\right)}}}\right)$ and $P_f(T) = 1 - P\{g(x,t) > 0 \text{ for all } t \in [0, T]\}$ and $\beta = -\Phi^{-1}(P_f)$

R_{cl}^{d} is design chloride resistance (year/mm^2, inverse of chloride diffusion coefficient) and t is the time (year). The probability of corrosion initiation within time period [0; T], denoted as $P_f\,(T)$ is defined as

$$P_f(T) = 1 - P\{g(x,t) > 0 \text{ for all } t \in [0,T]\} \quad \text{-------------(Eq. 15)}$$

The acceptance criteria is given in terms of a reliability index (β_T), defined by

$$\beta_T = -\Phi^{-1}(P_f(T)) \quad \text{----------------(Eq. 16)}$$

where, Φ is the cumulative distribution function of standard normal distribution. Computed values of β_T are compared against the design or target value of the reliability index. This model is based on the realistic and sufficiently accurate environmental and material models that are capable of predicting the behaviour of a concrete structure.

Table 1 provides a summary of the approaches used by the four models in consideration. Life–365™ is based on finite element method as well as both deterministic and probabilistic approaches (with an assumed 10% variation in the input parameters D_{ref}, C_S, m, C_{th}, and x). ClinConc, a physical model, considers the chloride binding capacity in predicting t_i. In concrete structures, both free and bound chlorides exist. The free chlorides can diffuse towards the steel reinforcement while the bound chlorides cannot. Most empirical models consider the diffusion of total chlorides (i.e., both free and bound chlorides) for modeling t_i. This simplistic approach of considering total chlorides can result in errors in the predictions. However, engineers tend to prefer the simple and reasonably accurate mathematical models. The governing equations for Life–365™, CHLODIF, ClinConc and DuraCrete models, along with the closed–form solutions by Carslaw and Jaeger [5] are shown in Table 2.

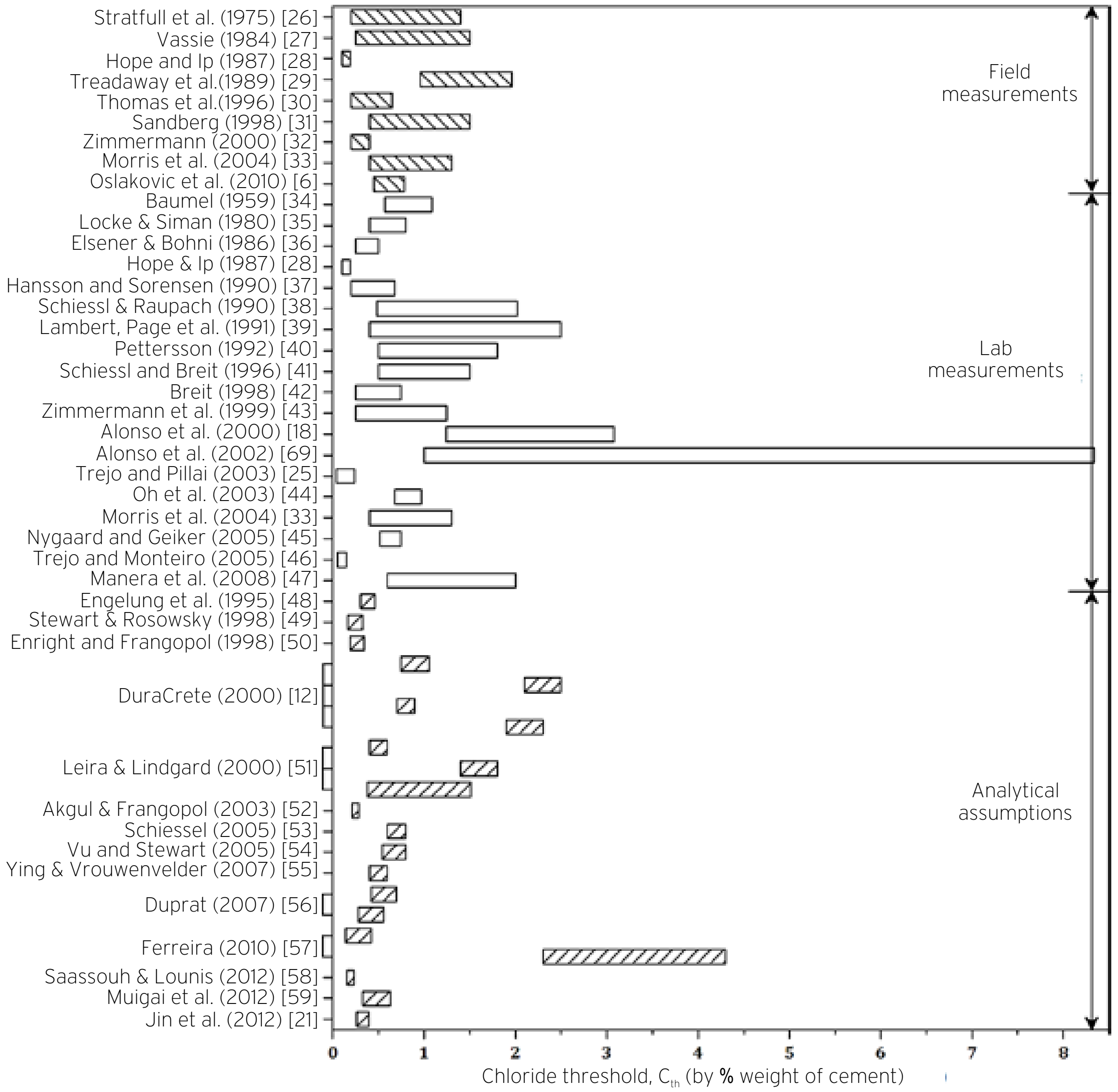


Figure 2. Scatter in the data reported on the chloride threshold

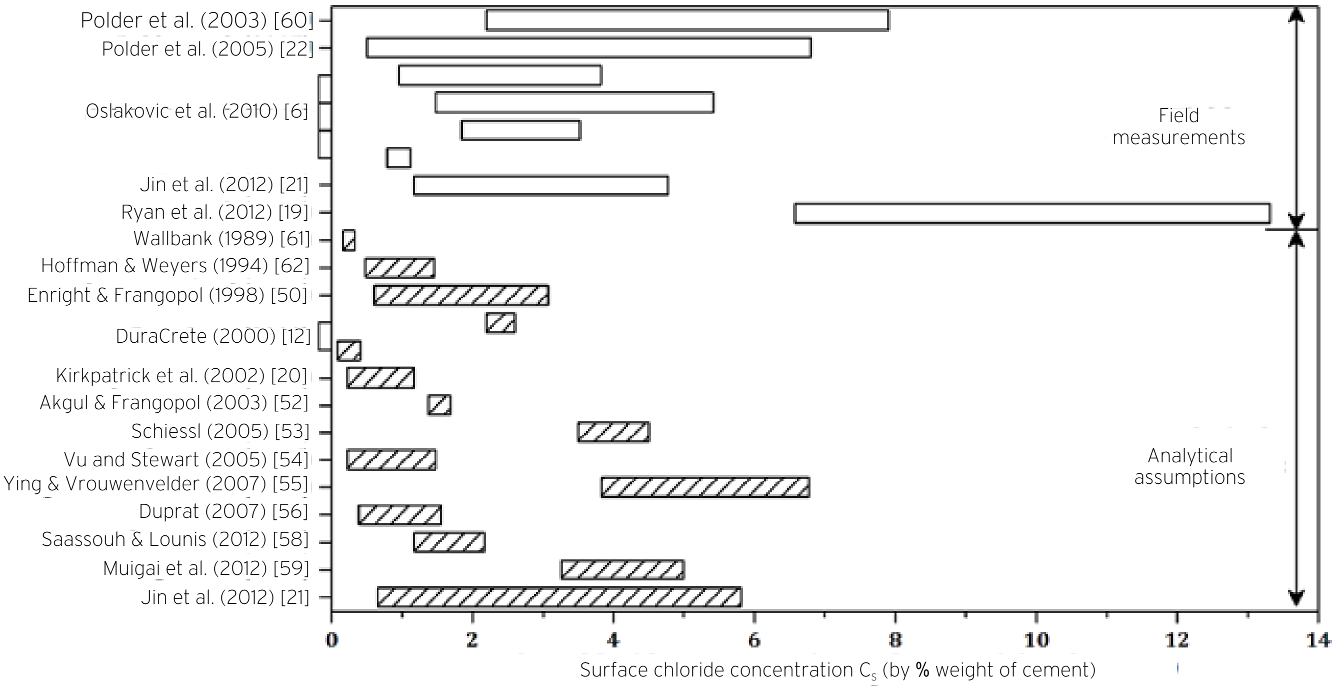


Figure 3. Scatter in the data reported on surface chloride concentration

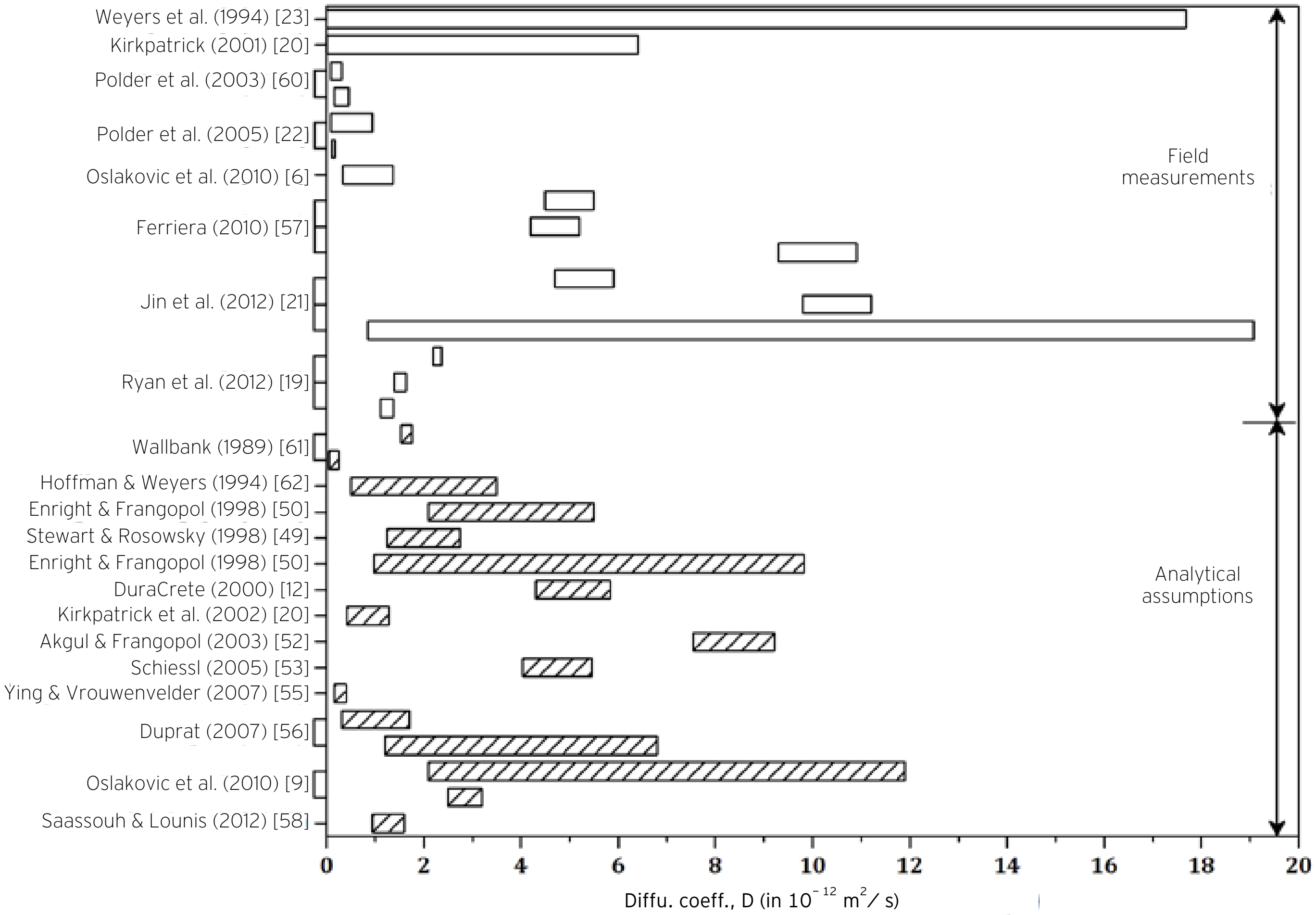


Figure 4. Scatter in the data reported on the chloride diffusion coefficient

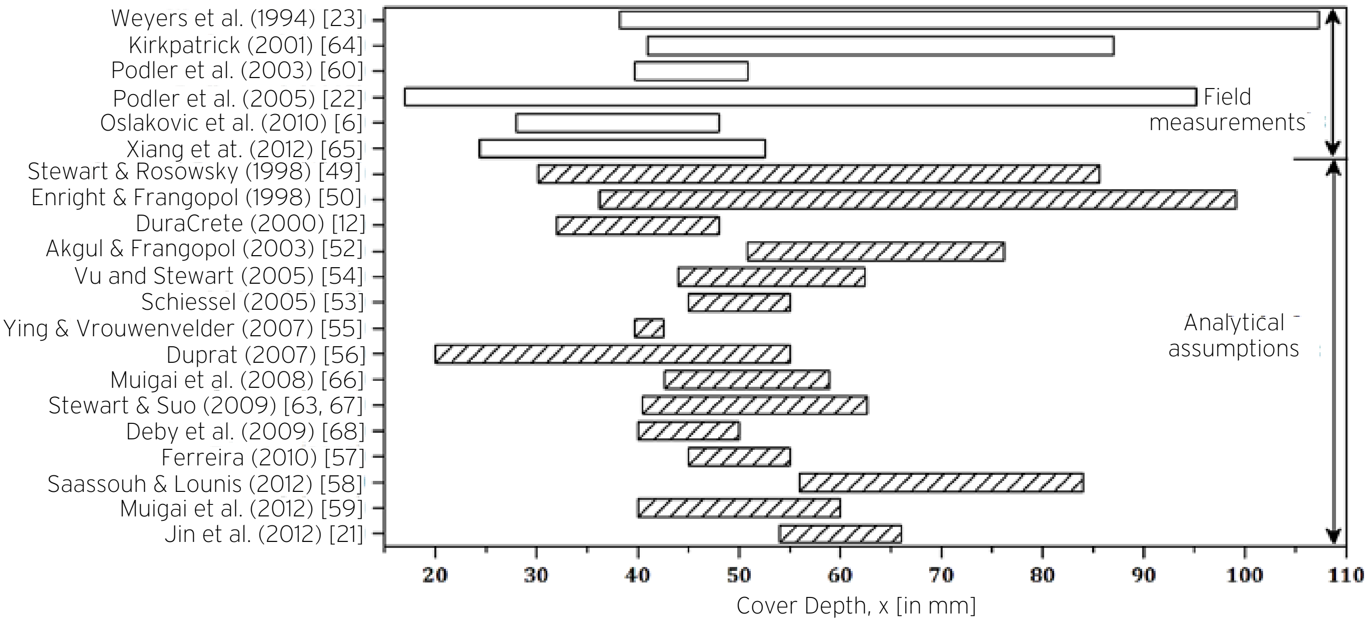


Figure 5. Scatter in the data reported on the cover depth

3.2 Large Scatter in the Critical Parameters

Since 1900s, there has been considerable effort, worldwide, to investigate the chloride-induced corrosion [13,14]. However, several aspects of chloride-induced corrosion remain to be understood. As mentioned earlier, not only the material properties, but also the construction practices have significant influence on corrosion initiation. According to Zhang and Lounis [15], Trejo and Reinschmidt [16] and Eq. (2), the concrete cover depth (x), chloride diffusion coefficient (*D*) chloride threshold (C_{th}) and surface chloride concentration (C_S) are the four most critical parameters in predicting t_i. There exists a lot of experimental (both field as well as laboratory) and analytical data on these critical parameters. However, there is no general agreement on the reported values of these parameters, especially in the case of C_{th} and *D*. Data collected from various sources on the C_{th}, C_S, *D* and *x* has been presented in Figure 2, Figure 3, Figure 4 and Figure 5, respectively.

Figure 2 provides the range of C_{th} values (in % by weight of cement) measured on real structures, in laboratory and assumed in various analytical works. The observed C_{th} values range from as low as 0.04 [24] to as high as 8.34 [18]. Similarly, Figure 3 provides the range of C_S values (in % by weight of cement) measured on real structures and assumed in various analytical works. The C_S values range from as low as 0.08 [12] to as high as 13.32 [19]. Figure 4 provides the range of *D* values (in 10^{-12} m^2/s) measured on real structures and assumed in various analytical works. The *D* values range from as low as 0.0032 [20] to as high as 19.08 [21]. Figure 5 provides the range of *x* values (in mm) measured on real structures and assumed in various analytical works. The *x* values range from as low as 17 [22] to as high as 107[23].

Overall, there exists a large scatter across the experimental (i.e., lab and field) and analytical data. The scatter is also varied across geographical location for the same type of materials and vice versa. There exist various reasons as to why there exists such a large scatter in the values reported in the literature for these critical parameters. Some of the reasons for this are (1) the differences in which these parameters are defined by the individual researcher, (2) the testing methodology, (3) measurement and human errors, and (4) inherent uncertainties in the corrosion mechanism itself. All these make the prediction of corrosion initiation time not only difficult but also complex.

3.3 Need for the Probabilistic Service Life Predictions

Most of the available service life prediction models, including these considered here, are either deterministic or semi-probabilistic. Concrete has been long identified as a very complex material with inherent randomness in its properties, as evident from the Figure 2 through Figure 5. There has been no prediction model that promises to predict accurately the service life of concrete structures. Every model has its own limitations. The random nature of the critical parameters also tends to suggest that it is no longer acceptable to treat the critical parameters as deterministic. For example, cover depth (x), one of the simplest of the critical parameters, can vary along the length of a concrete beam. One of the reasons for this is the insufficient quality control at the site and the other being the sagging of the reinforcement between the supports and the stirrups. One of the objectives of this paper is to emphasize the need for probabilistic prediction of service life of concrete structures.

4.0 PARAMETRIC SENSITIVITY ANALYSES OF VARIOUS MODELS

This section provides the sensitivity analysis of the four models, namely Life-365™, CHLODIF, ClinConc and DuraCrete, to various critical parameters. Towards this purpose, the Life-365™ software package was used for computing the values of t_i. For studying the other models, the values of ti are predicted using the equations summarized in Table 2. Table 3 shows all the values of the various parameters used in the calculation of t_i. As shown in the last column in Table 2, it should be noted that all these parameters are not required for the prediction using all the models. For example, a reliability index of 3.72 (corresponding to a situation, where the cost of repair is higher than that of design and construction) is used only for the analysis using DuraCrete model.

Table 3. Values of input parameters required for models

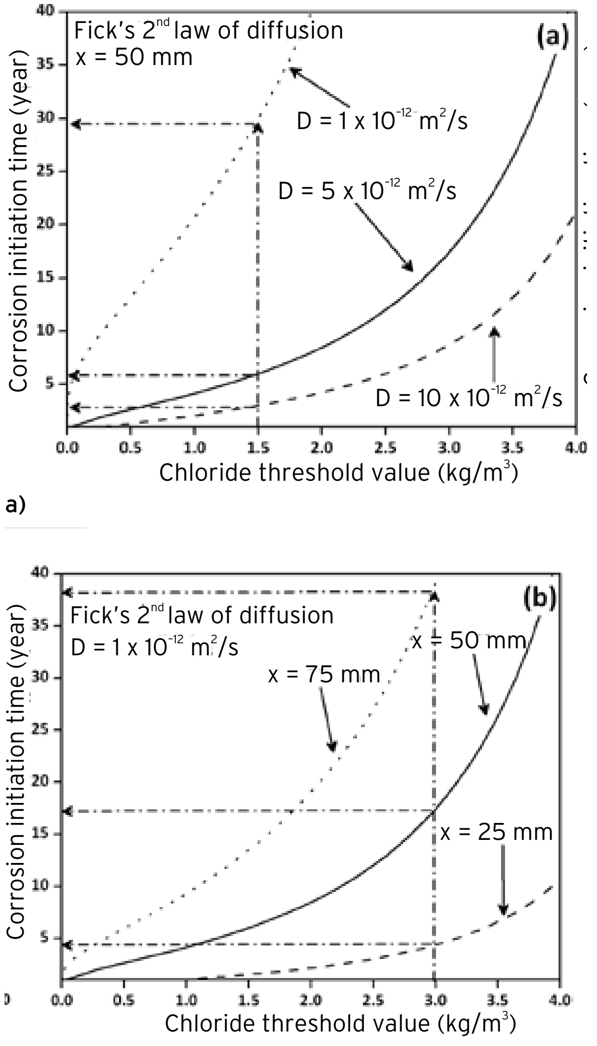
Input parameter	Symbol	Value	Models in which these parameters are used*
Surface chloride concentration	C_S (kg/m^3)	6	L3, CD, CC and DC
Chloride threshold value	C_{th} (kg/m^3)	1.2	L3, CD, CC and DC
Concrete cover depth	x (mm)	50	L3, CD, CC and DC
Water-cement ratio	w/c	0.42	L3, CD, CC and DC
Chloride diffusion coefficient	D (m^2/s)	$5\text{x}10^{-12}$	L3, CD, CC and DC
Age factor	m	0.2	L3, CD and DC
Reliability index	β	3.72	DC
Chloride binding coefficient	f_b	3.6	CC
Chloride binding exponent	β_b	0.33	CC
Time-dependent factor of chloride binding	a_t	0.36	CC

*L3 = Life-365™, CD = CHLODIF, CC = ClinConc, and DC = DuraCrete

4.1 Analysis Using Closed-Form Solution

The influence of the parameters x, D, and C_{th} on t_i of a concrete structure, according to Eq. (2) is plotted in Figure 6. As shown b y the solid curve in Figure 6(a), t_i of structure is ~ 6 years for a C_{th} value of 1.5 kg/m^3 and D value of $5\text{x}10^{-12}$ m^2/s. As shown by the dash curve, 100% increase in the value of D (from $5\text{x}10^{-12}$ to $10\text{x}10^{-12}$m^2/s) can reduce the t_i by half (i.e., from about 6 to 3 years). On the other hand, the dot curve indicates that an 80% decrease in D (from $5\text{x}10^{-12}$ to $1\text{x}10^{-12}$ m^2/s) can result in a five-fold increase in t_i (i.e., from about 6 to 30 years).

As shown in Figure 6(b), a 50% reduction in the value of x (from 50 to 25 mm) can result in a 75% reduction in t_i value (i.e., from about 17 to 4 years). On the other hand, a 50% increase in the value of x increases the t_i by two-fold (i.e., from about 17 to 38 years). The solid curves in Figure 6(a) and (b) indicate that a two-fold increase in the C_{th} values (i.e., from 1.5 to 3 kg/m^3) can result in a three-fold increase in the t_i (from about 6 to 17 years).



a)

b)

Figure 6. Influence of chloride diffusion coefficient, concrete cover thickness and chloride threshold value on the corrosion initiation time [70].

4.2 Sensitivity of Life-365™ Model to Various Parameters

Figure 7 shows the change in t_i as a function of the change in the three input parameters (x, D, and C_{th}). Note that the range of abscissa (minimum and maximum limits) is different in these four plots. The limits of the ordinate in these plots have been kept identical. Figure 7(a) shows the sensitivity of t_i to all the three parameters (using only Life-365™), whereas the Figure 7(b), (c), and (d) shows the sensitivity of t_i to a particular parameter across the four models considered.

Figure 7(a) shows the sensitivity of t_i with respect to x, D and C_{th}, with the data obtained from Life-365™. A parameter can be said to have (relatively) higher

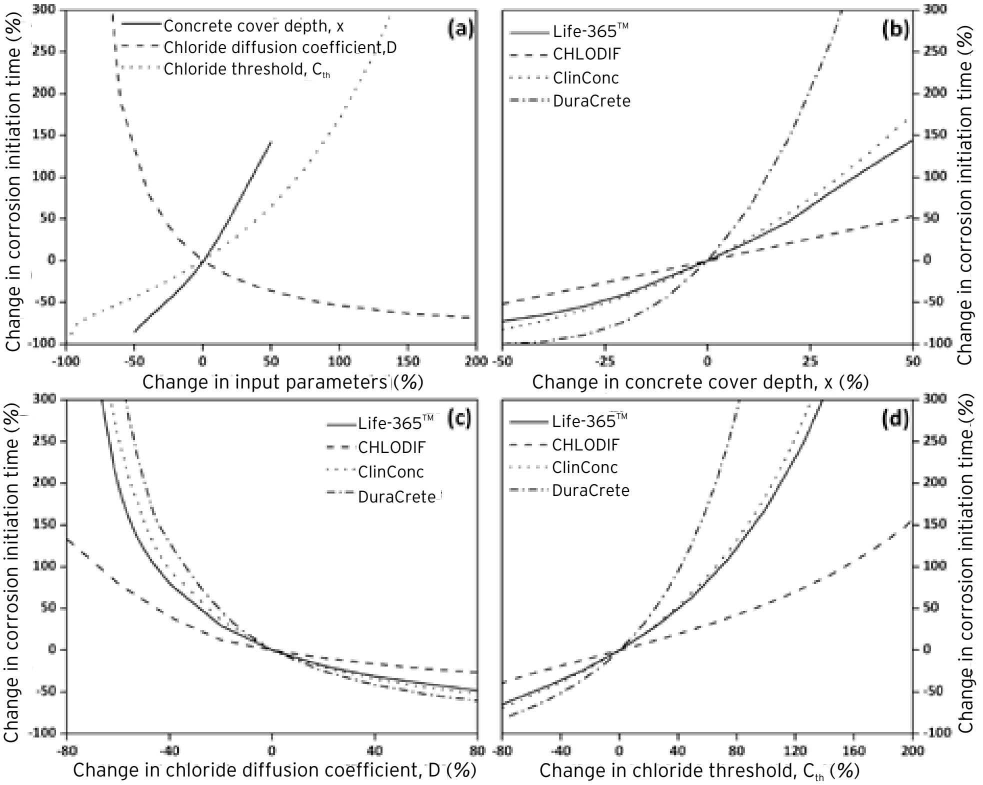


Figure 7. Change in corrosion initiation time as a function of the change in the input parameters [70].

impact on t_i, if the slope of the curve corresponding to the said parameter is higher. In the Figure 7(a), solid curve corresponds to *x*, dash curve corresponds to *D* and dot curve corresponds to C_{th}. It can be observed that the slope of solid curve is more than the slope of dash curve, which in turn is more than the slope of dot curve. This indicates that t_i is more sensitive to *x* than *D*. In addition, t_i is more sensitive to *D* than C_{th}. Also, note that decrease in *D* has more impact than an increase in *D* (dash curve). In general, a small increase in C_{th} does not have a significant impact on t_i. However, at higher percentages this is not the case because slope of the dot curve increases as C_{th} increases.

4.3 Sensitivity of all Models to Cover Depth (*x*)

Prescribed design values for concrete cover depth, *x*, are seldom achieved in practice and it is very difficult to ascertain the real cover depth, which is evident from Figure 5. As shown in Table 3, this analysis used a base value of $x = 50$ mm. Depending on the quality of construction and possible sag, a ± 50% variation in cover depth can be observed in the field. Figure 7(b) shows the sensitivity of t_i to *x*, when predicted using Life–365™, CHLODIF, ClinConc and DuraCrete models. For a variation of – 50% to 50% in *x*, the variation in t_i according to Life–365™ (solid curve) is – 80% to 150%, CHLODIF (dash curve) is – 50% to 50%, ClinConc (dot curve) is – 80% to 180% and DuraCrete (dash-dot curve) is – 100% to > 300%. Based on the observations on the slopes of the curves, it can be concluded that CHLODIF seems to assume a linear relationship between 'change in *x*' and 'change in t_i'. In the case of Life–365™ and ClinConc models, this relationship seems to be slightly non-linear in nature (dash and dot curves, respectively). The non-linearity of this relationship is maximum in the case of DuraCrete (dash-dot curve).

4.4 Sensitivity of All Models to Chloride Diffusion Coefficient (*D*)

The chloride diffusion coefficient, *D*, largely depends on the quality of concrete, which in practice can vary significantly, as evident from Figure 4. This variation can be due to the variations in the skill level of workers, mixture proportion within the matrix, placing, compaction, and curing methods, and many other factors. Locally imperfect regions (i.e., pores and cracks) in the concrete can function as an easy path for the ingress of moisture, oxygen and chlorides towards the embedded steel, leading to corrosion. Figure 7(c) shows the sensitivity of t_i to *D*, when predicted using Life–365™, CHLODIF, ClinConc and DuraCrete models. When predicted using Life–365™ (solid curve), a ± 80% variation in *D* can result in > 300% to – 55% variation in t_i This variation in t_i according to CHLODIF (dash curve) is 130% to – 30%, ClinConc (dot curve) is > 300% to – 60% and DuraCrete (dash-dot curve) is > 300% to – 70%. Considering the slopes of the curves in Figure 7(c), it can be concluded that the sensitivity of t_i to *D* is similar in the case of Life-365™, ClinConc and DuraCrete models. CHLODIF seems to be less sensitive to *D* when compared to the other three models.

4.5 Sensitivity of All Models to Chloride Threshold (C_{th})

Angst et al.[24] has concluded that "… despite the multitude of studies undertaken … no general agreement on a C_{th} value has been achieved …". This is also evident from the C_{th} values presented in Figure 2. Figure 7(*d*) shows the sensitivity of t_i to C_{th}, when predicted using Life-365™, CHLODIF, ClinConc and DuraCrete models. As per Life-365™, a variation of – 80% to 200% in C_{th} can result in a variation of – 70% to > 300% in t_i. This variation in t_i according to CHLODIF (dash curve) is – 40% to 150%, ClinConc (dot curve) is – 70% to > 300% and DuraCrete (dash-dot curve) is – 80% to > 300%. Based on the slopes of the solid and dot curves, it can be concluded that Life-365™ and ClinConc models exhibit similar sensitivities. Also, CHLODIF is least sensitive while DuraCrete is most sensitive to 'change in C_w'.

5.0 PROBABILISTIC SERVICE LIFE PREDICTION BASED ON DURACRETE

In order to demonstrate the effect of the large scatter that exists in the reported values of the critical parameters, a Matlab™ program is developed based on DuraCrete (Eq. 14, 15 and 16). For the analysis, all the critical parameters have been assumed to follow normal distributions, as it is the most common distribution reported and/or assumed in the literature. Other distributions reported in the literature are lognormal, truncated normal, uniform, beta, and gamma. Table 4 shows the base values of the parameters considered in the probabilistic modeling. Results of the analysis are presented in Figure 8 (Note: Each curve in Figure 8

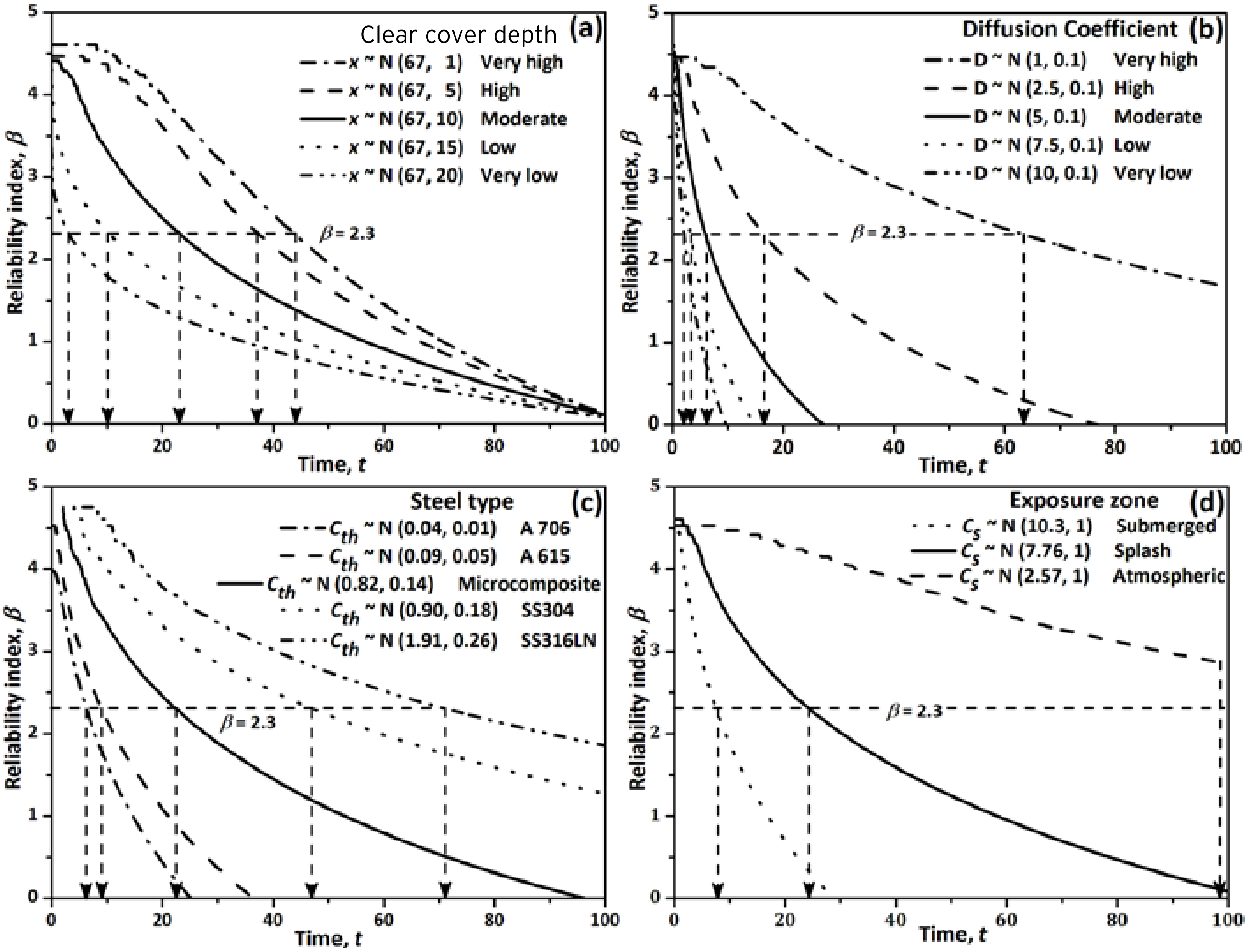


Figure 8. Reliability index v/s time for (a) various quality controls achieved at site, represented by scatter in the cover depth values; (b) various qualities of concrete, represented by scatter in the values of chloride diffusion coefficient; (c) various types of steel, represented by scatter in the values of critical chloride threshold; and (d) various atmospheric zones, represented by scatter in the values of surface chloride concentration.

passes through 1000 points, each of which is obtained using one million simulations).

Table 4. Values of input parameters used in the Matlab™ program

Input parameter	Symbol	Mean	Standard deviation
Surface chloride concentration	C_S (in % by weight of cement)	7.76	2
Chloride threshold	C_{th} (in % by weight of cement)	0.9	0.2
Concrete cover depth	x (mm)	67	10
Chloride diffusion coefficient	D ($\times10^{-12}$ m^2/s)	2	0.1
Age factor	m (constant value)	0.37	---

Various levels of quality in maintaining particular concrete cover depth can be explored by normal distribution with a mean value and various standard deviation; poorer the quality, larger will be the standard deviation. Figure 8(a) presents the change in reliability index (β) as a function of time (t), for various levels of quality control achieved at the site. As shown in Figure 8(a), five quality control levels ranging from 'very high' to 'high' to 'moderate' to 'low' to 'very low' (represented by the same mean value (67 mm) and different standard deviation values of 1 mm, 5 mm, 10 mm, 15 mm and 20 mm) have been considered in the analysis. For a β value of 2.3 (corresponds to a probability of failure, P_f, of 1.1×10^{-2}), 'moderate' quality (solid line) represented by N (67, 10) [N (mean, standard deviation)] yields a t_i of 23.5 years. Similarly, 'very high' quality [dash-dot line, N (67, 1)], 'high' quality [dash line, N (67, 5)], 'low' quality [dot line, N (67, 15)] and 'very low' quality [dash-dot-dot, line N (67, 20)] yields a t_i value of 44.2, 37.7, 10.6 and 3.3 years, respectively. As can be seen, when the quality is improved from 'moderate' to 'very high' the increase in t_i is ~ 88% and when the quality falls from 'moderate' to 'very low', the reduction in the t_i is ~ 86%. This emphasizes the importance of educating the contractors and site workers on how maintaining good and uniform concrete cover can play a vital role in extending the service life of a structure.

Figure 8 (b) presents the change in reliability index (β) as a function of time (t), for various levels of concrete quality. The concrete quality can be described by the chloride diffusion coefficient, which is a critical parameter used in all the life prediction models. In the present analysis, concrete quality is represented by the scatter in the mean values of the diffusion coefficient. As shown in Figure 8 (b), five quality control levels ranging from 'very high' to 'high' to 'moderate' to 'low' to 'very low' (represented by the mean values of 1×10^{-12} m^2/s, 2.5×10^{-12} m^2/s, 5×10^{-12} m^2/s, 7.5×10^{-12} m^2/s and 10×10^{-12} m^2/s; and a same standard deviation value of 0.1×10^{-12} m^2/s) have been considered in the analysis. For a β value of 2.3, 'moderate' quality concrete (solid line) represented by N (5, 0.1) yields a t_i of 6.2 years. Similarly, 'very high' quality [dash-dot line, N (1, 0.1)], 'high' quality [dash line, N (2.5, 0.1)], 'low' quality [dot line, N (7.5, 0.1)) and 'very low' quality (dash-dot-dot line, N (10, 0.1)) yields a t_i value of 64, 16.6, 3.2 and 2.1 years, respectively. A 9-fold increase in the t_i value occurs when the concrete quality is improved from 'moderate' to 'very high', while there is only a 66% reduction in the t_i values as the concrete quality from 'moderate' to 'very low'. This emphasizes the importance of proper mix-design and other issues related to the concrete quality.

Figure 8 (c) presents the change in reliability index (β) as a function of time (t), for several steel types available in the market. For the analysis, chloride threshold values for several steels reported by Trejo and Pillai [17,25] have been adopted. As shown in Figure 8 (c), the different steels A706 steel, A615 steel, microcomposite steel, SS304 stainless steel and SS316LN stainless steel [represented by (mean, standard deviation) values of (0.04, 0.01), (0.09, 0.05), (0.82, 0.14), (0.90, 0.18) and (1.91, 0.26) (units are % by weight of cement)] have been considered in the analysis. For a β value of 2.3, the commonly used reinforcement type A706 [dash-dot line, N (0.04, 0.01)] yields a t_i of 6.5 years. Similarly, A615 [dash line, N (0.09, 0.05)], microcomposite steel [solid line, N (0.82, 0.14)], SS304 [dot line, N (0.90, 0.18)] and SS316LN [dash-dot-dot line, N (1.91, 0.26)] steel yields a t_i value of 9, 22.5, 47.2 and 71.5 years, respectively.

Figure 8 (d) presents the change in reliability index (β) as a function of time (t), when the structure exposed to various chloride environments. For the analysis, three environments, namely submerged, splash and atmospheric zones and their corresponding values mentioned in DuraCrete [12] have been adopted as C_S values. As shown in Figure 8d, three surrounding environmental conditions, namely submerged, splash and atmospheric zones [represented by the mean values of 10.3, 7.76 and 2.57 and a standard deviation values of 1 (units are % by weight of cement)] are considered in the analysis. For a β value of 2.3 (corresponds to a probability of failure, P_f, of 1.1×10^{-2}), atmospheric conditions (dash line) represented by N (2.57, 1) yields a t_i of > 100 years. The splash [solid line, N (7.76, 1)] and submerged [dot line, N (10.3, 1)] yield a t_i value of 24.4 and 7.5 years, respectively. This emphasizes the need to take proper remedial measures for structures that are situated in harsh environmental conditions.

6.0 NOMOGRAPHS BASED ON FICK'S 2ND LAW OF DIFFUSION & LIFE–365™

The use of the "design-charts" for the design of various structural steel and reinforced concrete systems is well-known. Such design charts are prepared based on specific criteria, assumptions, and complex mathematical formulations. Similarly, nomographs for service life prediction can be prepared for the durability-based design of concrete structures. Such nomographs can be a handy tool for engineers, especially those who are not accustomed to computer programs. Therefore, a framework is proposed in the form of a nomograph, shown in Figures 9 and 10, to predict whether corrosion can initiate in a particular structure at a particular age.

The nomograph presented in Figure 9 is developed based on Eq. (2) for the condition with continuous and constant surface chloride concentration. Example ① in Figure 9 explains how to use the nomograph for checking if corrosion can initiate for a set of parameters. The parameters for Example ① are cover depth (x_1 = 60 mm), diffusion coefficient (D_1 = 5 x 10^{-12} m^2/s), surface chloride concentration (C_S, *1* = 7.5% wt. of cement) and age of the structure (t_i = 60 years). To start working with Example ①, go to the third quadrant and choose the horizontal line corresponding to x_1. On this line, identify the point corresponding to D_1. In Figure 9, this point is marked as (D_1, x_1). Now, move upward from the point (D_1, x_1) to the fourth quadrant and choose the vertical line corresponding to D_1. On this vertical line, identify the point corresponding to t_i. This point is marked as (D_1, t_i). Now, calculate $\frac{x}{\sqrt{D}}$ value and choose the corresponding curve in the first quadrant. These curves are plotted between the age of the structure (*t*) and normalized chloride content (C_n) for various $\frac{x}{\sqrt{D}}$, where in *x* and *D* must be in mm and, $10^{-12}\,m^2/s$ respectively. Now, draw a horizontal line connecting (D_1, t_i) and the curve identified for the calculated $\frac{x}{\sqrt{D}}$ = 26.8. The point of intersection is marked as (C_n, 1, t_i). Now, identify the line in the second quadrant corresponding to C_S, 1. Now, draw a vertical line from (C_n, 1, t_i) to the selected line in second quadrant. This point of intersection is marked as (C_n, 1, C_S, 1). Finally, draw a horizontal line from (C_n, 1, C_S, 1) to the C-ordinate on the right side. This point of intersection is marked as C_1, which is the expected chloride concentration at the surface of steel embedded in concrete. If C_1 is greater than C_{th} of the steel used, then the designer can assume that the corrosion can initiate at t1 and consider another set of *x*, *D*, and C_{th} (C_S depends on environmental conditions and is typically not changeable) to attain a safe design for t_1. On the other hand, if C_1 is less than C_{th}, then the designer can assume that the corrosion cannot initiate at t_1 and the selected variables are safe.

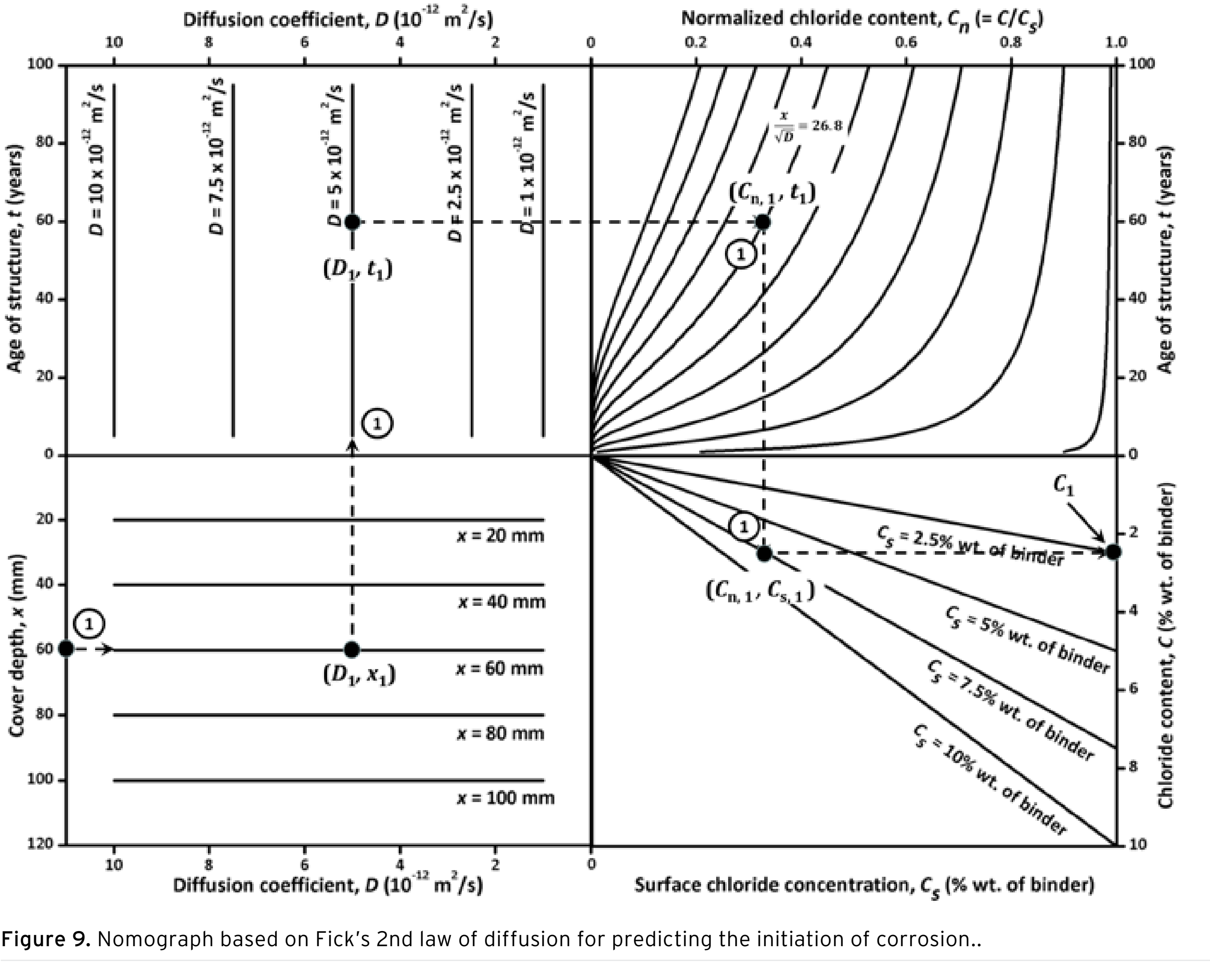


Figure 9. Nomograph based on Fick's 2nd law of diffusion for predicting the initiation of corrosion..

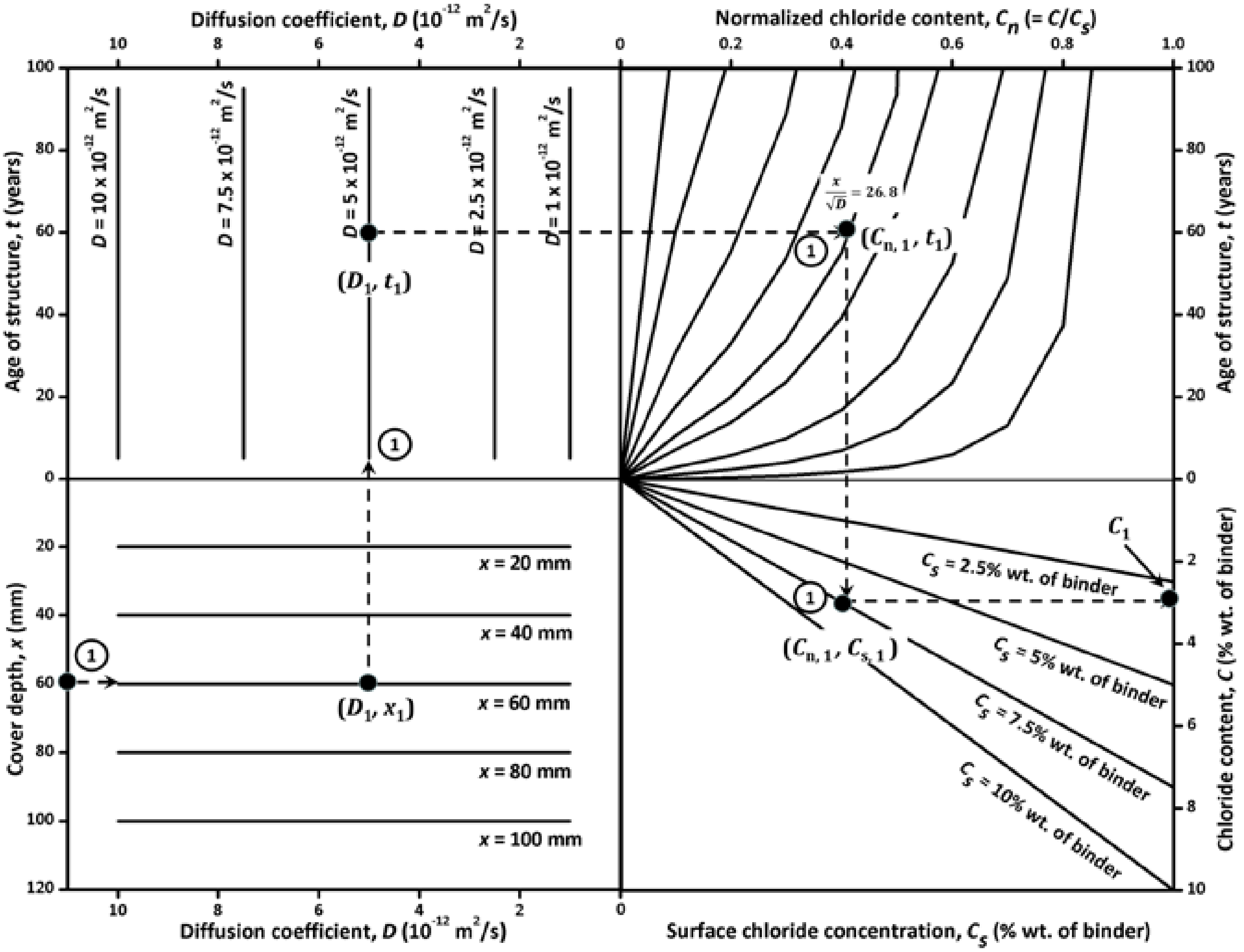


Figure 10. Nomograph based on Life-365™ predicting the initiation of corrosion.

Following is a brief discussion on the comparison of Examples ① worked using the nomograph in Figure 9. For Example ①, $\frac{x}{\sqrt{D}}$ is 26.8; C_n is 0.663; C_S is 7.5% wt. of cement; and C is 4.97% wt. of cement. As an application, imagine that SS316LN steel (C_{th} = 1.91% wt. of cement,) [17] is considered during the design stage. Then, the parameter combinations in Example ① will lead to corrosion initiation in 60 years. Therefore, other parameter combinations must be evaluated for their suitability, prior to the selection of the materials and design parameters. Table 5 summarizes the results based on two additional parameter combinations and Example ①.

Figure 10 shows a nomograph for service life design based on Life-365™ software program. Although Figure 9 and Figure 10 look similar, there are significant differences in the curves in the first quadrants, i.e., the plot between C_n and t. Examples have been worked out using identical parameter combinations as in Figure 9 and the results are summarized in Table 5. It can be seen that Life-365™ yields lower C values than the values obtained through closed-form solution [i.e., Eq. (2)]. The reason for this is that the Eq. (2) is a closed form solution and Life-365™ uses finite-difference approach. The significance of these differences for various parametric combinations needs to be investigated further.

Table 5. Details of corrosion initiation analysis using nomographs based of Fick's 2nd law of diffusion and Life-365™.

Example	Parameter combination	Model	C_n	C_s	C_{th}	Can corrosion initiate at *t* ?
1	x = 60 mm, $D = 5.0 \times 10^{-12}$ m^2/s, C_S = 7.5% wt. of cement and t = 60 years	Fick's law	0.663	7.5	1.91	Yes
		Life-365™	0.451	7.5	1.91	Yes
2	x = 40 mm, $D = 2.5 \times 10^{-12}$ m^2/s, C_S = 2.5% wt. of cement and t = 40 years	Fick's law	0.615	2.5	1.91	No
		Life-365™	0.402	2.5	1.91	No
3	x = 80 mm, $D = 7.5 \times 10^{-12}$ m^2/s, C_S = 10% wt. of cement and t = 80 years	Fick's law	0.681	10	1.91	Yes
		Life-365™	0.615	2.5	1.91	No

7.0 SUMMARY AND CONCLUSIONS

Four service life prediction models (Life-365™, CHLODIF, ClinConc and DuraCrete models) were studied. The approach of each model is different and hence one must be cautious in choosing a particular model for predicting the corrosion initiation time (t_i). In literature, the concrete cover depth (x), chloride diffusion coefficient (D) and critical chloride threshold (C_{th}) have been identified as critical in predicting t_i. The large range of scatter present in the values reported on these parameters is briefly reviewed. When predicted using Life-365™, t_i seems to be more sensitive to x than to D than to C_{th}. In addition, the sensitivities of t_i predicted using all the four models to x was compared. Similar comparisons for the sensitivities of t_i predicted using all the four models to D and C_{th} were also performed. It was found that both Life-365™ and ClinConc models predict similar or comparable t_i values. The results indicate that the DuraCrete model is highly sensitive to each of the input parameters considered. Therefore, the use of DuraCrete is recommended for service life prediction, if the input parameters can be accurately modeled. However, Life-365™ model seems to be the most user-friendly among the models studied in this paper.

The probabilistic analysis based on the DuraCrete model, considering the uncertainties in the values of x, D, C_{th} and C_S, emphasizes the need for probabilistic analysis and demonstrates the effect of uncertainties in the values of critical parameters on t_i. The use of nomographs for the service life prediction of concrete structures has been illustrated. Field data on and modeling of the input parameters is very critical for making realistic service life predictions. The future work on the service life prediction models need to be directed towards these. In fact, developments are underway in modeling chloride ingress by taking into account the combined effects of diffusion, convection, and chloride binding for the future versions of Life-365™.

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