

HISTORY AND DEVELOPMENT OF PREDICTION MODELS OF TIME-TO-INITIATE-CORROSION IN REINFORCED CONCRETE STRUCTURES IN MARINE ENVIRONMENT

Norbert S. Que¹

Institute of Civil Engineering, University of the Philippines Diliman

ABSTRACT

This paper presents the history and development of mathematical models for the prediction of time to initiate corrosion of reinforced concrete exposed to chlorides in marine environment. Emphasis is given to prediction models (empirical and mathematical) that consider Fick's 2nd law of diffusion as the theoretical basis. Since repair and rehabilitation of corroded reinforced concrete marine structures draw significant portion of the budget for infrastructures, the capability to accurately predict deterioration levels due to chloride attack, especially the time-to-initiate corrosion, in reinforced concrete structures exposed to chloride-induced corrosion can translate to major economic savings and possible extension of service life of a member or a structure.

Keywords : Chloride, Marine Environment, Fick's 2nd Law, Reinforced Concrete, Corrosion

1. INTRODUCTION

A reinforced concrete structure exposed to water containing soluble salt (e.g. NaCl) imposes high risk of penetration of ions (in this case chloride Cl⁻ and Sodium Na⁺) into concrete (HETEK, 1997a). Chloride ion penetration is a major concern on durability issues and service life design of reinforced concrete structures in the marine environment. Among structures vulnerable to chloride attack include ports, bridges and other marine infrastructures. The economic importance played by these structures demands careful attention in the study of chloride ion penetration phenomena so as to minimize its damaging effects and extend the service life of these important structures.

The penetration of chloride ions into the concrete material is through a system of capillary pores dominated mainly by diffusion and capillary absorption. When the amount of chloride deposited onto the surface of the reinforcing bar reaches a critical value between 0.2% and 0.6% by weight of cement, corrosion process is assumed to start. The time elapse from the construction of the structure up to this point is referred to as the time to initiate corrosion.

*Correspondence to: Institute of Civil Engineering, University of the Philippines Diliman, Quezon City 1101 PHILIPPINES. email:cunedizon@yahoo.com

Corrosion of steel reinforcing bars is generally accepted as electrochemical in nature. The naturally occurring alkaline environment in concrete forms a thin passive film around the surface of reinforcing steel bars which serves as a barrier against carbonation induced corrosion and chloride induced corrosion. For marine exposed structures, the gradual penetration of chloride ions into the concrete structure will eventually lead to the weakening of the passive film where depassivation process starts. Figure 1 illustrates a chloride induced corrosion process.

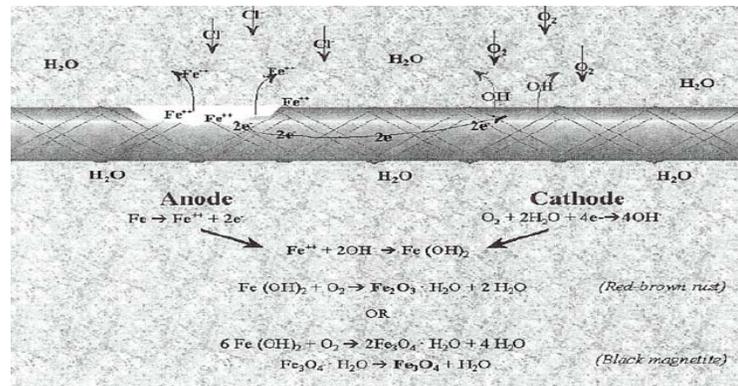


Fig. 1. Chloride induced corrosion process (Keller 2004)

A notch-like shape corrosion that affects rebar locally is formed after the passive film is destroyed by the penetration of chloride ions. The expansion of rust around the reinforcing bar will cause cracking and spalling of concrete. Service life of a structure is often equated when cracking due to corrosion occurs.

A conceptual model for service life prediction of corroded reinforced concrete structure as developed by Tuutti (1980) is shown in Figure 2. As the figure shows, there are two distinct stages in the evolution of deterioration caused by chloride corrosion. The first is the initiation period at which the chloride threshold value is reached at the concrete-steel interface to activate corrosion. The second is the propagation period which represents the period between corrosion initiation and cracking of concrete.

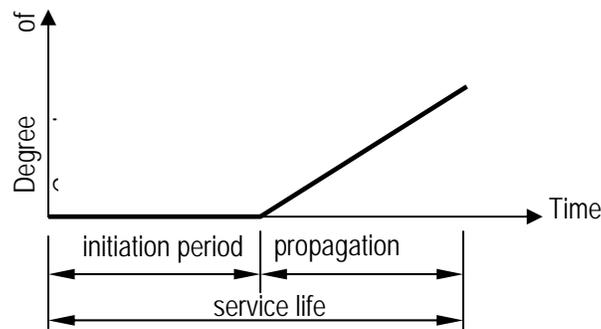


Fig 2. Tuutti (1980) service life model of corroded structures

When cracking occurs, formation of rust oxide accelerates growing to a sufficient size affecting the stress-strain property of the steel on the corroding site and the near vicinity (HETEK, 1997a). Based on corrosion theories, when only 8% of the approximate area has corroded, the steel can no longer be treated as linear-elastic, ideal plastic material.

Progressing corrosion will continue to consume the affected steel area reducing the area of the steel section until it reaches a critical level where it may no longer be able to resist loads as required by design. This may cause the structure or a structural member to act in ductile manner since the steel strength capacity has been significantly reduced. It may even be more threatening if the affected area is a critical section of a structural member.

Inspection of reinforced concrete structures in marine environment is important. The use of NDT techniques in combination with coring may enable one to detect the early onset of corrosion where appropriate steps may be taken to slow down the corrosion process. Such inspection procedures, however, are quite costly as they require experts to conduct the tests and interpret the results.

To wait for the appearance of visible signs of corrosion in a structure such as rust stains and/or cracks before repair will be conducted is not cost effective. The presence of such visible signs is indicative of an advanced stage of corrosion which may require a thorough investigation of the entire structure in order to properly assess the type of repair or rehabilitation needed for the corroded structure.

The use of prediction models, specifically, the time to initiate corrosion can provide useful information regarding the early onset of corrosion which allows one to appropriately schedule the required maintenance.

2. PREDICTION MODELS

2.1 Fick's 2nd Law of Diffusion

Most of the existing mathematical models on the diffusion of chloride into concrete that predict chloride concentration as functions of time and depth, and time to initiate corrosion are based on Fick's 2nd law of diffusion. The differential equation is expressed as

$$\frac{\partial C}{\partial t} = D * \frac{\partial^2 C}{\partial x^2} \quad (1)$$

In this expression, only four parameters are involved, namely, C for chloride concentration, D for diffusion coefficient, x for depth referred from the concrete surface, and time t .

Solution to this one-dimensional diffusion problem depends on boundary conditions and certain simplifying assumptions. Those who first attempted to create a model based on equation (1), to simplify an inherently difficult problem, assumed that the diffusion parameter and the surface chloride content C_s are constants. The following boundary and initial conditions are specified as:

$$C(x, t) = 0, \quad x > 0, \quad t = 0$$

2.2 Constant Chloride Diffusivity Case

Many authors came up with the general solution below considering constant diffusivity. With C_{sa} & D treated as constants, Fick's 2nd law described by (1) leads to the following solution:

$$C(x, t) = C_i + (C_{sa} - C_i) \operatorname{erfc} \left(\frac{x}{\sqrt{4(t - t_{ex}) D_a}} \right) \quad (2a)$$

where:

$C(x, t)$ = chloride concentration at any time t and depth x

C_i = initial chloride concentration (constant thru depth).

C_{sa} = chloride concentration at concrete surface (constant)

D_a = apparent diffusion coefficient (constant)

x = depth referred from surface

t = time of inspection / time in consideration

If the initial surface chloride concentration is zero, then Equation (2a) can be rewritten as:

$$C(x, t) = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right] \quad (2b)$$

$$C(x, t) = C_s \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{Dt}} \right) \right] \quad (2c)$$

Equation (2b) (Zhang, J.Y. and Lounis, Z., 2006) is famously known as the error function solution and is widely referred to by journals and books. Equation (2c) is just another form of equation (2b) using the error-function complement.

From this solution, considering constant diffusivity, the depth of chloride ingress and time to initiate corrosion can be evaluated or derived. Authors who have proposed prediction models of this case are Collepardi, *et. al.* (1972), Tuutti (1982), Browne (1980), and Poulsen (1990).

It had been shown, however, that models based on the assumption that chloride diffusivity is constant had exhibited gross errors. Experts found that this concept's applicability is limited to old structures and concrete samples with very long exposure time. This is due to the fact that at significantly longer chloride exposure, concrete's chloride diffusivity exhibits a constant behavior.

2.3 Time-Dependent Chloride Diffusivity

Laboratory tests & field experiments had established that chloride ingress into concrete is time dependent. Diffusion of chloride into concrete decreases with time and this behavior can be mathematically captured using a power function equation. Since the amount of

chloride at any depth x of the structure depends on the diffusion rate, the concentration of chloride also varies with time. It was found out that chloride concentration increases with the increased exposure of a reinforced concrete member to a chloride-rich environment. In light of the observations from laboratory tests and field experiments, a more realistic model to predict chloride ingress into concrete was formulated which takes into account the time dependence of chloride diffusivity.

Poulsen (1993) derived an expression for a time-dependent diffusion coefficient (D_a) as,

$$D_a = \frac{1}{t} \int_0^t D(\tau) d\tau \quad (3)$$

It should be noted the D_a is not the true diffusion coefficient.

Through the years, researchers had come to formulate varying expressions for the apparent diffusion coefficient. A power function for D_a , however, became widely used and expressed generically as:

$$D_a = D_o \left(\frac{t_o}{t} \right)^a \quad (4)$$

Where D_o is the diffusion coefficient at time t_o and a is an aging factor.

Mangat and Molloy (1994) proposed an expression in the form of equation (4) given by:

$$D_a = D_1 t^{-m} \quad (5)$$

where D_a is the diffusion coefficient after exposure time t , D_1 is the diffusion coefficient at one year, if t is expressed in year, and m is a material constant. The material constant m may be estimated as a function of the the water-cement ratio as:

$$2.5 w/c - 0.6 \quad (6)$$

Takewaka and Mastumoto (1988) and Maage, *et. al.* (1993) used a variation of the equation presented in (4) to model to the time dependence of the diffusion coefficient expressed as:

$$D_a = D_{aex} \left(\frac{t}{t_{ex}} \right)^\alpha \quad (7)$$

where D_{aex} is the apparent diffusion coefficient at the time of first exposure, t_{ex} is the time of first exposure and α is an aging factor. For ordinary concrete with $0.25 \leq w/c < 0.60$, one may use Poulsen's (HETEK, 1997b) proposed expression for α given by:

$$\alpha = \exp\left[-\left(\frac{(w/c)^2}{0.19}\right)\right] + 0.1 \times \exp\left[-\left(\frac{0.1}{w/c}\right)^{2.5}\right] \quad (8)$$

The time dependency of chloride diffusion coefficient is considered to be the effect of a complex physical phenomenon during chloride ingress and the varying intensity of chloride exposure environment (HETEK, 1996; HETEK, 1997b).

It is not only the diffusion coefficient that varies with time. Surface chloride concentration is also claimed to vary with time. Uji *et al.* (1990), among other researchers suggested that the surface chloride concentration should be proportional to the square root of time expressed as:

$$C_{sa}(t) = S_1 t^{0.5} \quad (9)$$

where:

S_1 = surface chloride concentration after year 1 of exposure
 t = time of exposure (years)

To satisfy the boundary conditions, equation (9) was re-written as:

$$\begin{aligned} C_{sa} &= C_i \quad \text{for } 0 \leq t \leq t_{ex} \\ &= C_i + S_1 \sqrt{t_{in} - t_{ex}} \quad \text{for } t \geq t_{ex} \end{aligned} \quad (10)$$

where:

C_i = equally distributed initial concentration of chloride
 t_{ex} = time of exposure
 t_{in} = time of inspection

It was highlighted in HETEK (1996) and HETEK (1997b) that in cases where C_{sa} is a function of time, the error function *erf* is not the solution of Fick's 2nd law. However, the error function is still widely used in practice to find C_{sa} & D_a from chloride profiles using regression analysis.

For special cases, a solution for Fick's 2nd law with chloride diffusivity as a function of time was presented in HETEK (1996). A solution was presented given that D_{ao} is constant, D_a is a function of time, and the chloride concentration, $C(x,t)$ is of the form

$$C_{sa}(t) = S_1 t^p \quad (11)$$

$$C(x,t) = S_1 t^p \Psi_p(z) \quad (12)$$

$$z = \frac{x}{\sqrt{4tD_{ao}}} \quad (13)$$

For $p = 0$, Equation (11) reduces to the basic and well-known error function solution, equation (2b). In general, with C_{sa} obeying the form of equation (9), Equation (11) can be expressed as:

$$C(x,t) = C_i + S_1 \sqrt{t - t_{ex}} (\exp(-z^2) - z \sqrt{\pi} \operatorname{erfc}(z)) \quad (14)$$

The Meijlbro function, Ψ_p , is defined as:

$$\Psi_p(z) = \sum_{n=0}^{\infty} \frac{p^n (2z)^{2n}}{(2n)!} - \frac{\Gamma(p+1)}{\Gamma(p+0.5)} \sum_{n=0}^{\infty} \frac{(p-0.5)^n (2z)^{2n+1}}{(2n+1)!} \quad (15)$$

A number of models for the prediction of time to initiate corrosion is summarized in Table 1. Time dependent diffusivity models are discussed in the following section.

3. TIME DEPENDENT DIFFUSIVITY MODELS TO PREDICT THE TIME-TO-INITIATE CORROSION

3.1 Anacta Model

Anacta (2009) proposed a model that computes for time-to-initiate corrosion. The model takes into account environmental factors such as temperature, rainfall and humidity. It also takes into account the influence of duration of exposure.

A model to compute for depth of chloride ingress was also formulated which was utilized in computing for the time-to-initiate corrosion. The expression to compute for the depth of chloride ingress model is:

$$x_c = 2 S \sqrt{D_c t} \quad (16)$$

Table 1. Time-to-initiate corrosion prediction models

Model	Equation	Basis	Remarks
<i>A. Constant Diffusivity Models</i>			
Bazant (1979)	$t_{ic} = \frac{x_c^2}{4D_c} \left[\operatorname{erf}^{-1} \left(1 - \frac{C_{cr}}{C_0} \right) \right]^{-2}$	Fick's 2nd law	One of the first model created.
Yamamoto (1995)	$t_{ic} = \frac{1}{D_c} \left[\frac{x_c}{2 \operatorname{erf}^{-1} (1 - C_{cr} / C_0)} \right]^2$	Fick's 2nd law	
Clear (1976)	$t_{ic} = \frac{129 \cdot x_c^{1.22}}{(w/c) \cdot [C_s]^{0.42}}$	Empirical	
<i>B. Time-Dependent Diffusivity Models</i>			
Anacta (2009)	$t_{ic} = \frac{f_s}{D_c} \left[\frac{x_c}{2S} \right]^2$	Fick's 2nd law	Considers local envi and mat'l impact.
Poulsen-Mejlbro (2006)	$t_{ic} = t_{ex} \times \left(\frac{0.5 x_c}{\sqrt{t_{ex} D_{aex}}} \right)^{\frac{2}{1-\alpha}} \times \left(\frac{1}{\operatorname{inv} \Lambda_p (y_{cr})} \right)^{\frac{2}{1-\alpha}}$	Fick's 2nd law	Hetek.
Tang-Nilsson (1992)	$Q_{i,j} (total) = Q_{i,j-1} (total) + \Delta Q_{i,j} (diff)$	Numerical	ClinConc / submerged

is a shape factor for depth of chloride ingress and α is an exponential constant obtained from curve fitting. The chloride diffusion coefficient, which is function of material and environmental parameters is given as:

$$D_c = D_{c, rmt} \times f_1(t) \times f_2(T) \times f_3(RH) \times f_4(R) \quad (18)$$

where $D_{c, rmt}$ is the reference chloride diffusion coefficient taken from the rapid migration test. The different factors f_i are defined as follows:

$$f_1(t) = k \left(\frac{t_{ref}}{t} \right)^n \quad (19)$$

$$f_2(T) = \exp \left[\frac{E}{G} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (20)$$

$$f_3(RH) = \left[1 + \frac{(1 - RH)^4}{(1 - RH_{ref})^4} \right] \quad (21)$$

$$f_4(R) = 1 - \left(\frac{R}{5000} \right)^{1.5} \quad (22)$$

where $f_1(t)$, $f_2(t)$, $f_3(t)$, and $f_4(t)$ are factors representing the influence of duration of exposure, influence of temperature, influence of relative humidity, and influence of rainfall, respectively.

To determine the time at which chloride ions will reach the depth of the reinforcing bars, equation (16) is used where the depth of chloride ingress is set equal to the concrete cover depth. The computed time, t , will be used to calculate the shape factor (S) and the diffusion coefficient (D_c) which is one of the parameters in computing for the time-to-initiate corrosion.

$$t_{ic} = \frac{f_s}{D_c} \left[\frac{x_c}{2S} \right]^2 \quad (23)$$

$$f_s = 0.316 \xi \sqrt{t_{ic,ref}} \quad (24)$$

where:

- t_{ic} = time to initiate corrosion (years)
- $t_{ic,ref}$ = reference time-to-initiate corrosion derived from laboratory experiments (days)
- x_c = concrete cover thickness (mm)
- f_s = reinforcement factor
- ξ = curve-fitting parameter due to effect of corrosion

The advantage of using Anacta's prediction model is the applicability of local data available for validation purposes which considers the influence of local environmental factors and materials.

The influences of local materials were indirectly considered in some of the parameters included in the model. The parameter α , which is used in computing for the shape factor S , is derived by curve-fitting the chloride ingress v.s. time curve. The chloride ingress v.s. time curve has been performed on materials of varying w/c ratio & fly ash content. Other parameters like k & n , used in calculating f_1 (age factor), were determined by curve fitting, thus, it reflects the influence of local materials on chloride ingress into concrete indirectly.

The procedure in predicting the time to initiate corrosion using this model basically involves 3 steps:

- (1) Equate equation (16) to a given concrete cover depth, x_c , and solve for t ,
- (2) The computed t will then be used to calculate for the shape factor, S , and diffusion coefficient using equations (17) & (18), respectively,
- (3) Once D_c is known, the time to initiate corrosion can then be computed using equation (23)

To be able to use this model, one must have the data for the following:

- (1) Rapid migration test (reference diffusion coefficient is obtained from this),
- (2) Plot of chloride ingress v.s. time (for determination of values of α), and
- (3) Environmental Data (rainfall & relative humidity can be taken from PAG-ASA)

However, this model has been limited to marine concrete or concrete samples exposed under the tidal zone environment. Study has yet to be done if the same model can be applied for marine concrete & concrete samples exposed under different exposure conditions. This could be a topic of research for future development of the model.

Since the Anacta model to predict the time-to-initiate corrosion is dependent on material and environmental factors, massive verification studies have to be carried out using both laboratory and field tests to validate the model. The prediction equations, due to the presence of curve fitting parameters such as α , k , and n are not expected to change in form as more tests will be conducted for validation.

3.2 Mejlbro-Poulsen (Hetek) Model

Mejlbro-Poulsen model is based on the assumption that the flow of chloride into concrete is proportional to the gradient of chloride concentration in the concrete, or basically the Fick's law. Its applicability assumes that the following conditions are met:

- D_a (apparent diffusion coefficient) is time-dependent
- C_{sa} (chloride concentration of the exposed surface) is time-dependent
- C_i initial chloride concentration is constant (independent of time & distance from surface)

The apparent diffusion coefficient considered for this model is assumed to have taken the form of a power function (7):

$$D_a(t) = D_{aex} \left(\frac{t_{ex}}{t} \right)^\alpha$$

Mejlbro has mathematically derived that the surface chloride concentration takes the following form:

$$C_{sa} = C_i + S[(t - t_{ex}) * D_a(t)]^p \quad (25)$$

With these two relationships, and the assumptions mentioned above, Mejlbro and Poulsen came up with the following prediction of chloride concentration at any time t and at any depth from the surface of concrete, expressed as:

$$C(x,t) = C_i + (C_{sa} - C_i) * \Psi_p \left(\frac{x}{\sqrt{4(t - t_{ex})D_a(t)}} \right) \quad (26)$$

where:

- $C(x,t)$ = chloride concentration at any depth and time
 C_i = initial chloride concentration
 C_{sa} = achieved surface chloride concentration
 $D_a(t)$ = achieved diffusion coefficient (function of time)
 t_{ex} = time of first exposure to chlorides
 t = time of inspection
 Ψ_p = Mejlbro function, as described by equation (15)

Vast studies conducted by Hetek Group enabled them to come up with tables and factors to determine the decisive parameters used in the prediction model. These include the parameters D_{aex} , α , S_p , p which are expressed in terms of diffusion coefficient at year 1 & year 100, and chloride concentrations at year 1 & year 100.

The procedure in using the Mejlbro-Poulsen's model (Hetek, 1997b) involves:

- (1) The determination of year 1 & year 100 diffusion coefficients and chloride concentrations
- (2) D_1 & D_{100} parameters are then used to solve for the decisive parameters
- (3) Once the decisive parameters are known, D_a & C_{sa} can be determined
- (4) D_a & C_{sa} will then be substituted to equation (26) to predict chloride concentration at any time & depth

To predict the time to initiate corrosion, when the decisive parameters are known, equation (26) has to be re-written as follows;

$$C(x,t) = C_i + S_p \times \left(\frac{0.5x}{\sqrt{t_{ex} D_{aex}}} \right)^{2p} \Lambda_p(z) \quad (27)$$

$$C(x,t) = C_i + S_p \times z^{2p} \times \Lambda_p(z) \quad (28)$$

where:

$$\Lambda_p(z) = \frac{\Psi_p(z)}{z^{2p}} \quad (29)$$

$$z = \frac{0.5x}{\sqrt{\tau \times t_{ex} D_{aex}}} \quad (30)$$

Equating $x = x_c$ (i.e. making the depth equal to the cover depth), the initiation time can then be solved by the following steps:

$$C_{cr} = C_i + S_p \times \left(\frac{0.5x_c}{\sqrt{t_{ex} D_{aex}}} \right)^{2p} \Lambda_p(z_{cr}) \quad (31)$$

$$z_{cr} = \frac{0.5c}{\sqrt{\tau_{cr} \times t_{ex} D_{aex}}} \quad (32)$$

$$\tau_{cr} = \left(\frac{t_{cr}}{t_{ex}} \right)^{1-\alpha} - \left(\frac{t_{ex}}{t_{cr}} \right)^{\alpha} \cong \left(\frac{t_{cr}}{t_{ex}} \right)^{1-\alpha} \quad (33)$$

$$z_{cr} = \text{inv}\Lambda_p(y_{cr}) \quad (34)$$

$$y_{cr} = \frac{C_r - C_i}{S_p} \times \left(\frac{\sqrt{t_{ex} D_{aex}}}{0.5c} \right)^{2p} \quad (35)$$

$$t_{ic} = t_{ex} \times \left(\frac{0.5c}{\sqrt{t_{ex} D_{aex}} \times \text{inv}\Lambda_p(y_{cr})} \right)^{\frac{2}{1-\alpha}} \quad (36)$$

Equation (36) is the time to initiate corrosion equation and is measured from the time of mixing. Note that the above derivation has been shown in Hetek Report No. 83 (Hetek, 1997b).

The highlight of Hetek Model is its applicability for three different exposure types, namely, submerged, splash & atmospheric. Calculation of time-to-initiate corrosion can also be performed using a diagram method Hetek (1996) since tables and graphs obtained from studies are available. However, these tables, graphs, and even, the tabulated efficiency factors (used in computing for D_1 & D_{100} parameters) were localized and highly dependent on the experiment performed by Hetek. Its application here in the Philippines has yet to be verified.

3.3 Tang/ ClinConc Model

This corrosion prediction model has been developed by Tang (1996, 2007, 2008) utilizing the concept of finite-difference numerical method. Among the highlights of this prediction model is its use of experimental data as input thus, limiting the reliance of prediction to various curve-fitting procedures employed by other models.

However, the model is hampered by its limitation to be applicable only for structures exposed to chloride under submerged setting (it models only the pure diffusion of chloride transport into concrete).

Basically, the prediction equation is expressed as:

$$Q_{i,j}(\text{total}) = Q_{i,j-1}(\text{total}) + \Delta Q_{i,j}(\text{diff}) \quad (37)$$

$$\Delta Q_{i,j}(\text{diff}) = A_{i,j}(\text{diff}) * D_{i,j} \left[\frac{c_{i-1,j-1} - 2c_{i,j-1} + c_{i+1,j-1}}{\Delta x^2} \right] \Delta t_j \quad (38)$$

$$A(\text{diff}) = \varepsilon_{\text{capillary}} = 1 - \sum \frac{m}{\rho} - 0.75W_n - \varepsilon_{\text{air}} \quad (39)$$

$$D_{i,j}(\text{Cl}) = D_o(@T_o) f_D(T_j) g(t_j) f(x_i) \quad (40)$$

$$D_o(@T_o) = D_{CTH}(@T_o) \left(1 + K_b \frac{W_{\text{gel}}}{\varepsilon} \right) \quad (41)$$

$$f_D(T) = \frac{D_o}{D_o(@T_o)} = e^{\frac{E_D}{R} \left(\frac{1}{T_o} - \frac{1}{T} \right)} \quad (42)$$

$$g(t) = \left(\frac{t_o}{t} \right)^{\beta_t} \quad \text{if } t < t_o \quad (43)$$

$$= 1 \quad \text{if } t \geq t_o$$

$$f(x) = \varphi + (1 - \varphi) \left(\frac{x}{x_s} \right)^{\beta_x} \quad \text{if } x < x_s \quad (44)$$

$$= 1 \quad \text{if } x \geq x_s$$

As we can see from above set of expressions, the required parameters for equations (37) and (38) are all given and can be obtained mathematically (or experimentally). Only the expressions for $c_{i,j}$ are not provided. Similar to other finite difference calculations, this has to be computed progressively with the initial values obtained from initial & boundary conditions.

The computed total chloride concentration above based on ClinConc model can also be decomposed into “free” and “bound” chlorides part. Tang & Nilsson (1992) utilized the concept of mass-balance equation to decompose total chlorides into parts.

4. CONCLUSION

As we can see from above set of expressions, the required parameters for equations (37) and (38) are all given and can be obtained mathematically (or experimentally). Only the expressions for $c_{i,j}$ are not provided. Similar to other finite difference calculations, this has to be computed progressively with the initial values obtained from initial & boundary conditions.

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ACKNOWLEDGMENT

The author would like to acknowledge the Engineering Research and Development for Technology - Department of Science and Technology (ERDT-DOST) for funding the research under the Environment and Infrastructure Track of the ERDT program. He would also like to acknowledge his research assistants, namely, Mr. Richard de Jesus and Mr. Rogers Perdiguerra.

APPENDIX

Definition of Terms

α	= exponential constant determined from curve-fitting
$C(x,t)$	= chloride concentration at any depth and time
C_{cr}	= critical chloride concentration (chloride threshold value)
C_i	= initial chloride concentration (assumed to be equally distributed thru depth)
C_o	= initial chloride concentration
C_s	= surface chloride concentration
C_{sa}	= achieved surface chloride concentration
$D_a(t)$	= achieved diffusion coefficient (function of time)
D_{aex}	= apparent diffusion coefficient at time of 1 st exposure to chlorides
D_c	= diffusion coefficient
$D_{c,mt}$	= reference cl diffusion coefficient (from migration test)
D_i	= effective diffusion coefficient at $t = 1$ sec
E	= activation energy of cl diffusion process (kJ/mol) (~10 to 50 kJ/mol)
	= curve-fitting parameter due to effect of corrosion
f_s	= corrosion factor / reinforcement factor
G	= universal gas constant (8.314 J/mol · K)
m	= material constant, equal to $2.5 w/c - 0.6$ (Mangat)
n	= empirical exponent depending on mat'l properties (from curve-fitting)
p	= Mejlbro factor ($p^0 = 1, p^1 = p, p^2 = p \times (p-1), \dots, p^n = p(p-1) \dots (p-n+1)$)
	= 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, ...
$Q_{i,j}$	= Chloride concentration at point $i, j-1$ (Tang & Nilsson)
$Q_{i,j-1}$	= Chloride concentration at point i, j (Tang & Nilsson)
$\Delta Q_{i,j}$	= increase in Chloride concentration (Tang & Nilsson)
R	= rainfall intensity (mm)
RH	= actual relative humidity in concrete (%)
RH_{ref}	= reference relative humidity in concrete (%)
S	= shape factor
S_1	= surface chloride concentration after year 1 of exposure
t	= duration of exposure (years)
t_{ic}	= time to initiate corrosion
$t_{ic, ref}$	= reference time-to-initiate corrosion derived from lab expt (days)
t_{ex}	= time of 1 st exposure to chloride
t_{ref}	= time when D_{ref} was computed (28days)
T	= actual absolute temperature in concrete (K)
T_{ref}	= reference temperature at which $D_{c,mt}$ is determined (296K)
w/c	= water to cement ratio

- x_c = concrete cover thickness
 x_c = depth of chloride penetration (mm)
 Ψ_p = Mejlbro function, as described by Equation (12)

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