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Input parameters and nomograms for service life-based design of reinforced concrete structures exposed to chlorides

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ABSTRACT

Civil engineers are trying to promote the service-life-based design of reinforced concrete (RC) structures to ensure long corrosion-free service life with minimal maintenance, repair, rehabilitation, and life cycle costs. This paper highlights the difficulties in adopting the existing tools as a general practice, especially for high-performance concrete with novel materials. To overcome these difficulties, "SL-Chlor," a MATLAB® computer program is developed to estimate service life, which uses Fick's 2nd Law of Diffusion to model chloride ingress, a major factor causing corrosion. Based on SL-Chlor, user-friendly nomograms are then developed to estimate the service life of RC structures located at various distances from the seashore. With the development of nomograms, this paper attempts to bring a new perspective to promote service life-based design with the help of user-friendly tools. The use of nomograms is demonstrated using case studies with multiple input parameters. The effect of different input parameters on service life is found to be synergistic, in the following descending order of influence: cover depth (d) > chloride diffusion coefficient (D_{Cl}) > ageing coefficient (m) [maturity constant of D_{Cl})] > chloride threshold of the steel-cementitious system (Cl_{th}). These findings encourage not only the use of blended cements but also the implementation of 3C's (adequate cover depth, compaction, and curing, which inherently influences d, D_{Cl}, and m) to help structures achieve the desired service life.

1. Introduction

Chloride-induced corrosion of the embedded steel is one of the major deterioration mechanisms in reinforced concrete (RC) structures, leading to frequent repair and rehabilitation works and significant costs. Based on a market study, Krishnan et al. [1] found that the typical frequency with which major repairs to mitigate corrosion in RC structures are undertaken is about every 5 years. The IMPACT study by the former NACE International (now AMPP) estimated that the cost of corrosion in the USA, India, the European region, the Arab world, China, Japan, and the Rest of the World in 2013 was about 2.7, 4.2, 3.8, 5, 4.2, 4, 1, and 3.4 percent, respectively, of the GDP of these regions [2]. The cost proportion can be higher when measures to enhance durability, reduce preventive maintenance, and manage corrosion are given less importance during the design phase of structures. Current practices to increase the corrosion-free service life and minimize corrosion costs include increasing the cover depth or using chloride-resistant concretes and/or corrosion-resistant steel reinforcement. Many new steel and cementitious materials claiming enhanced durability are being introduced to the market – usually with *deemed-to-satisfy* performance requirements in severe chloride environments according to provisions prescribed in the code. However, local exposure conditions such as chloride concentration, temperature, or moisture vary depending on the structural element. Therefore, it is advisable to estimate their service life, i.e., long-term performance without major intervention in the anticipated local exposure condition, and to make consequent modifications to the structural and materials design features during the planning/design phase of the structure. This approach also gives room for innovation in design and construction, facilitating a performance-based approach [3]. While attempting such an approach, it is recommended to consider the

Abbreviations: %bwob, Percentage by weight of the binder; %bwoc, Percentage by weight of concrete; Cl_i, Initial chloride concentration; Cl_s, Surface chloride concentration; Cl_{th}, Chloride threshold; CoV, Coefficient of variation; d, Clear cover depth; D_{Cl}, Apparent diffusion coefficient; k, Chloride build-up rate; LC3, Limestone calcined clay cement; m, Ageing coefficient; OPC, Ordinary Portland cement; FA, Fly ash; S-B, Steel-cementitious binder; SCMs, Supplementary cementitious materials; QST, Quenched and self-tempered rebar; w/b, Water-to-binder ratio; ~N(μ, s), Normal distribution; ~LN(μ, s), Lognormal distribution; t_{CH}, Time for complete hydration; Cl_b, Chloride binding; MK, Metakaolin; SRPC, Sulphate resisting Portland cement.

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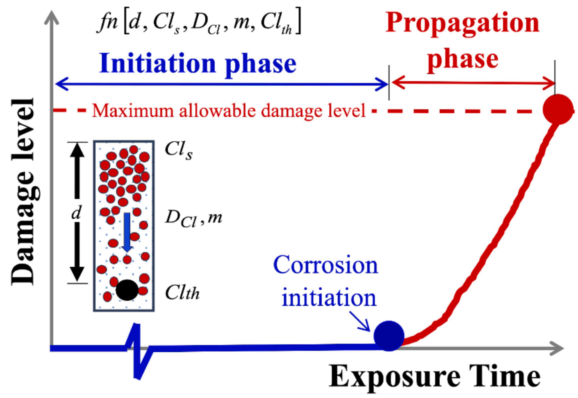

Fig. 1. Schematic showing various phases and factors affecting the service life.

Table 1
Comparison of models/tools available for estimation of service life.

Models/Tools	Features	Limitations
Tuutti model (1982) [9]	• Square root of time model • Simple and easy to calculate	• Only time is considered • Material and exposure parameters are not considered • Leads to highly erroneous estimates in some cases, especially with SCMs
Life 365™ (Life-365, 2012) [10]	• Easy to use • Finite difference approach	• Upper limit of '*m*' is defined as 0.6; hence, cannot be used for some SCMs • Coefficient of variation (CoV) for all major input parameters is fixed to 25%. The user cannot change this. • Chloride binding is not considered; hence, not applicable for some SCMs
Duracrete [11]	Probabilistic and performance-based assessment	• Chloride binding is not considered; hence, not applicable for some SCMs • Corrosion inhibitor is not considered • Empirical model
ClinConc [12]	• Finite difference approach • Multi-ionic transport • Treats materials and exposure parameters separately	• Assumes that pores in concrete are always saturated; hence, very good for submerged structures • Applications to other structures are questionable
CHLODIFF [13]	• Developed for new structures for which no data is available	• Over-estimation of service life due to the number of empirically obtained or assumptions on correction factors employed, such as cement type and age factor
Cerema Model [14]	• Based on Fick's first law of diffusion • Combines the thermodynamic equilibrium/kinetic and surface properties to derive at the chloride concentration	• Can be used only for determination of chloride concentration (NaCl) in high pH concrete and not for multi-ionic transport

materials holistically instead of focusing on the effect of a single parameter on service life. This is because of the synergy between input parameters where the adverse effects of one parameter can be overcome by its positive effects on another parameter in the same material, resulting in longer service life [4]. It is, therefore, necessary to have user-friendly tools to understand the synergy of input parameters and enable widespread use of service-life-based design practices.

This paper reviews various approaches for estimating service life and challenges with modeling various input parameters followed by the proposal of "SL_Chlor" computer program, which accepts the input parameters as user-defined random variables (i.e., more flexible) and estimates probabilistic service life. Further, a set of nomograms developed using the 'SL_Chlor' for various chloride exposure conditions, and the order of influence of the input parameters on service life are discussed. Finally, the 'Mx-Dy' and '3Cs' concepts for increasing the service life of concrete structures have been presented prior to the conclusions of this study.

1.1. Modelling service life as the time to corrosion initiation

Fig. 1 presents the schematic representation of the corrosion initiation and propagation phases, and the rectangle represents the cross-section of a structural element. The small circles in the rectangle indicate the ingress of chlorides from the immediate environment towards the embedded steel resulting in the build-up of chlorides at the steel surface and thus corrosion. Typically, the initiation phase is significantly longer than the propagation phase, and hence, traditionally, the end of the corrosion initiation phase is considered the end of service life. The duration of the propagation phase depends on the corrosion rate, which varies significantly due to the presence of cracks and is hard to estimate. Many studies have therefore considered a single lumpsum estimate for the propagation period, e.g., 6 years in Life 365™. However, this paper focuses mainly on the corrosion initiation phase and its estimation in uncracked concrete systems, mainly to facilitate the material selection for longer service life.

To estimate the chloride concentration at the steel surface, various chloride ingress models have been developed accounting for several environmental factors and ingress mechanisms. The models can be broadly categorized as (i) physical models (ii) empirical models and (iii) analytical models. In the physical models, the chloride ingress is treated as a transport parameter with interaction of chlorides and other ionic species within the cementitious matrix. Multi-ionic species transport can be represented either using the Nernst-Planck equation or Fick's 1st law of diffusion, where flux due to the movement of ionic species is in relation to the concentration gradient. The movement of ions can also be described by Fick's 2nd law of diffusion where the change in concentration gradient with time is considered. On the other hand, empirical models have been developed by adopting field or laboratory data collected from structural elements with a particular design/exposure condition, reflecting the combined effects of various phenomena. However, caution should be exercised when these models are used to estimate chloride concentrations for general structures. In the case of analytical models, the accuracy of the estimation depends on the correctness of the boundary conditions and is challenging in the case of numerical modeling of chloride ingress in structural elements with various design/exposure conditions.

Table 1 presents some of the service life models (SL models) with their features and limitations. The lack of temporal field data for different environmental conditions poses difficulty in validating these models and there exists a significant variation between the estimated and actual service life of the structure. In addition, the lack of standard test methods to assess the evolution of material properties with time, cover depth, and environment make it difficult for practising engineers to determine the input parameters. On the other hand, the emergence of new low-carbon materials to fulfil the NetZero commitment requires the necessary steps to include them in service life-based designs. Many existing SL models have limitations in accommodating new materials because of out-of-scope data/input values and predefined and/or inappropriate quantification procedures. For example, in the Life 365™ model (second row in Table 1), the input parameter *m* cannot have values greater than 0.6. However, many researchers have reported that the *m* value can be higher than 0.6 if slag or fly ash is used [5–8]. The complexity of the service life models, and lack of user-friendly tools are the main reasons for the poor understanding and implementation of

Table 2
A sensitivity analysis for service life estimation parameters – A review.

Parameter/ technique used	Order of influence	Remarks	Reference
Standard deviation	$m > d > D_{cl} > Cl_{th} > Cl_s$ (w/b = 0.5) $d > m > D_{cl} > Cl_{th} > Cl_s$ (w/b = 0.7)	The ranking of parameters changes depending on the w/b	Pettersson and Norberg [15]
Reliability analysis	$Cl_{th} > Cl_s > D_{cl}$	The probability of depassivation is independent of cover thickness and time of exposure	Zhang et al. [16]
Reliability analysis	$d > m > D_{cl} > t_i > Cl_{th} > Cl_s$	For some case studies, the same ranking is obtained for D_{cl}, t_i, and Cl_s	Ferreira [17]
Simple and Parametric Boot strap	$D_{cl} > d$; $Cl_{th}/Cl_s < 1 \rightarrow t_i$ is shorter	The normal distribution can be assumed for all the input parameters	Kirkpatrick et al. [18]
% change in the partial derivative of service life w.r.t. the parameter	$d > D_{cl}$ & $Cl_{th} > Cl_s$	The sensitivity analysis was done holistically for all the parameters	Khatri and Sirivivatnanon [19]
% change in the variable w.r.t. the % change in the service life	$d > D_{cl} > Cl_{th}$	Different surface chloride concentrations were analysed	Trejo and Reinschmidt [20]

Table 3
Statistical distributions adopted for cover depth in literature.

Statistical distribution (mm) [~N(μ, σ) or ~ LN(μ, σ)]	Reference	Source
~N(50, 5)	[26]	Assumption
~N(20, 6), ~N(30, 9), ~N(40, 12), ~N(50, 15)	[16]	Assumption
~N(76, 19)	[27]	Assumption
~N(60, 18)	[28]	Assumption
~N(58.6, 14.7) ~N(33.6, 14.7) ~N(83.6, 14.7) (truncated at 15 mm)	[29]	Assumption
~N(50, 7.6) (truncated at 17 mm)	[30]	Field data from China
~LN(38, 1.89) ~LN(50.8, 6.8) ~LN(65.5, 3.62) ~LN(76.2, 4.78)	[25]	Field data from USA
~LN(38, 10)	[31]	Assumption
~LN(70, 14)	[32]	Assumption
~LN(25, 4) ~LN(30, 6.8) ~LN(30, 6)	[19]	Field data from Japan &Australia
~LN(μ, 0.15μ)	Authors' suggestions for modeling service life in the absence of field data	

service life-based designs. This paper attempts to fill such gaps in practical applications to some extent by developing nomograms to promote service life-based designs, which in turn reduce the consumption of concrete in repair and maintenance, which is significant and unaccounted for.

1.2. *Influence of input parameters*

Engineers need to understand the order of influence and relation of input parameters on service life to carry out tradeoffs, achieve maximum durability, and choose materials effectively. The order of influence can be found based on sensitivity analysis considering one parameter at a time or interaction of parameters (global sensitivity analysis) on the estimated service life. Table 2 shows the review of such analysis of the parameters involved in service life estimation. Here, there is no clear order of influence for enhancing the service life since the order changes based on the parameters considered for sensitivity analysis and method of analysis. For example, the sensitivity analysis based on standard deviation (Table 2 - Row 1) yields a different order of influence than the one based on reliability (Row 2 and 3). The reported order of influence also has a large scatter depending on the technique employed, the range of input parameters employed, and the assumptions made. This paper also attempts to understand the sensitivity of the input parameters in the estimated service life through the developed nomograms.

2. Research significance

Many special materials (supplementary cementitious materials, corrosion inhibitors, microstructurally modified and coated rebars, etc.) are now available to enhance the service life of reinforced concrete structures. However, the lack of user-friendly service life estimation tools prevents the promotion of durable and sustainable materials, innovation and performance-based design approach to many construction projects, especially small and moderate scale projects. The SL-Chlor model and the nomograms developed in this paper could enable designers to use more durable steel-cementitious systems and specify performance parameters (say, D_{Cl}) for increasing the service life. Also, the nomograms (to be used like the typical structural design-charts) would be useful for design engineers for quick decision making. The order of influence identified for the input parameters, and the Mx-Dy and 3Cs concepts can help site engineers to prioritize and implement quality control measures at site and help achieve the desired service life.

3. Input parameters for service life estimation

The chloride ingress through the concrete cover occurs mainly through diffusion beyond 5 to 10 mm [21]. The estimation based on pure diffusion is therefore reasonable for practical purposes and most researchers model the chloride ingress using Fick's 2nd Law of Diffusion, the solution for which is given as follows [22]:

$$Cl(x,t) = Cl_i + (Cl_s - Cl_i).\,erf\left(\frac{x}{\sqrt{4D_{Cl,t}}}\right) \text{ when } Cl_s \text{ is constant} \quad (1)$$

where, $Cl(x,t)$ is the chloride concentration at depth, x, and time, t; Cl_i is the initial chloride concentration at the steel surface, Cl_s is the chloride concentration at the concrete surface; D_{Cl} is the apparent chloride diffusion coefficient of the cover concrete, and erf() is the mathematical error function. The ageing effect of the concrete is accounted for by a factor known as ageing coefficient, m, in the calculation of D_{Cl} as follows.

$$D_{Cl,t} = D_{Cl,ref}\left(\frac{t_{ref}}{t}\right)^m \quad (2)$$

where, $D_{Cl,\ t}$ and $D_{Cl,\ ref}$ are the diffusion coefficient at exposure time, t, and reference time, t_{ref} (e.g., 28 days), respectively. According to Eq. (1), when the chlorides at the steel-binder (S-B) interface, $Cl(x = d, t)$, reaches Cl_{th}, then the corresponding time, t, is considered as the time to corrosion initiation. Therefore, the key parameters influencing the initiation phase are cover depth (d), surface chloride concentration (Cl_s), apparent chloride diffusion coefficient (D_{Cl}), ageing coefficient (m) related to D_{Cl}, and chloride threshold (Cl_{th}). Following is a discussion on these primary parameters, test procedures, their models, and the way forward.

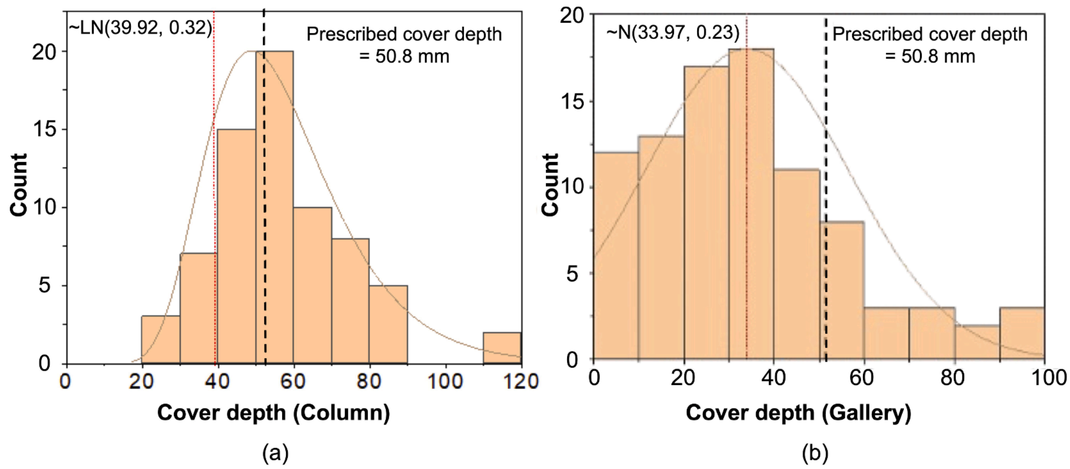

Fig. 2. Variations in cover depth observed in the field (a) Column and (b) Gallery.

Table 4
Relation between surface chloride concentration and time from the literature.

Surface chloride concentration, Cl_s	Reference	Location
Increases linearly with the square root of time	[39]	Field/lab data based on various exposure
Increases as a power function of time	[34]	
Non-linear increase	[33]	
Linearly varying until reaching a maximum constant value	Life-365™ [10]	
13 kg/m^3	Standard specification for concrete structures – 2007, Design (Japanese code) in the absence of field data [40]	Splash Zone
9–4.5 kg/m^3 (high to low air-borne chlorides)		Near shoreline
4.5 – 2 kg/m^3 (high to low air-borne chlorides)		Within 0.1 km
3 – 2 kg/m^3 (high to low air-borne chlorides)		0.1–0.25 km
2 – 1.5 kg/m^3 (high to low air-borne chlorides)		0.25–0.5 km
1.5 – 1 kg/m^3 (high to low air-borne chlorides)		0.5 – 1 km

3.1. Cover depth (d)

As a durability-based design feature, most standards prescribe a minimum cover depth, d, for various exposure conditions. For example, the Indian standard [23] suggests cover depths of 45, 50 and 75 mm for severe (coastal environment/submerged structures), very severe (spray zone) and extreme (tidal) exposure conditions, respectively. The American standard [24] recommends a minimum cover depth of 3 in. (76.2 mm) for elements experiencing severe changes in moisture and temperature. Increasing the cover depth beyond certain limits is not recommended due to propensity for cracking.

Table 3 shows that most researchers have modelled cover depth, d, as normal and lognormal distributions. Based on the typical allowable limit of error and field observations, the variable d can be assumed to be a normal distribution for typical calculations with pre-defined number of simulations. For assessments without a pre-defined number of simulations (say, reliability assessments), it is better to assume a lognormal distribution to avoid negative random realizations and associated mathematical challenges. In addition, a lognormal distribution is better fitted for cover depth as it varies considerably in the field [25]. The authors have collected data from various projects in India, and found that the data follows a lognormal distribution when confined shutters such as column formwork are used during construction and other distributions when such confinement is not possible (see Fig. 2). For modelling service life in the absence of field data, this paper suggests a

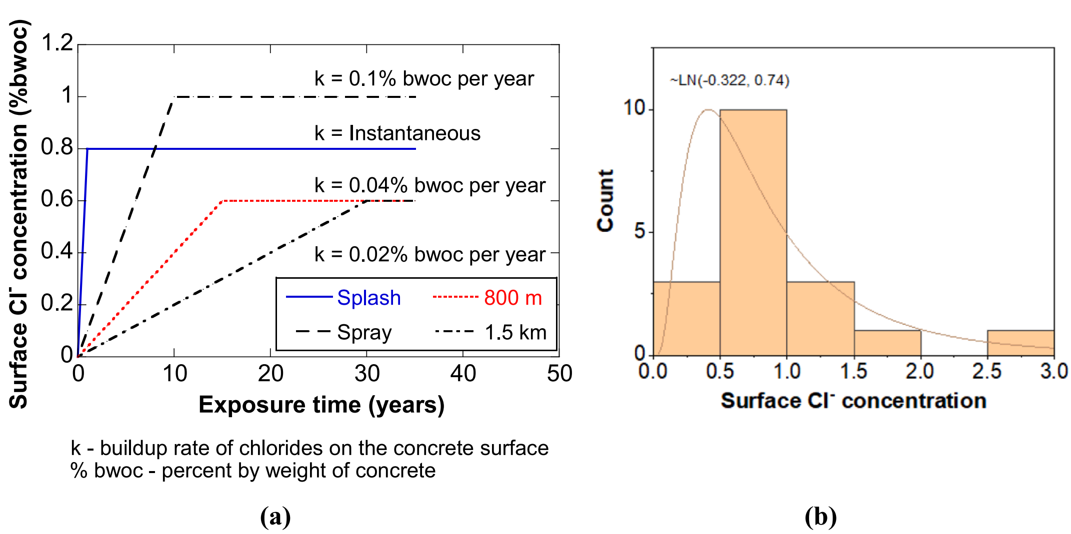

Fig. 3. (a) Cl_s as per Life-365™ and (b) Statistical distribution of Cl_s.

Table 5
Statistical distribution adopted for maximum Cl_s in literature.

Statistical distribution* (kg/m^3)	Reference	Source
~N (2, 0.2)	[26]	Assumption
~N (4, 0.2)		
~N (6, 0.2)		
~N (8, 0.2)		
~N (15, 3) (truncated at 0)	[30]	Assumption
~LN (6, 1.8)	[32]	Assumption
~LN (3.5., 0.5)	[29]	Field (USA)
~LN (2.4, 0.12)	[25]	Field (USA)
~LN (3.6, 0.36)		
~LN (4.8, 0.72)		
~W (α = 0.5, β = 3.1)	[16]	Field (China)
~LN(μ, 0.15μ)	Authors' suggestions for modeling service life in the absence of field data	

*N – Normal; LN – Lognormal; W – Weibull

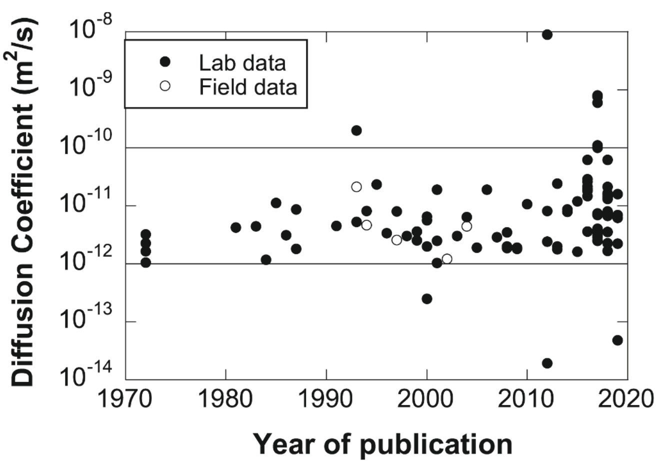

Fig. 4. Chloride diffusion coefficient values from literature.

standard deviation of 15% of the design mean cover depth [i.e., $d \sim$ LN (μ, 0.15μ)].

3.2. Surface chloride concentration

Surface chloride concentration (Cl_s) plays a key role in the estimation of service life as chloride diffusion through concrete cover depends on the concentration gradient. Cl_s depends on the chloride concentration in the environment and the local humidity conditions of the structure. Local humidity depends on factors such as the orientation of the structure (windward or leeward side), contact with seawater or soil, seasonal variations and distance from the sea, and influences the Cl_s to a great extent [33]. Kim et al. [34] found that Cl_s is higher in permanently submerged structural elements than those in splash and spray zones. In addition to environmental conditions, concrete properties such as mix design (the ingredients and proportioning of concrete) also influence Cl_s [35,36]. Further, Andrade et al. [37] showed that the chloride profile is influenced by the skin effect; the concentration of chlorides at the surface can be lower than that measured at a certain depth. Literature reports that this skin effect depends on many factors such as type of binder, w/b, temperature, and exposure condition [38].

Although the time to corrosion initiation depends on Cl_s, there is no standard method to determine the value, which often leads to erroneous estimation of service life. Table 4 gives the expressions for Cl_s as a function of exposure time and the recommended values in the literature. This paper recommends the Life365™ model in the absence of data, which adopts a linear variation of Cl_s over time until the attainment of a

Table 6
Summary of different approaches for calculation of $D_{cl.}$

Models	Equations **for diffusion coefficient**
Time dependent [48]	$D_{Cl}(t) = D_{Cl,ref}\left(\frac{t_{ref}}{t}\right)^m$ $D_{Cl,ref}$ – D_{Cl} at reference time; t_{ref} (usually, 28 days); $D_{Cl}(t)$ – D_{Cl} at any time instant, t
Life-365™ (Life–365, 2012)[10]	$D_{Cl}(t,T) = D_{Cl,ref}\left(\frac{t_{ref}}{t}\right)^m e^{\frac{U}{R}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)}$ $D_{Cl,ref} = 10^{-12.06+2.4(w/b)}.e^{-0.165.SF}$ U - activation energy of the diffusion process; R - gas constant; T_{ref} = 293 K; T - absolute temperature; w/b - water to binder ratio; SF - % of silica fume (valid upto 15%)
ClinConc [12]	$D_{Cl} = \frac{(0.8a_t^2 - 2a_t + 2.5)(1+0.59K_{b,ref}).k_{TD}}{1 + k_{OH,ref}.K_{b,ref}.k_{Tb}.f_b.\beta_b.(\frac{C_s}{35.45})^{\beta_b - 1}}.D_{ref}$ a_t - time–dependent factor for chloride binding; $K_{b,ref}$ - binding factor found at t_{ref}; f_b and β_b - chloride binding constants; k_{OH} - factor for alkalinity; k_{TD} and k_{Tb} are the temperature factors for D_{Cl} and chloride binding; C_s - chlorides in sea water
CHLODIFF [13]	$D_{Cl} = D.\frac{w}{c}.f_{int}(CIAs, SCMs, SPs, curing, crack).f_{ext}(t, T, RH, W_s, C_s)$ $D_{Cl} = 5\times 10^{-13}.e^{4.8708(w/c)}.f_{int}.[1+256\,(1-\frac{RH}{100})^4]^{-1}.t^{-m}$ CIA - Corrosion inhibiting admixtures, SCMs - supplementary cementitious materials; SPs - Super plasticizers, RH - relative humidity; W_s - wing influence
DuraPGulf [49]	$D_{Cl} = D_{Cl,ref}(\frac{t_{ref}}{t})^m.\exp\left[\frac{U}{R}\times\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right].[1+256(1-\frac{RH}{100})^4]^{-1}$
Duracrete [11]	$D_{Cl} = k_e.k_c.D_{RCM}.(\frac{t_{ref}}{t})^m$ k_e is environmental factor; k_c is curing factor, and D_{RCM} is D_{Cl} obtained from migration tests

maximum constant value when the concrete is saturated with chlorides (See Fig. 3(a)).

Table 5 shows that researchers have assumed a normal distribution in the absence of data, and other distributions, such as lognormal and Weibull distribution, based on data availability during modelling Cl_s. The chloride concentration measured in ponding tests conducted at IIT Madras follows lognormal distribution as shown in Fig. 3(b) [41,42]. Hence, in the absence of data, this paper suggests the lognormal distribution for modelling Cl_s.

3.3. Chloride diffusion coefficient (D_{Cl})

The D_{Cl} indicates the rate at which chlorides penetrate through the cover concrete. Fig. 4 shows the spread of D_{Cl}-values of different concretes reported in the literature, representing both laboratory and field specimens in various exposure conditions with and without SCMs [43]. It should be noted that a significant band lies between 10^{-12} and 10^{-10} m^2/s and hence this range of D_{Cl}-values is taken for charting the nomograms. As the concrete microstructure becomes more refined due to prolonged hydration, D_{Cl} decreases with time indicating more resistance against chlorides. This decrease in D_{Cl} depends on parameters such as the binder type, mixture proportioning of concrete, degree of curing and the presence of cracks. D_{Cl} also changes due to the interaction of chlorides with the hydrated cement products resulting in bound chlorides [44]. The addition of SCMs with low w/b reduces D_{Cl} in concrete due to compact, highly resistive microstructure, which induces both tortuosity and very low penetrability [45]. D_{Cl} at any time instant is determined through curve fitting of the values of chloride concentration at different depths. Typically, the chloride concentration at the outermost layer of concrete (exposure surface) is taken as Cl_s. It is important to note that D_{Cl} and Cl_s values are interconnected, and the estimation of one parameter can affect the value of the other when examining chloride profiles. Therefore, when selecting these parameters for service life estimation, it is crucial to exercise caution and make careful considerations to ensure

Table 7
Statistical distribution for D_{Cl} reported in literature.

Statistical distribution (m^2/s)	Reference	Source
~N(8.87×10^{-12}, 2.22×10^{-12})	[50]	Assumption
~N(0.85×10^{-12}, 7.14×10^{-12})	[31]	Field (Montenegro, Europe)
~LN(2×10^{-12}, 4×10^{-13})	[30]	Assumption
~LN(1.27×10^{-12}, 3.16×10^{-13})	[32]	Assumption
~LN(2.4×10^{-11}, 3.81×10^{-12})	[25]	Field (USA)
~LN(4.95×10^{-11}, 7.61×10^{-12})		
~LN(9.82×10^{-11}, 1.14×10^{-11})		
~LN(1.48×10^{-10}, 1.52×10^{-11})		
Weibull($\alpha = 0.533$, $\beta = 3.07$)	[16]	Field (China)
Gamma($k = 27.05$, $\theta = 1.42$)	[26]	Assumption
~LN(μ, 0.15μ)	Authors' suggestions for modeling service life in the absence of field data	

that realistic values are reflected.

Table 6 summarizes the equations for D_{Cl} used by different models. The equations developed for calculating D_{Cl} are based on either empirical formulations or theoretical phenomena. Life-365™ considers D_{Cl} as a function of time and temperature. CHLODIFF [13] considers D_{Cl} as a function of water-binder ratio, admixtures, temperature, crack density, curing conditions and wind direction [13]. ClinConc [12] considers D_{Cl} as a function of time, temperature, chloride binding, alkalinity, factor compensating for field condition, leaching, etc. [12]. Since the determination of D_{Cl} from bulk diffusion tests (as per ASTM C1556-11a [46]) is time-consuming, Duracrete [11] offers an equation that converts the non-steady state migration coefficient (as per NT BUILD 492 [47]) to the D_{Cl} of concrete. Considering too many factors in the calculation of D_{Cl} will be cumbersome and difficult to arrive at those parameters. Hence, a simple expression as described by de Vera et al. [48] (Row 1 in Table 6) is considered for D_{Cl} in this paper.

Table 7 shows the probability distributions assumed for D_{Cl} in the literature. As the D_{Cl} is time-dependent and can vary with environment, the reported distributions could classify as more than nature; it is common to assume it as lognormal in the absence of data.

3.3.1. Ageing coefficient (m)

The use of SCMs (slag, fly ash, calcined clay, etc.) in concrete is highly recommended to achieve sustainable low carbon concrete. Most SCMs have low reactivity in the initial stages of hydration and need prolonged time for complete hydration; Hence, D_{Cl} of SCM-based concretes must be modelled as a time-variant diffusion coefficient say,

Table 8
Properties of various type of steel–concrete systems.

Ingredients of concrete	m	Cl_{th} (%bwoc)
> 50 %Slag/Fly ash + OPC + CIA	0.7	0.03
20—30% Metakaolin/Fly ash + OPC + CIA	0.6	0.075
> 50% Slag/Fly ash + OPC	0.7	0.02
20–30% Metakaolin/Fly ash + OPC	0.6	0.05
OPC + CIA	0.4	0.1
LC3 + CIA	0.5	0.025
OPC	0.4	0.067
LC3	0.5	0.017
< 10% Silica fume + OPC	0.4	0.02

CIA – Corrosion inhibiting admixture; OPC – Ordinary Portland cement; %bwoc – percent by weight of concrete.

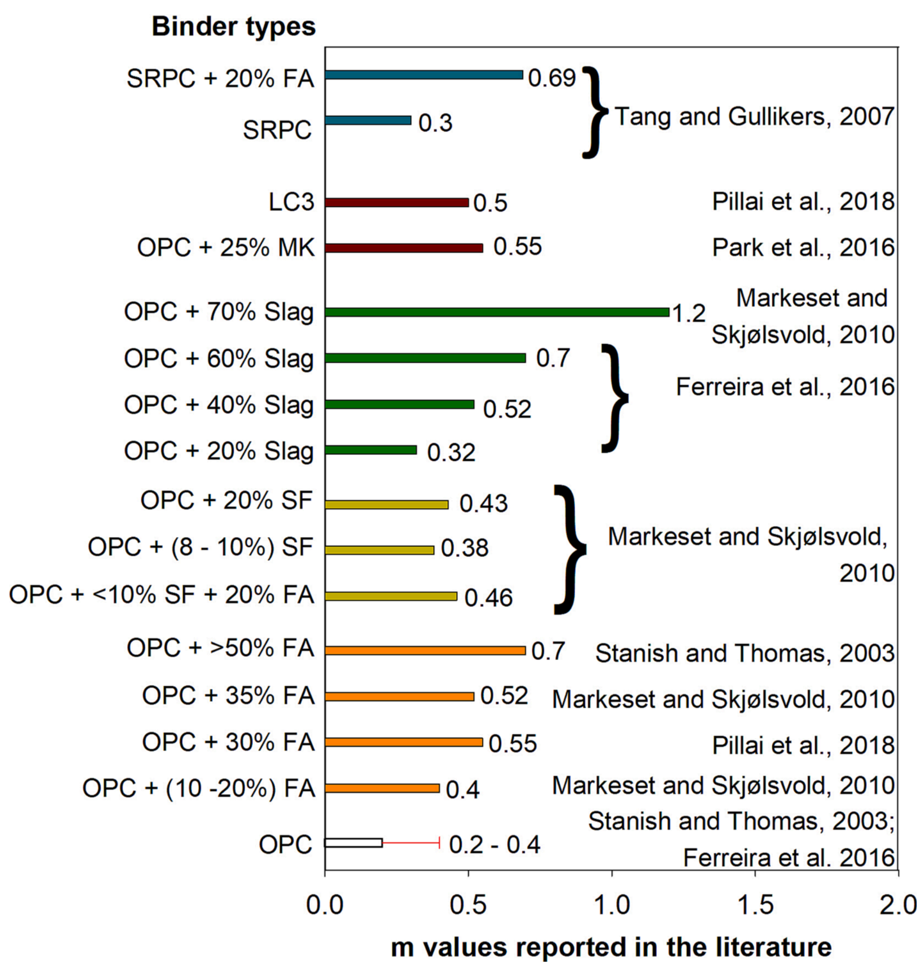

Fig. 5. Ageing coefficient (*m*) of different binders reported in the literature.[4–8,53]

Table 9
Statistical distribution for Cl_{th} reported in literature.

Statistical distribution (kg/m^3)	Reference	Source
Symmetric triangular (upper limit = 5, lower limit = 0.6, mode = 2.2)	[26]	Assumption
~N (2, 0.4) (truncated at 0)	[30]	Assumption
~LN (0.24, 0.46)	[16]	Field (China)
~LN (0.7, 0.014)	[32]	Assumption
~LN (0.72, 0.036) ~LN (0.84, 0.084) ~LN (0.96, 0.14)	[25]	Field (USA)
~LN (2.64, 0.72)	[31]	Assumption
Uniform (0.6, 1.2)	[29]	Assumption
~LN(μ, 0.40μ)	Authors' suggestions for modeling service life in the absence of field data	

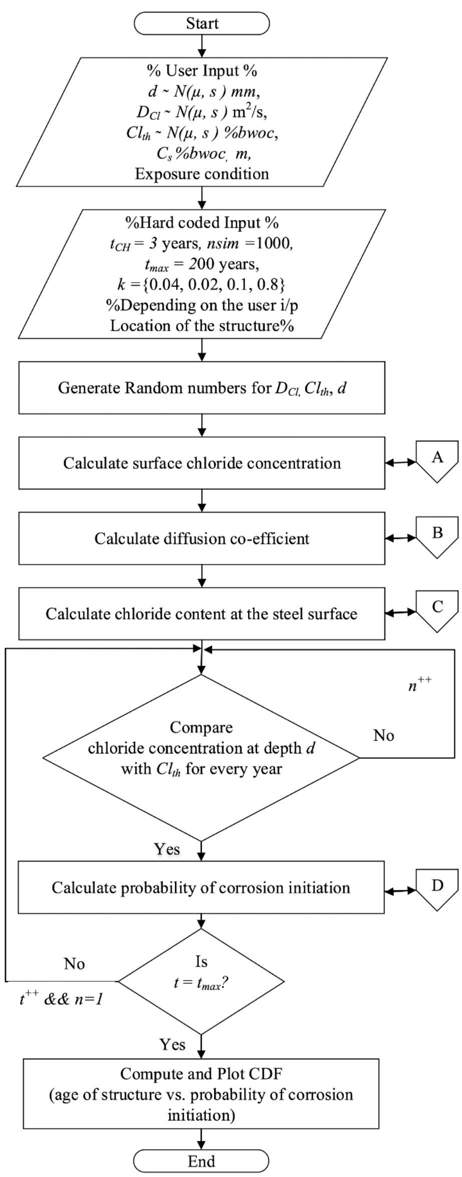

Fig. 6. Flowchart for estimating service life of structure.

$D_{Cl}(x, t)$, where x is the depth of the point under consideration and t is the age of concrete. This ageing effect has a strong influence on D_{Cl} and hence accounted for by a factor known as ageing coefficient, m, in its

Table 10
Input parameters required for service life estimation.

Input parameters	Typical mean values for the input parameters	Is standard deviation considered?	Test methods to arrive at the input parameter
Cover depth (d), mm	10–100 mm	Yes (User Input)	Fixed by the designer
Ageing coefficient (m)	0.2–1	NA	ASTM C1556-11a at 28, 90, 180 days [46]
Diffusion coefficient (D_{Cl}), m^2/s	$1 \times 10^{-12} - 1 \times 10^{-10}$	Yes (User Input)	ASTM C1556-11a [46]
Time for complete hydration (t_{CH}), years	3	NA	Considered as 3 years for all types of concrete
Chloride threshold (Cl_{th}), %bwoc	0.01–0.1	Yes (User Input)	hr-ACT [73]
Maximum surface chloride concentration (Cl_s), %bwoc	0.6–1	NA	ASTM C1556-11a [46] / NT BUILD 443 [74]
Buildup rate (k) (%bwoc per year)	Instantaneous – 0.04	NA	Life-365™ recommendations based on the location of the structure [10]

%bwoc – by weight of concrete; NA – not applicable.

calculation as described in Equation (2) mentioned earlier.

The higher the value of m, longer will be the duration of hydration. Most of the SCM based concretes have higher values of m than OPC based concrete. As time elapses, the ageing effect takes precedence and leads to lower D_{Cl} as mentioned in Eq. (2). Thus, the influence of m is more prominent in the calculation of D_{Cl} when blended cement is used [51]. The omission of m can lead to the underestimation of service life in case of blended cements, and careful consideration should be given for the evaluation of m in such cases.

Fig. 5 summarizes the values of m for concrete, which vary depending on the type of binder, replacement level, water-binder ratio and method of determination. Table 8 presents the summary of values of m derived for various concretes including different type of SCMs and corrosion inhibiting admixtures (CIAs) based on the literature used for generating the nomograms, which are described in detail in later part of the paper. The SCM blends were carefully selected, taking into consideration the allowances in the code, such as BS EN 197–5:2021, which promote high volume replacement of OPC (Ordinary Portland Cement). These choices align with the objective of achieving NetZero goals and reducing carbon emissions. Since m is a secondary parameter influencing D_{Cl}, the influence of CIAs has not been studied widely in the literature. Hence, the values of m are assumed to be the same for concretes with and without CIAs. Additionally, not many researchers have included the statistical distribution of m in the service life estimation. Bentz [50] assumed a normal distribution for m (~N(μ = 0.2, σ = 0.15μ)) whereas Lindvall [52] assumed it to be a beta distribution (~B(α = 4.075, β = 9.508, a = 0, b = 1) for OPC cement concretes in marine, submerged condition).

3.3.2. Time for complete hydration (t_{CH})

Hydration of cement in concrete occurs if moisture and space are available for the reaction. In OPC concrete, about 90% of hydration is completed in 28 days of curing. Considering this, it is industry practice to test the compressive strength of OPC concretes at 28 days of curing. However, in the case of SCM-based cement, depending on the nature of SCM used, the duration of hydration can differ. For example, in case of fly ash and slag, this could be about 56 days or even more to have the same level of strength as that of OPC [54,55]. In the case of Limestone Calcined Clay Cement (LC3), this could be about 7 days. Though many

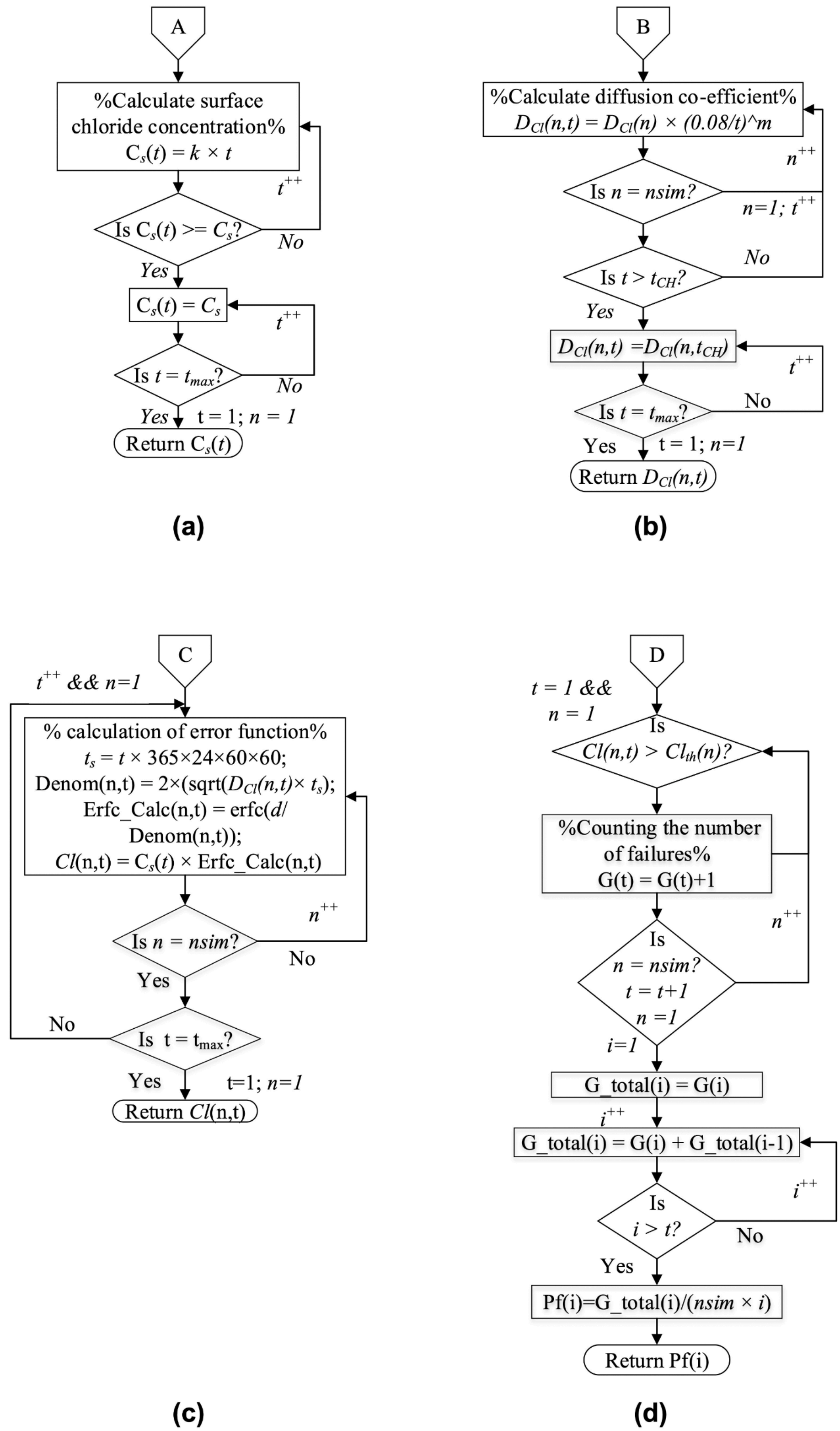

Fig. 7. Subroutines to calculate (a) Cl_S, (b) D_{Cl}, (c) chloride content at steel surface and (d) probability of corrosion initiation.

construction sites do not practice 90 days of curing for high strength concrete, it is recommended to perform tests at such longer curing period to realize the full potential of blended cement concretes [56], and use them in design steps and avoid significant underestimation of their strength and durability properties. It is difficult to predict t_{CH} as concrete will evolve based on the binder type, reactivity of the SCM, replacement level, curing and exposure conditions. In the context of service life estimation, some models assume a longer t_{CH} to take this hydration duration into account. For example, ClinConc model uses the exposure time of the structure as t_{CH} as diffusion is time-dependent and the field exposed samples continued to show low D_{Cl} [12] whereas Life 365 assumes t_{CH} as 25 years. However, the authors of this study express

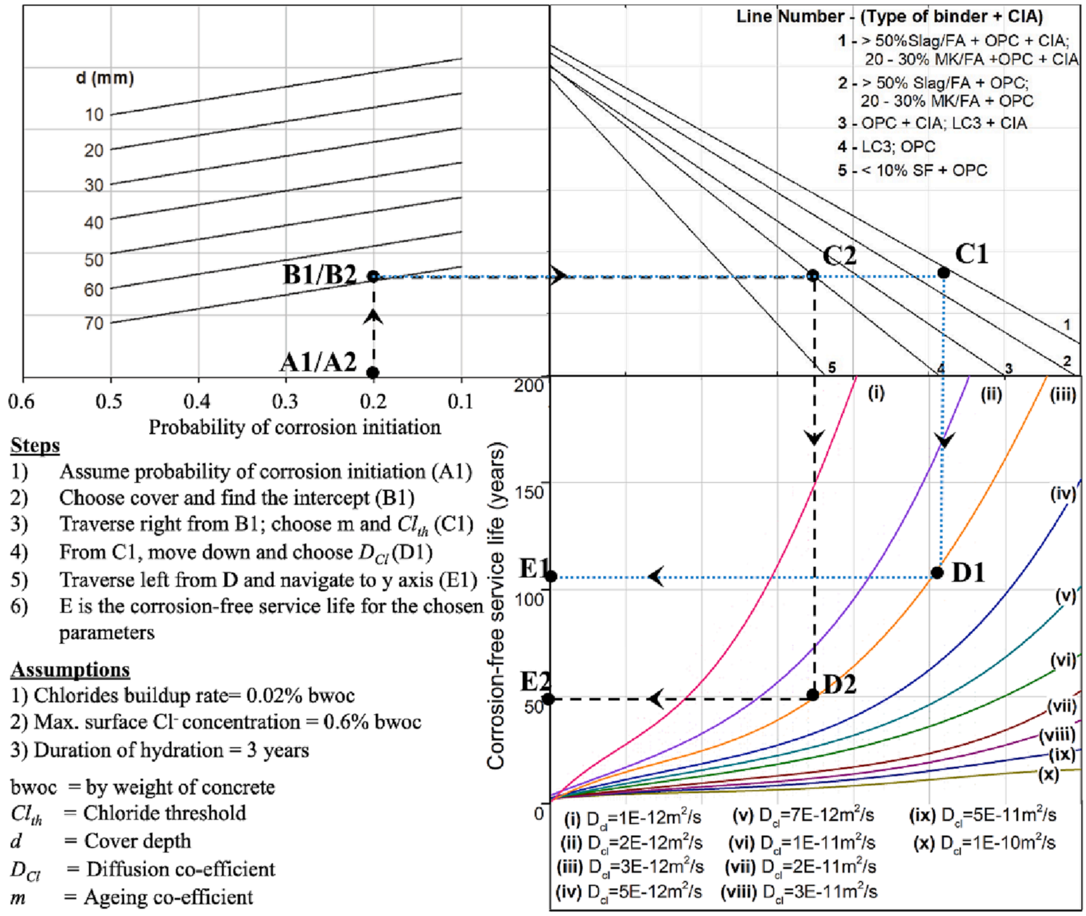

Fig. 8. Nomogram for estimating service life of RC elements located 1500 m away from the sea/ mild chloride exposure condition.

concerns that such an extended t_{CH} value may lead to an overestimation of the service life, as it does not account for the natural aging and deterioration processes that occur over time. Hence, In this paper, t_{CH} is considered as 3 years, which ensure a more cautious and realistic estimation for SCM-based concrete and aligns with the understanding that the aging and degradation of concrete structures should be considered as integral aspects of the overall service life estimation process.

3.3.3. Chloride binding (Cl_b)

The formation and stability of the bound chlorides are highly dependent on the composition of the binder (C_3A, C_4AF, and aluminate phases) and pH of the pore solution [57,58]. The chlorides present in the pore solution interact with the AF_m phases and aluminate phases of SCMs to form Friedel's salt ($3CaO.Al_2O_3.CaCl_2{\cdot}10H_2O$), Kuzel's salt ($3CaO{\cdot}Al_2O_3{\cdot}1/2CaSO_4{\cdot}1/2CaCl_2{\cdot}11H_2O$), etc. The binding of chlorides also happens in C-S-H, depending on the Ca/Si ratio. Chloride binding in silica fume concrete is less due to low Ca/Si and higher packing density of C-S-H. In contrast, chloride binding in concrete with SCMs, such as fly ash and slag, is high due to high Ca/Si in addition to the presence of alumina [44]. Martin-Perez et al. [59] and Lin et al. [60] showed that not considering the chloride binding phenomenon in the computation of D_{Cl} leads to a severe underestimation of service life, as only free chlorides participate in the corrosion initiation process. Only the ClinConc model accounts for the chloride binding factor during the calculation of D_{Cl}. Since chloride binding is highly dependent on the pH and the alumina content (type of SCM), and the method of determination is sophisticated, it is often neglected in service life modeling as done in this paper. While chloride binding is a significant aspect of concrete's resistance to chloride ingress, its exclusion from nomograms can be attributed to the challenges associated with quantifying and incorporating this mechanism into simplified prediction tools. In addition, the exclusion will also result in a conservative estimate of service life.

3.4. Chloride threshold (Cl_{th})

The chloride concentration required at the steel surface to initiate corrosion is defined as the chloride threshold. This is not a unique value and varies spatially, influenced by local conditions such as pH, voids, and microcracks [61]. In addition, it is also dependent on the type of steel, choice of mix design (binder type and w/b), presence of inhibitors and coatings, stress, and the exposure conditions [62]. Cl_{th} also varies due to the testing methodology adopted. The term 'chloride threshold' is not yet clearly defined and no generally accepted test method exists (RILEM TC 235-CTC [63]). Researchers are still trying to standardize the test procedure for determining the Cl_{th}. Hence, there is a huge variation in the Cl_{th} values reported in the literature [64–66]. Angst [67] showed that because of this variation in Cl_{th}, the time to corrosion initiation also fluctuates leading to large difference in the estimated service life.

Despite these variations, for practical considerations, it is safe to assume Cl_{th} as 0.4% by weight of binder for OPC [68] and a reduction in Cl_{th} value when blended cement is used based on their composition and replacement level [4,68,69]. For instance, Hansson and Poursaee (1990) reported that the addition of 10% silica fume decreases the Cl_{th} to 1/3rd as that of OPC [68]. Similarly, addition of slag (>50%) reduces Cl_{th} by 45% when compared to OPC [69]. On the other hand, presence of coatings and inhibitors can enhance the Cl_{th} as much as 50% [70–72]. Based on this information, Cl_{th} used to generate the nomograms were derived and are presented in Table 8. It is to be noted that Cl_{th} value is dependent on both steel and concrete, and steel here is considered as

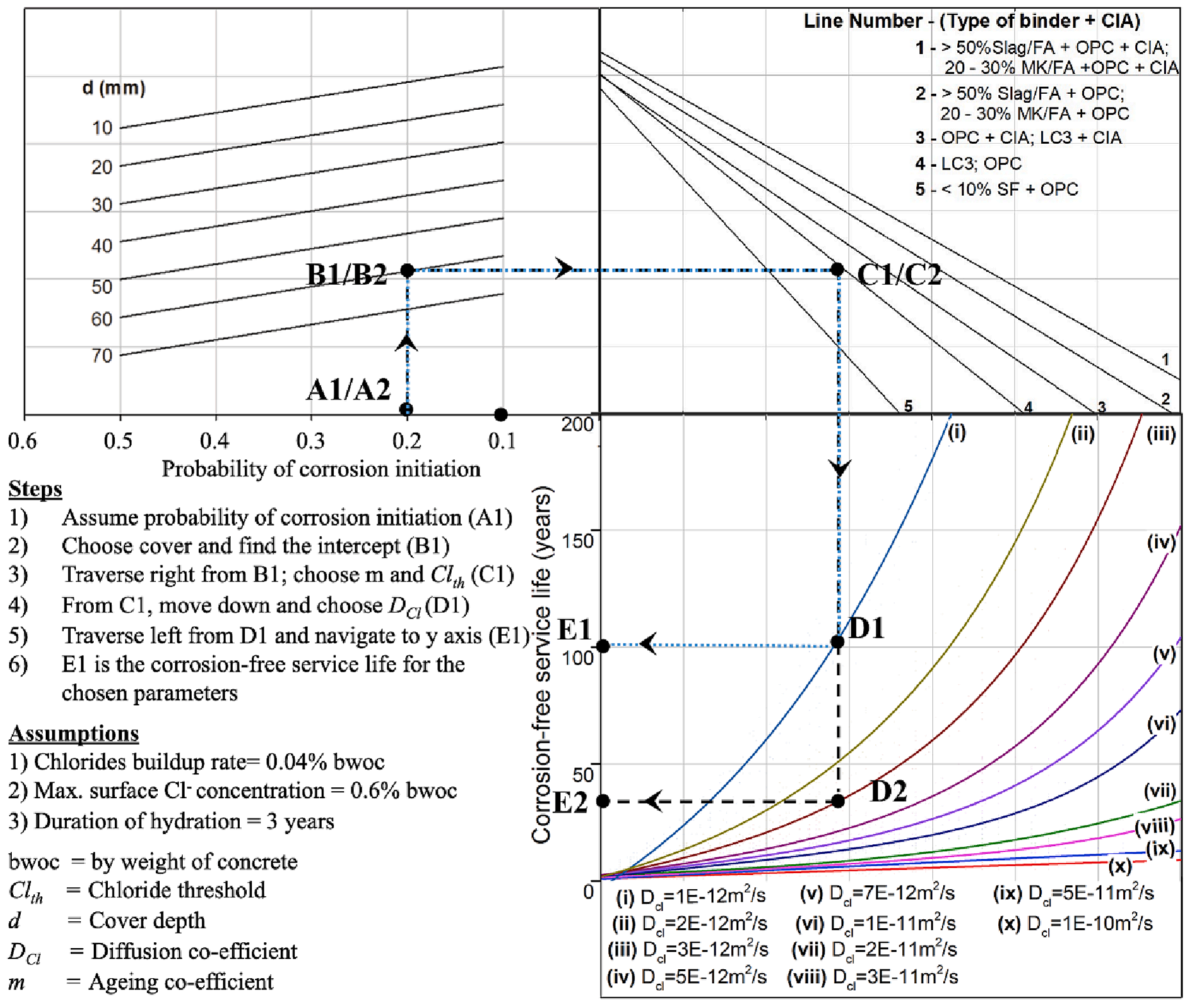

Fig. 9. Nomogram for estimating service life of RC elements located 800 m away from the sea/ moderate chloride exposure condition.

TMT steel by default. CIAs are included to reflect their influence on the Cl_{th} values. In addition, the combination of SCM and CIAs are also included to mitigate the effect of Cl_{th} reduction due to their partial replacement of OPC as described earlier. Table 9 shows the probability distribution of Cl_{th} reported in the literature. A log-normal distribution with a standard deviation of 40% can be assumed (chloride induced corrosion is stochastic in nature and such higher variations are expected) for the calculation of service life in the absence of data.

4. Computer program and nomograms

To develop a user-friendly tool for the materials including new age low carbon materials, it was decided to develop a new MATLAB program based on Fick's 2nd Law of Diffusion. The intention behind developing the MATLAB program is to provide a complementary tool that can account for the higher values of m and offer a comprehensive analysis of service life estimation, specifically tailored to the characteristics and behavior of novel concrete systems. This program is then used to generate nomograms (like design charts) for easy understanding and implementation of service life with new materials.

4.1. SL_Chlor model for service life estimation

SL_Chlor, a MATLAB program was written to estimate the service life using the solution (Eq. (1)) of Fick's 2nd Law of Diffusion considering one-dimensional chloride ingress and constant values of Cl_s. The estimated service life was validated against Life 365 results for values of m less than 0.6. This program considers the following parameters to estimate service life: d, D_{Cl}, m, t_{CH}, Cl_{th}, and Cl_s. Then, by simulation, the probability of corrosion initiation at any time can be determined. Fig. 6 shows the flowchart and the step-by-step procedure for estimating the service life. When the chloride concentration at the depth, $x = d$, and time, t [i.e., $Cl(d, t)$] exceeds the Cl_{th}, the system indicates the end of its service life. D_{Cl} depends on the type of binder/concrete and decreases due to the continued hydration over time. This is accounted for by the ageing coefficient, m, as in the Eq. (2). The surface chloride concentration, Cl_s, at the beginning can be considered as zero and increase is taken to following the build-up rate, k, (as per Life–365^{TM}) until a maximum value Cl_s, which depends on the exposure condition and the pore structure of surface concrete. The details of the steps are given in Fig. 6.

Step 1: Obtain all the input parameters needed to compute chloride content at the surface of steel.

The statistical distribution of the input parameters d, D_{Cl} at 28 days, Cl_{th}, m, Cl_s and the exposure condition is obtained. Table 10 gives the typical values and test methods to determine the input parameters. The maximum service life is taken as 200 years, k as per Life-365^{TM} and duration of complete hydration of concrete (t_{CH}) as 3 years.

Step 2: Generate 1000 random numbers for d, D_{Cl} and Cl_{th}. [Note: these are the most critical random variables].

Step 3: Calculate Cl_s (see Fig. 7(a) for the steps involved) for each year using the build-up rate k for the given exposure condition until it attains the maximum Cl_s. Once Cl_s is attained, the value remains unchanged for the rest of the service life.

Step 4: Calculate D_{Cl} (see Fig. 7(b) for the steps). For each of the

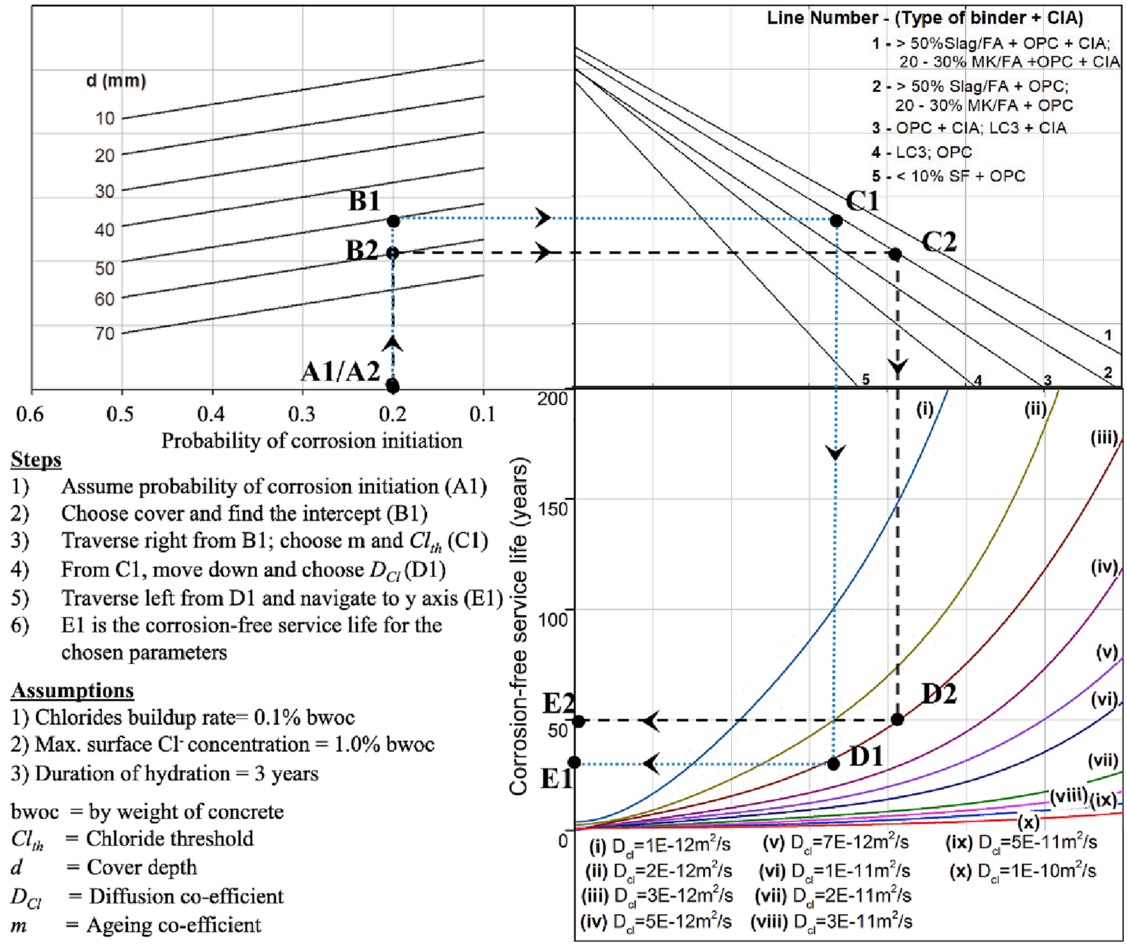

Fig. 10. Nomogram for estimating service life of structures located in the spray zone/ severe chloride exposure condition.

1000 simulations, D_{Cl} profiles are generated considering the Eq. (2). As discussed earlier, D_{Cl} of a particular type of concrete is not constant and evolves over a period, depending on factors such as internal temperature, internal humidity, type of blended cement, stress, etc. However, the present work considers the change in D_{Cl} as a function of time and assumes it to be constant after t_{CH} (3 years).

Step 5: Calculate the chloride concentration at the steel surface (see Fig. 7(c) for the steps involved). For each time step (every year), the chloride concentration at the steel surface is calculated using the error function (Eq. (1)) considering the 1000 random numbers generated for d and D_{Cl} calculated for that year, see Step 4.

Step 6: Compare the chloride concentration at the steel surface with Cl_{th}. The chloride concentration estimated for each time step is compared against 1000 random numbers generated in Step 1.

Step 7: Calculate the probability of corrosion initiation at every time step (see Fig. 7(d)). The number of instances of failure (i.e., $Cl_x \geq Cl_{th}$) at every time step is used to calculate the probability of corrosion initiation.

Step 8: Compute the cumulative distribution function (CDF). The service life is taken as the time at which the probability of corrosion initiation exceeds the acceptable probability of failure (to be decided by the user).

4.2. Nomograms for service life estimation

Designers are required to adhere to prescribed provisions in the code, which include specifying the minimum required cover depth based on the anticipated exposure conditions. Additionally, contract documents may also stipulate the desired service life of the structure. To accommodate these important considerations, the nomogram presented in this study has been specifically designed to provide flexibility to the designer.

Based on the database generated using the SL-Chlor models, a set of nomograms were developed, which offers the freedom to choose materials based on either the mandated cover depth or the desired service life. This allows the designer to make informed decisions and select appropriate materials that align with the specific requirements and objectives of the project. The scope of these nomograms includes 10 to 70 mm cover depth, D_{Cl} ranging from 10^{-12} to 10^{-10} m^2/s and various types of concrete. The structural requirements, such as the grade of concrete, and the durability requirements, such as d and w/b, vary depending on the exposure conditions. Hence, the nomograms were designed for four critical chloride exposure conditions, namely (i) 1500 m away from the seashore (Fig. 8), which gives a mild exposure condition, (ii) 800 m away from the seashore (Fig. 9), which gives a moderate exposure condition, (iii) spray zone (Fig. 10), which gives a severe exposure condition, and (iv) splash zone (Fig. 11), which gives an extreme exposure condition. For the durability requirements, the minimum d required for the exposure condition and w/b specified in the codes can be considered. For the chosen concrete, properties such as m and Cl_{th} can be determined either in laboratory or from literature. Table 8 gives the values of m and Cl_{th} for various binders upon which the straight lines (1–5 mentioned in Table 11) in Quadrant C of the nomogram were developed. It is important to note that the lines were derived through a best-fit analysis of various combination points of m (ageing coefficient) and Cl_{th} (threshold chloride concentration) that depend on the specific combination of binder and steel and steel here is considered as TMT steel by default. The intention behind combining different binders

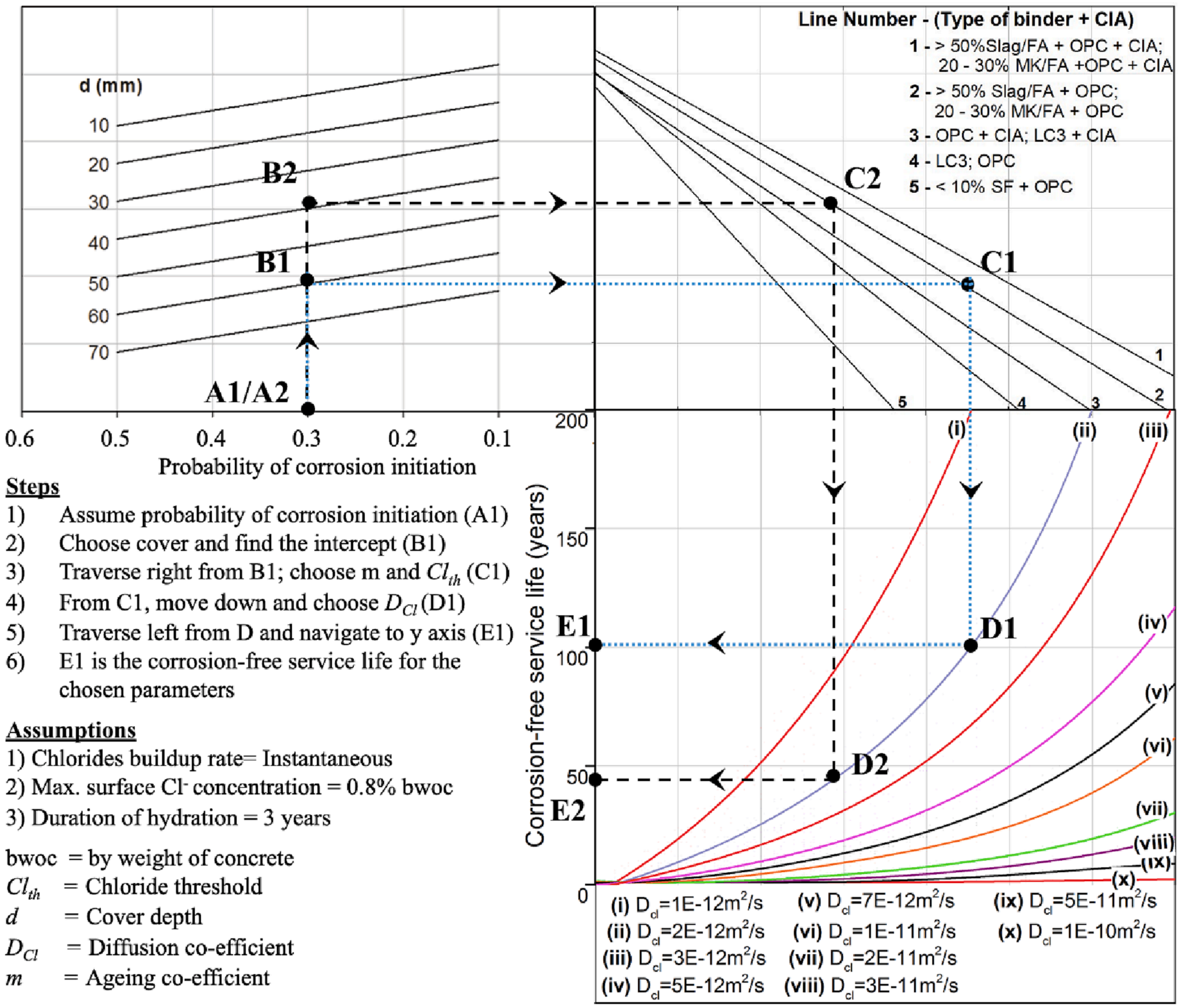

Fig. 11. Nomogram for estimating service life of structures located in the splash zone/ extreme chloride exposure condition.

Table 11
Identification of various type of steel–concrete systems in the nomogram.

Line number to identify Point C.	Ingredients of concrete
1	> 50 %Slag/Fly ash + OPC + CIA
	20–30% Metakaolin/Fly ash + OPC + CIA
2	> 50% Slag/Fly ash + OPC
	20–30% Metakaolin/Fly ash + OPC
3	OPC + CIA
	LC3 + CIA
4	OPC
	LC3
5	< 10% Silica fume + OPC

CIA – Corrosion inhibiting admixture; OPC – Ordinary Portland cement.

is not to emphasize their equivalence but to assess their respective performance and suitability in chloride resistance ultimately leading to the estimation of service life. The D_{Cl} values can be determined either by migration tests (after converting migration to diffusion) or by bulk diffusion tests.

The nomogram can be easily used to estimate the service life of a structural element with the chosen parameters. For example, if the design office fixes the probability of corrosion initiation as 0.2 (A1) and d as 70 mm (B1), two choices of concrete can be made to achieve the desired service life of 100 years. Either, the type of binder at C1 or C2 with the same D_{Cl} (3×10^{-12} m^2/s) can be chosen as in Fig. 8 or D_{Cl} of concrete can be lowered with appropriate mix design as in Fig. 9 to extend the service life.

4.3. Influence of input parameters

Assume probability of corrosion as 0.2, d *as* 40 mm, Line 4 in quadrant C (m as 0.4 and Cl_{th} as 0.067 %by weight of concrete) and D_{Cl} as 5×10^{-12} m^2/s as base values. From the nomogram, the corrosion-free service life is estimated to be 18 years. An increase in cover depth d of 50% keeping all other parameters same increases the service life from 18 years to about 28 years. But this effect of cover will be realized only when the quality is assured. Now, assume a decrease in D_{Cl} by 50% keeping all the initial parameters constant, which gives a service life of about 26 years. Instead of d and D_{Cl}, if m is increased from 0.4 to 0.6 (Line 2 in quadrant C), then the service life is estimated at about 24 years. It can be inferred from the nomograms that extended service life of structures can be achieved with the appropriate choice of concrete mix design (binder type and w/b). The effect of cover depth is also accentuated when appropriate concrete is used. Instead of concrete, if we increase the service life by protecting the steel, the scenario is different. For instance, if Cl_{th} is increased from 0.067 %bwoc to 0.1 % bwoc (Line 3 in quadrant C), then the service life is estimated at about 20 years. Hence, the order of influence is $d > D_{Cl} > m > Cl_{th}$, which explains the reason for longer service life in case of SCM based concrete despite having lower Cl_{th} in such cases. Even though the influence of steel (Cl_{th}) does not have the same effect compared to the choice of concrete, a fine balance is necessary in order to achieve the desired service life. Blended cement with lower D_{Cl} has a synergistic effect between *d*, *m*, Cl_{th} and D_{Cl} which improves the overall beneficial outcome of ensuring the durability of concrete structures. The results also encourage the use of alternative materials which help to achieve reduced emissions and specify performance parameters for quality control in the field.

4.4. Mx-Dy concrete

Nowadays, it is proven that the concrete compressive strength specified as Mx (grade of concrete) does not directly translate into high durability [75]. Also, the prescriptive approach with deemed to satisfy requirements does not necessarily enhance the service life of reinforced concrete structures. Hence, globally, researchers are recommending a performance-based approach and specifications for civil infrastructure [76]. However, globally the concrete industry still procures concrete mixes specifying compressive strength (Mx) alone. This study, therefore, emphasizes the need to specify a durability indicator in terms of diffusion coefficient D_{Cl} (Dy) while procuring concrete, to delay the onset of corrosion. As the first step in achieving the desired service life against chloride-induced corrosion, performance-based specification "Mx-Dy" is recommended for concrete instead of Mx alone. Since cover depth (*d* is the greatest influencing parameter, this Mx-Dy specification will be useful only when the "3Cs" – cover depth, compaction, and curing are provided adequately. This can be achieved by providing cover blocks and proper placement of formwork to ensure cover depth; by avoiding the congestion of reinforcement or using self-compacting concrete to ensure proper compaction; and by providing evaporation barriers or shields and using curing compounds or adequate water curing to ensure proper curing at site conditions. Meeting 3C requirements should be enforced by specifying measurable parameters reflecting quality, and reward and penalty clauses can be introduced in the contract documents to encourage good site practices. Additionally, we recommend that the contract documents include an obligation to create a database with the details of design parameters such as concrete mix design and cover and performance specifications such as D_{Cl}. This should involve all the stakeholders including the owner, the contractor, the subcontractor, and the consultant with the quality control personnel. This database can act as an invaluable resource for adopting good practices, learning from failures, assuring maintenance-free service life and can be an input to improvise the industry standards. Such an approach will help to achieve the desired corrosion-free service life for reinforced concrete structures.

5. Conclusions

A set of nomograms (durability design charts) has been developed to help on-site engineers to work within the constraints to achieve the best possible combination of design and material parameters to ensure a longer service life. The following conclusions can be drawn from the nomograms.

1. The order of influence of the parameters affecting service life is cover depth (*d*) > diffusion coefficient (D_{Cl}) > ageing cofficient (*m*) > chloride threshold (Cl_{th}). Providing 3Cs can help to achieve material potential and enhance the service life. To reduce high maintenance and repair costs, providing good site practices is the only recommended solution.
2. The choice of mix proportioning targeting reduced D_{Cl} is the most efficient option apart from increasing the cover depth (*d*).
3. A low D_{Cl} accentuates the effect of *d* and ageing coefficient (*m*) and compensates for the low chloride threshold (Cl_{th}) in case of blended cement and thus increases the service life. The synergistic effect of *d*, D_{Cl}, *m*, and Cl_{th} in the blended cement leads to longer service life.

It is therefore strongly recommended to use Mx-Dy, in the specifications of concrete where Mx and Dy represent characteristic compressive strength and target D_{Cl}, respectively. In addition, creation of a database with all the key parameters considered during construction is recommended for future maintenance and improvising the standards.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Radhakrishna G. Pillai reports financial support was provided by Indian Institute of Technology Madras. Radhakrishna G. Pillai reports a relationship with Indian Institute of Technology Madras that includes: employment and funding grants. Ravindra Gettu reports a relationship with Indian Institute of Technology Madras that includes: employment and funding grants.

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