A Simplified Chloride Diffusion Co-efficient Model

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Abstract: Concrete exposed to chloride environment such as Marine and Cold Regions experience Chloride Ingress. Chloride Diffusion in concrete is concentration dependent process. Generally chloride ions move from higher concentration to lower concentration. Chloride ion concentration wen accumulates to a threshold level on the surface of steel in concrete; it causes steel de-passivation and ultimately process of corrosion starts. Chloride diffusion modeling is generally done using Fick's second law of diffusion. For tis purpose a number of diffusion models are available, which mainly dependent on ageing factors. A new simplified model has been developed which consider the decreasing effect of chloride diffusion over time period. This simplified diffusion model mainly depends on the decrease of diffusion of chloride ions rate over time based on up-dated ageing factor.

Keywords: Durability, Marine and Cold Regions Concrete, Chloride Diffusion in concrete, Chloride diffusion modeling, Corrosion

1. Introduction

Chloride diffusion in concrete is a complicated process which involves a number of factors. These factors are mainly water cement ration and cement and aggregate type and content. Also environment factors such as temperature and humidity have also an important effect on diffusion properties of concrete. A number of researchers have developed chloride diffusion models. Chloride diffusion models have an importance in service life estimation of concrete structures exposed to chloride environment. A correct selection will give better results.

A number of researchers have developed a number from which selected models are as sown in the Table-01 Available Diffusion Models. These models are based mainly on the ageing factor concept, using tis value of ageing factor expected value of chloride diffusion predicted. On this approach first model was developed by P.S. Mangat and B.T Molloy [12], their model predicts expected chloride diffusion coefficient using ageing factor. Similar models were proposed by Magne and Maage [10]. Andrea Boddy et al [1] proposed their model based on the temperature effect. Kyle Stanish and Michael Thomas [8] proposed a model based on the effect of ageing factor on the effective time (t_{eff}).

Tang Luping and Joost Gulikers [15] proposed their model including the concept of exposure time of concrete. Ha – Won Song [8] proposed their models based on the ageing limit of exposure of concrete. Seung Woo Pack et al [13] proposed their models based on the ageing factor of concrete. Odd E Gjorv [11], proposed a model based on the temperature effect. D. H. Chisholm and N. P. Lee [3], proposed a model based on the integrated value of actual chloride diffusion co-efficient. E. Bastidas –Arteaga in [4] proposed their model including temperature and relative humidity effect. LU Chun – Hua et al [9], proposed their model including the effect of temperature, relative humidity and concrete strength. Aruz Petcherdchoo [2] proposed their model based on concrete exposure time and integrating the reference chloride diffusion over a range of time.

Table-01- Available Chloride Diffusion Models

S. No	Researcher	Diffusion Model	Comments / Remarks
01.	B S Mangat and Molloy (1994)	$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$	Based on ageing factor, m

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02.	Magne and Maage, et al (1996)	$D(t) = D_o\left(\frac{t_o}{t}\right)^k$	Based on ageing factor, k
03.	Andrea Boddy et al (1999)	$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m . exp\left[\frac{U}{R}\left(- \frac{1}{T}\right)\right]$	Based on temperature effect
04.	Bamforth (1999)	$D_{ca} = at^n$	Based on ageing factor, n
05.	Kyle Stanish and Michael Thomas (2003)	$D_{AV} = D_{ref}\left(\frac{t_{ref}}{t_{eff}}\right)^m$ $t_{eff} = \begin{cases} \frac{(1-m)(t_2-t_1)}{t_2^{1-m} - t_1^{1-m}} & m \neq 0{,}1 \\ \frac{t_2 - t_1}{ln\left(\frac{t_2}{t_1}\right)} & m = 1 \end{cases}$	Based on modification in t_{eff}
06.	Tang Luping and Joost Gulikers (2007)	$D_a = \frac{D_{ref}}{1-m}\left[\left(1 - \frac{t_{ex}}{t}\right)^{1-m} - \left(\frac{t_{ex}}{t}\right)^{1-m}\right] . \left(\frac{t_{ref}}{t}\right)^m$	Based on exposure time
07.	Ha – Won Song (2009)	$D_m(t) = \frac{D_R}{1-m}\left(\frac{t_R}{t}\right)^m$ (t < 30 years) $D_m(t) = \frac{D_R}{1-m}\left[(1-m) + m\frac{t_{lim}}{t}\right]\left(\frac{t_R}{t_{lim}}\right)^m$ (t > 30 years)	Based on maturity of concrete
08.	Seung Woo Pack (2010)	$D_m(t) = \frac{D_R}{1-m}\left(\frac{t_R}{t}\right)^m$	Based on ageing factor, m
08.	Odd E Gjorv (2011)	$D(t) = \frac{D_o}{1-\alpha}\left[\left(1 + \frac{t'}{t}\right)^{1-\alpha}\right] . \left(\frac{t'}{t}\right)^{1-\alpha} . k_e$ $k_e = \exp\left[b_e\left(\frac{1}{293} - \frac{1}{t+273}\right)\right]$	Based on ageing factor and temperature effect
09.	D.H.Chisholm and N.P.Lee (2011)	$D_{eff} = \frac{1}{t - t_{ex}}\int_{t_{ex}}^{t} D_{act}(U)du$	Based on integration of actual chloride diffusion co-efficient
10.	E. Bastidas –Arteaga (2011)	$D_c = D_{c,ref}. f_1(T). f_2(t). f_3($ $f_1(T) = \exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$ $f_2(t) = \left(\frac{t_{ref}}{t}\right)^m$ $f_3(h) = \left[1 + \frac{(1-h)^4}{(1+h)}\right]^{-1}$	Based on ageing factor, temperature effect and relative humidity
11.	LU Chun – Hua(2011)	$D(t) = D_{ref} . \left(\frac{t_{ref}}{t}\right)^m k_T k_{RH} k_c$ Where, $t_{ref} = 28\ days$ $k_T = exp[0.028\ (T - 273)]\ \ T > 0°C$ $k_{RH} = \left[1 + \left(\frac{1-RH}{1-0.75}\right)^4\right]^{-1}$ $k_\sigma = 1 + \left(\frac{\sigma_{c/t}}{f_{ck/tk}}\right)\ \ 0 \leq \frac{\sigma_{c/t}}{f_{ck/tk}} \leq\ 0.8$	LU Chun - Hua
12.	Aruz Petcherdchoo (2013)	$D_a = \frac{T}{t} = \frac{\int_{t_{ex}}^{t+t_{ex}} D(t)dt}{t}$	Based on integration of chloride diffusion co-efficient

2. Background

Chloride diffusion in concrete is a concentration gradient phenomenon, which depends on the available of chloride content on the surface of concrete and available chloride content inside of concrete. Other properties are based on concrete properties such as strength and material properties. Also environment has and influence on the diffusion on chloride ion in concrete such as temperature and relative humidity. Generally, equation 01 is used for the analysis of the chloride diffusion in concrete. This equation calculates value of C(X,T) over a period of time from the known values of surface chloride content, depth of concrete under study and diffusion co-efficient. This equation has been used to find the time to corrosion initiation by various researchers such as An Duan[2], Aruz Petcherdchoo [3], Ha-Won Song et al [8-9],K.Y.Ann et al [11] and Seung-Woo Pack et al [16].

$$C(X,T) = C_S\left(1 - \text{erf}\frac{X}{2\sqrt{DT}}\right) \qquad \text{Equation 01}$$

3. A New Proposed Model for Chloride content in Concrete

This equation uses the chloride diffusion obtained from equation 02. Although this equation is widely used in the analysis for time to corrosion initiation in reinforced concrete, but question arises which chloride content? Simply this equation gives an instant chloride content. Mathematically this C(X,T), obtained is correct, but actually, instead of using at every new position of time like Tn , Tn+1, Tn+2, Tn+3 and so on. So, we neeed to add the chloride content obtained at each time step. This accumulation of chloride content is within the concrete body.

$$C(X,T) = C_S\left(1 - \text{erf}\frac{X}{2\sqrt{DT}}\right)$$

Equation 01

Now consider the time steps where C(X,T) is required, for example we are starting from first year to twenty five years of time period. So, we have to add the C(X,T), obtained at each time step. Because this value is obtained from the instant chloride diffusion. So, we consider time steps as Tn , Tn+1, Tn+2, Tn+3……….Tn+24, for the time period of year-one to twenty five years. So, at first step we are getting chloride content as

For First Year, chloride content

$$C(X,T)n = C_S\left(1 - \text{erf}\frac{X}{2\sqrt{DnTn}}\right)$$

For Second Year, chloride content

$$C(X,T)n+1 = C_S\left(1 - \text{erf}\frac{X}{2\sqrt{Dn+1Tn+1}}\right)$$

For Third Year, chloride content

$$C(X,T)n+2 = C_S\left(1 - \text{erf}\frac{X}{2\sqrt{Dn+2Tn+2}}\right)$$

So for a time period,

$$C(X,T)_{n+i} = \int_{n=1}^{n=I+1} C(X,T) \qquad \text{Equation 1-a}$$

Equation 1-a adds all the chloride content obtained up-to reference time. So, practically this equation is more relevant to use to find the corrosion ignition time in reinforced concrete structures.

4. A New Proposed Model for Chloride diffusion in Concrete

Looking at the dependency of chloride diffusion in concrete, it can be easily observed that expected value of diffusion in concrete mainly depends on the reference chloride diffusion co-efficient and time and expected time with ageing factor. This can be seen in the references [5,7-9, 13, 15-20] and models presented in the Table 01. These models predict Diffusion co-efficient for the next time period from the two previous value of diffusion co-efficient D and Time T. Equation 02 mainly relies on the ageing factor. Ageing factor considers all the seasonal variation during the period under consideration. Generally this ageing factor is obtained from the first year chloride ingress. So question arises, the ageing factor obtained from the first year values of D and T , may be used for all the sequence of time such Tn , Tn+1, Tn+2 and Tn+3 and so on

$$\boldsymbol{Dn = D0\left(\frac{T0}{Tn}\right)^{m0}} \qquad \textbf{Equation 02}$$

Generally, m is found out as given by Yung Ming Sun et al [20],

$$m0 = \frac{In(D_2/D_1)}{In(T_1/T_2)}$$

Equation 03

So, based on the fact that the chloride diffusion in concrete decreases with time. So, it is proposed that, at each time step ageing factor m needs to be reworked from previous 2 values of D and T.

So, for next time step

$$\boldsymbol{Dn+1 = Dn\left(\frac{Tn}{Tn}\right)^{mn}}$$

Equation 2-a

At this time m may be found out as,

$$mn = \frac{In(D_n/D_{n-1})}{In(T_{n-1}/T_n)}$$

Equation 03-a

Equation 2-a has been proposed to use for the analysis of reinforced concrete structures in chloride environment. This considers the history of the chloride diffusion in concrete as time progresses. It can be seen in the Figure 01, that m has a significant effect on the prediction of chloride diffusion in concrete over time period.

5. Discussion

Although chloride diffusion process in concrete is a complicated one. But using ageing factor makes this estimation simple and easy to use. As ageing factor is found by using concrete chloride diffusion co-efficient over two time points. So, this value is including all material and environment properties. Using the equation-01 and assuming values of D_{ref} ,t_{ref}, and t from 1-to-25 years and selecting various values of m in the range of 0.1 -to- 0.9, a graph as shown in Figure -01 has been obtained, which clearly shows an increase of chloride diffusion co-efficient with an increase of m- value. Figure-01, show values for time period up-to 25 years. From 25 year onwards, chloride diffusion co-efficient, may be taken a constant value obtained over 25 years time period, assuming that concrete has been mostly hydrated, so a very slow diffusion process may occur after this time.

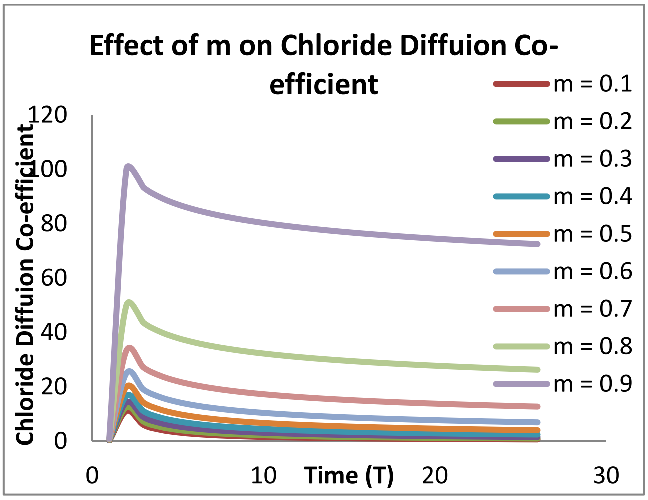

Figure -01- Chloride Diffusion Coefficient Using Various Values of m from 0.1 to 0.9

6. Conclusion

For a better analysis of reinforced concrete structures to find out the corrosion initiation time equations 1-a, 2-a and 3-a have been proposed. So, that a more accurate service life may be predicted.

References

[1] Initially, first model was developed by B.S Managat in 1994 [15]. This Model is based on the ageing factor and relates diffusion co-efficient and time at a reference and a fute time.As, this model is based on the ageing factor, and ageing factor is calculated from frst year chloride ingress, so it is not considering effect of chloride diffusion on subsequent years.

[2] A similar model has been proposed by Magne Maage (1996). This model uses ageing factor in same way as by B.S Managat in 1994 [15] model. Bamforth,A S well proposed a similar model in 1999.

[3] Andrea Boddy et al (1999)[1], Odd E Gjorv (2011)[14], E. Bastidas –Arteaga (2011)[6], and LU Chun –Hua[12], have included the temperature and humidity effect in their models. But drawback of these models is that, they are using as ageing factor, as ageing factor includes all the temperature and humidity effects for a year. So, it is recommended to not follow these parameters with ageing factor.

[4] Ha – Won Song (2009)[], has proposed a model on maturity of concrete, but this approach can not work, as diffusion continues for a much loner period.

[5] Kyle Stanish and Michael Thomas (2003)[], Tang Luping and Joost Gulikers (2007)[] and Aruz Petcherdchoo (2013)[] have proposed their modl on the concrete exposure period, which generally they take as 28-days. This is a good approach but chloride difuison in concrete as well depends on compressive strength of concrete and concrete gains its compressive strength in first 24 hours, so this approach is not a good choice and only consideration of ageing factor is a better choice.

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