

Durability of Pre-stressed Concrete Structure Suffering from Chloride Ions' Invasion

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Abstract: One of the major causes of deterioration of pre-stressed concrete (PC) members is chloride-induced corrosion of the pre-stressing steel. Some factors which influence the chloride diffusion in pre-stressed concrete suffering from chloride ions' invasion are reviewed, and a diffusion model of chloride in pre-stressed concrete, which take stress level of concrete into account specially, is built. Based on reliability theory, an analytical model of durability of PC members has been built, and an evaluation way of durability life has been also put forward. All analytical results show that the thickness of protection has a biggest influence on PC's durability and it is also revealed that values of w/c and m about certain pre-stressed concrete have great influence on durability of PC members in chloride environment.

Key words: chloride ions' invasion; pre-stressed concrete; durability; reliability probability; service life

1 Introduction

In the last half century, the pre-stressing technology has been widely used in civil, water conservancy and traffic engineering etc. As well as other concrete structures, pre-stressed concrete (PC) structures exposed to bad environment will also occur some durability problems such as function decline and structure failure. To some pre-stressed structures exposed to marine environment and de-icing salts, the attack of chlorine ion is the chief factor that causes corrosion of steel bars and shortage of structure durability, and then makes great damage. The durability failures of pre-stressed structures caused by the chloride contamination have happened continuously all over the world [1]. So, the researches on chloride invasion are one important part of the durability study of PC structures.

Compared with the ordinary reinforced concrete (RC), the materials of steel and concrete in PC are always in high stress state, and the working circumstance is very bad; so, the stress corrosions of concrete and pre-stressing steel are seen commonly. In another way, the work stress of pre-stressing steel is much higher than that of reinforcing steel and the cross-section of pre-stressing steel is smaller; so, even if there were slight corrosions in steel bars, the cross-section loss ratio of steel bar was still great. Therefore, if the pre-stressing steel in PC element corrodes, there aren't some phenomena such as producing rust around bars, causing internal microcracks, external longitudinal cracking and eventually spalling of concrete cover etc which will happen in RC element; while the PC structure is likely to happen brittle failure without any foretoken.

Durability analysis includes probabilistic information from all resistance and loading variables influencing the assessment process. So, on the basis of our test data [2], our paper firstly analyzes the mathematical model of chloride transport in pre-stressed concrete; and then determines the chloride-induced corrosion initiation time of pre-stressing steel as the durability limit state of PC structure. Secondly, a structural reliability (probabilistic) model is put forward herein to calculate probability of structural failure. At last, by

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taking thickness of concrete cover, chloride diffusion velocity and surface chloride concentration as main parameters, we have analyzed the reliability index of marine pre-stressed concretes with reliability theory and predicted their service lives.

2 Chloride diffusion in pre-stressed concrete

Chloride penetration in concrete may occur as a result of several transport mechanisms (ionic diffusion, capillary sorption, permeation, dispersion, and wick action), and the diffusion function is the foremost transport way. And, major researches about chloride diffusion all described that diffusion process by Fick's 2nd law of diffusion [3] under the assumption that the concrete cover is fully saturated. Then its one dimension diffusion equation is expressed as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D_{Cl} \cdot \frac{\partial C}{\partial x} \right) \quad (1)$$

where C = chloride concentration (kg/m³ of concrete) at a distance x (m) from the concrete surface at time t (sec); and D_{Cl} = chloride effective diffusion coefficient (m²/sec).

3 Chloride Diffusion Coefficient— D_{Cl}

The chloride diffusion coefficient D_{Cl} in concrete is an important index to analyze its transport process and structural durability. Papadakis [4,5] has built some theoretical or semi-empirical equations to estimate the intrinsic effective diffusivity of Cl^- . Here, several factors which influence the diffusion coefficient will be discussed and we will build some semi-empirical equations to simulate their effects.

There are large controversies about the type of chloride ion to cause corrosion of steel bars. Some articles hold that only free (water-soluble) chloride ion can induce corrosion of steel bar, and the critical threshold chloride content (C_{crit}) is based on free ion. However, other researches think the total (acid-soluble) chloride content should be used. For the purpose of safety, in our paper we adopt the total chloride content as criterion, and neglect the chloride binding with concrete.

To PC structure, the tiny cracks inside elements will close automatically when the loads are released, but it is hard to avoid being some deteriorations such as micro-cracks and flaws during work stage. And these inner deteriorations will influence the chloride diffusivity. At the same time, considering the concrete of PC elements are always under high stress state, we believe that compressive stress of concrete can make the micro-cracks close automatically and decrease the permeability of concrete. While tensile stress can accelerate development of deteriorations and increase the permeability of concrete. In order to consider the inner deterioration's effect on chloride diffusion, in our paper we adopt stress level of concrete (the ratio of practical stress value to limit strength) to describe it. Base on the our test data [2], we have established below relationship to describe this influence:

$$D_{Cl,\sigma} = D_{Cl,\sigma=0} \cdot \left[1 + A_{c(t)} \cdot \left(\frac{\sigma_c(t)}{f_c(t)} \right) \right]^2$$

where $D_{Cl,\sigma}$ = modified effective diffusion coefficient by concrete stress level; $\sigma_c(t)$ = nominal compressive (or tensile) stress value of concrete; $f_c(t)$ is limit compressive (or tensile) strength of concrete; and $A_{c(t)}$ = experiential coefficients whose values of A_c and A_t are -0.0236 and 0.0496 respectively.

The chloride diffusion coefficient is closely relevant to the hydration time of concrete. To some certain concrete, we use D_{Cl,t_0} as the chloride diffusion coefficient when the hydration time is t_0 , and $D_{Cl,t}$ denotes the coefficient of time t . Then, the relation between two above coefficients is given by:

$$D_{Cl,t} = D_{Cl,t_0} \cdot \left(\frac{t_0}{t} \right)^m = D_{Cl,1} \cdot t^{-m} \quad (2)$$

where $D_{Cl,1}$ = chloride diffusion coefficient at the hydration time of one year; and m = empirical parameter whose value is relevant to w/c ratio and cement category. Mangat and Molloy [6] proposed that the value of m can be described as: $m = 3 \cdot w/c - 0.6$. Helland [7] also gave an equation between parameter m and w/c ratio, the additive content. Usually, some papers held that for Portlant cement the value of m is between 0.2 and 0.3, while for fly ash and slag cement the value is between 0.6 and 0.7. And 0.64 was adopted by Maage et al .

ACI's (American Concrete Institute) Life-365 committee proposed that for all sort of concrete the 28-day's chloride diffusion coefficient be calculated as following:

$$D_{Cl,28} = 10^{(-12.06+2.4w/c)} (m^2/s)$$

where w/c = water-cement ratio in concrete. If the w/c is assumed to 0.40, then based on Eq(2) the chloride diffusion coefficient at any time can be expressed as Eq(3). So, at this moment the coefficient $D_{Cl,1}$ will equal to $1.7018e-12(m^2/s)$.

$$D_{Cl,t} = 1.7018 \times 10^{-12} \cdot t^{-m} (m^2/s) \quad (3)$$

And the environmental temperature is also an important factor to influence the diffusion coefficient. Stephen et al. [8] has built the relationship between chloride diffusion coefficient and temperature, i.e.,

$$D_{Cl,T} = D_{Cl,T_0} \cdot \frac{T}{T_0} \cdot e^{q\left[\frac{1}{T_0} - \frac{1}{T}\right]} \quad (4)$$

where $D_{Cl,T}$ and D_{Cl,T_0} = chloride diffusion coefficients at temperature T and T_0 (K) respectively; and q = an activation constant whose value is relative to w/c ratio. Stephen et al. [8] showed that when the w/c ratio is equal to 0.4, 0.5 and 0.6, the values of q are 6000K, 5450K and 3850K respectively.

Water molecule in concrete is the prior condition that chloride can diffuse in concrete. If the relative humidity is particularly low or high, the chloride diffusion coefficient will descend. Therefore, Anna and Roberto [9] has given the impact of relative humidity on chloride diffusion coefficient as follows:

$$D_{Cl,RH} = D_{Cl,RH_C} \cdot \left[1 + (1 - RH)^4 / (1 - RH_C)^4\right]^{-1}$$

where RH = relative humidity in concrete(%); RH_C = critical relative humidity (75%); and $D_{Cl,RH}$ and D_{Cl,RH_C} = chloride diffusion coefficients at relative humidity RH and RH_C respectively.

4 Surface Chloride Concentration- C_S

On the other hand, the surface chloride concentration C_S is another main factor that will affect the durability of PC structure. Though the surface concentration won't produce effects on the chloride diffusion coefficient, it will make great influence on the chloride accumulation at certain depth. For instance, when the surface chloride concentration is very high, there will be a large chloride accumulation at certain depth only if time is enough long.

To concrete surface exposed to de-icing salts, the surface chloride concentration may be influenced by the amount of de-icing salts applied to a bridge deck, efficiency of drainage, quality of expansion or construction joints, etc. Hoffman and Weyers compared the results of samples taken from 321 concrete bridge decks in the US, and showed that the mean of C_S is $3.5kg/m^3$ that is in broad agreement with other research results. Thus, the mean and coefficient of variation of surface chloride C_S (for the US) are $3.5 kg/m^3$ and 0.5, respectively.

To structures exposed marine environment, the concentration of air-borne chlorides on the surface of a concrete member is very much dependant on environment conditions, topography, orientation of the concrete surface and distance from the coastline. Unfortunately, the data for marine exposures is very limited; however, data reported by McGee [10] appears to be the most comprehensive study to date for bridges in marine zones in a temperate climate. In this study, McGee [10] suggests that the surface chloride concentration is a function of distance from the coast (d in km) is

$$C_s(d) = 2.95kg/m^3 \quad d < 0.1km$$

$$C_s(d) = [1.15 - 1.81 \cdot \lg(d)] kg/m^3 \quad 0.1km < d < 2.84km \quad (5)$$

$$C_s(d) = 0.03kg/m^3 \quad d > 2.84km$$

Based on above analyses, we believe that in the chloride containing environment, the chloride diffusion coefficient and the surface chloride concentration are two important factors that influence the durability of PC structure, and that the stress level of concrete, hydration time, temperature and relative humidity are four main external reasons which will affect the chloride diffusion coefficient.

5 Improved Chloride Deterioration Model for PC

When the hydration time of concrete, temperature and relative humidity are one year, T_0 and RH_C respectively, the chloride diffusion coefficient, we suppose thoughtless of the stress level of concrete, is $D_{Cl,1}$ [11]. Then, after synthetically considering above all factors, we can calculate the effective diffusion coefficient as below:

$$D_{Cl} = D_{Cl,1} \cdot \left[1 + A_{c(t)} \cdot \left(\frac{\sigma_{c(t)}}{f_{c(t)}} \right) \right]^2 \cdot t^{-m} \cdot \frac{T}{T_0} \cdot e^{q \left[\frac{1}{T_0} - \frac{1}{T} \right]} \cdot \left[1 + \left(\frac{1 - RH}{1 - RH_c} \right)^4 \right]^{-1} \tag{6}$$

So, in pre-stressed concrete, the Fick's 2nd law of diffusion can be modified as Eq(7):

$$\frac{\partial C}{\partial t} = (1 - m) \cdot k \cdot D_{Cl,1} \cdot t^{-m} \cdot \frac{\partial^2 C}{\partial x^2} \tag{7}$$

where

$$k = \left[1 + A_{c(t)} \cdot \left(\frac{\sigma_{c(t)}}{f_{c(t)}} \right) \right]^2 \cdot T \cdot \exp \left[q \left(\frac{1}{T_0} - \frac{1}{T} \right) \right] / T_0 / (1 - m) / \left[1 + \left(\frac{1 - RH}{1 - RH_c} \right)^4 \right]$$

For given initial and boundary conditions (accounting C_S constant), we can find the solution of Eq(3) and get the relationship between chloride concentration $C(x, t)$ at a distant x from the concrete surface at time t is:

$$C(x, t) = C_0 + (C_s - C_0) \left[1 - erf \left(\frac{x}{2\sqrt{k \cdot D_{Cl,1} \cdot t^{1-m}}} \right) \right] \tag{8}$$

where C_0 = initial chloride concentration in concrete (kg/m³ of concrete); and $erf(z)$ = error function as following:

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

6 Parameters' Probability Model

For the chloride attack, we should pay most attention to the chloride concentration at the surface of pre-stressing steel, and compare it with the critical threshold chloride concentration (C_{crit}). If the content of chloride at surface of pre-stressing steel surpasses the critical concentration C_{crit} , the pre-stressing steel would be corroded seriously provided that other essential conditions are enough. Here, for pre-stressed concrete it is assumed that the mean and coefficients of variation for C_{crit} are 0.24kg/m³ and 0.19, respectively (see table 1).

Because the chloride content $C(d, t)$ at the surface of steel (where d = the thickness of concrete cover; and t = time) is relative to numerous factors such as the chloride diffusion coefficient, the surface chloride concentration and time; the parameter $C(d, t)$ is a random variable. Some test results [12] show that the chloride content at the surface of pre-stressing steel at certain time t_0 is fairly obedient to normal distribution, and its one dimension's probability density function is

$$p [C (d, t_0)] = \frac{1}{\sqrt{2\pi}\sigma_C} \exp \left[-\frac{1}{2} \left(\frac{C (d, t_0) - \mu_C}{\sigma_C} \right)^2 \right]$$

where μ_C and σ_C = mean value and standard deviation of $C(d, t)$ respectively. The value of μ_C can be calculated by Eq.(6) and σ_C can be determined by following equation:

$$\sigma_C = \sqrt{\left(\frac{\partial C}{\partial \alpha_C} \Big|_m \cdot \sigma_{\alpha_C} \right)^2 + \left(\frac{\partial C}{\partial C_S} \Big|_m \cdot \sigma_{C_S} \right)^2 + \left(\frac{\partial C}{\partial D_{Cl,1}} \Big|_m \cdot \sigma_{D_{Cl,1}} \right)^2}$$

where α_C = the uncertainty parameter of the chloride diffusion computation model; σ_{α_C} = standard deviation of α_C ; σ_{C_S} = standard deviation of surface chloride concentration C_S ; and $\sigma_{D_{Cl,1}}$ = standard deviation of chloride diffusion coefficient $D_{Cl,1}$.

Statistical parameters for corrosion variables are shown in Table 1. Note that the statistical parameter for $D_{Cl,1}$ and the coefficient of variation for C_{crit} are from the papers [13], respectively.

Table 1: Statistical parameters for relevant variables

Parameter	Mean	Coefficient of variation	Distribution
$D_{Cl,1}$	2.0e-12m ² /s	0.1	Normal
α_C	1.0	0.2	Normal
C_S —de-icing salts	3.5kg/m ³	0.5	Lognormal
C_S —marine zone	Eq.(4)	0.5	Lognormal
C_{crit}	0.24kg/m ³	0.19	Normal

7 Time-dependent Degree of Reliability

From above analyses, we can know that when the chloride concentration at the pre-stressing steel's surface reaches the critical threshold concentration C_{crit} , the corrosion of pre-stressing steel may happen. The interval from chloride-induced steel corrosion initiation to structural failure of PC is very short and the failure is probable to be brittle. Therefore, in the chloride containing environment the durability limit state of PC structure is

$$Z(t) = C_{crit} - C_0 - \alpha \cdot C(d, t) = 0$$

Then, the probability of failure will be given by:

$$P_f(t) = p\{C_{d,t} > C_{crit} - C_0\} = 1 - p\{C_{d,t} < C_{crit} - C_0\} = 1 - \Phi(\beta_t)$$

where β_t = structural reliability index at time t and can be calculated by using reliability theory (Jin and Zhao 2002); and $\Phi(\cdot)$ = normally distributed function.

Here, we have adopted several important parameters to analyze the time-dependent reliability index of pre-stressed structural durability, and these parameters include thickness of concrete cover d , surface chloride concentration C_S and the chloride effective diffusion coefficient $D_{Cl,1}$, which can synthetically reflect concrete's strength level, w/c/ ratio and concrete construction quality et al. By taking these parameters as analytical variable, we have investigated the relationship between the reliability index β and time t , shown in Fig.1(a), (b) and (c). From these figures, we can obtain that under three different conditions the reliability index β descends fast in early period, and then the speed becomes slow. The main reason why the descent becomes slow is that the chloride diffusion velocity would become slow along with time. And, we can also get that the thickness of concrete cover has biggest influence on the durability of PC structure in chloride containing environment, and the effects of another two parameters are smaller comparatively.

8 Service Life Analysis

In chloride containing environment, the time t_p , which is the chloride-induced corrosion initiation time of pre-stressing steel, can be solved from the Eq. (5) and (6). Here, the parameter t_p is also a random variable and its expression is given by:

$$t_p = \left\{ \frac{d^2}{4 \cdot k \cdot D_{Cl,1} \cdot [erf^{-1}(\alpha)]^2} \right\}^{\frac{1}{1-m}}$$

with

$$\alpha = 1 - (C_{crit} - 2C_0) / (C_S - C_0)$$

Based on the norm of ISO2394 (1998), the reversible limit state refers to one kind of limit state that can no longer keep the exceeding state when the exceeding action is removed. So, we can recognize that the limit state of normal use of PC structure belongs to reversible limit state, and its reliability index β of limit state would be zero.

When the chloride diffusion coefficient $D_{Cl,1}$ is 1.75×10^{-12} m²/s and surface chloride concentration C_S is 1.2kg/m³, the relationships between concrete cover thickness d and durability life t_p are shown in Fig.2 (a). We can see that when the cover thickness increases 5mm each step from 40mm (the augment amplitude is about 10%), the relative service lives are 10.88y, 20.93y, 37.59y, 63.83y and 103.50y (the increase speed is 80% or so).

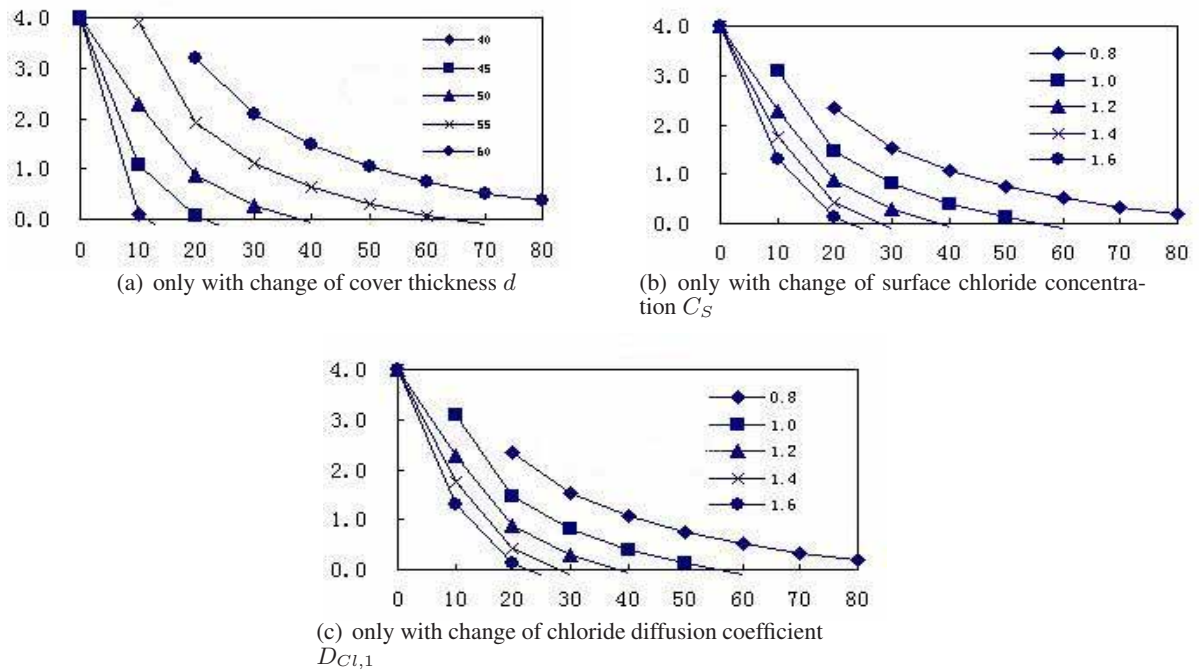


Figure 1: Time-dependent cumulative degree of reliability for PC structural durability suffering from marine chloride attack: at (a) change of d ; (b) change of C_S ; and (c) change of $D_{Cl,1}$. The horizontal coordinate indicates reliability index β and vertical coordinate indicates time.

Similarly, we can get the relationships between surface chloride concentration C_s and durability life t_p , and between chloride diffusion coefficient $D_{Cl,1}$ and durability life t_p (see Fig.2 (b) and (c), separately). From above two figures, we can obtain that when the surface chloride concentration decreases 0.05% each step from 0.4% (the decline amplitude is about 10% and another two parameters of $D_{Cl,1}$ and d are constant), the relative service lives are 22.09y, 27.98y, 37.59y, 55.38y and 96.65y (the increase speed is 30%~50%); and when the chloride diffusion coefficient decreases $0.25 \times 10^{-12} \text{m}^2/\text{s}$ each step from $2.25 \times 10^{-12} \text{m}^2/\text{s}$ (the decline amplitude is about 16% and another two parameters of C_S and d are constant), the relative service lives are 19.67y, 26.30y, 37.59y, 58.41y and 96.27y (the increase speed is 40%~50%).

Therefore, it is obvious that the parameter, which has maximal effect on durability life in chloride containing environment, is the thickness of concrete cover, and the surface chloride concentration and chloride diffusion coefficient are next. So, it is an effective measure for PC structure in chloride environment to work out a reasonable thickness of concrete cover. At the same time, some another factors such as water-cement ratio, concrete compressive strength and protection condition etc, which will affect the quality of concrete cover, can't be neglected too.

9 Numerical simulation for chloride diffusion

When these two parameters of C_S and D_{Cl} are regarded as constants, Eq.(1) can be solved with analytical solution (just like Eq.(8)). But in practical chloride environments, it is known that parameters of C_S and D_{Cl} will change with time. Based on above analysis, we know that D_{Cl} represents concrete permeability and is influenced by mix proportions (w/c ration, cement type), curing, compaction, environment (relative humidity and temperature) and time. And D_{Cl} is not significantly affected by the source of chlorides. To another parameter C_S , two main environmental categories, de-icing salts and marine zone, are considered. In these two environments, surface chloride concentration C_S also will be changed during the diffusion process in concrete. So, it is difficult to get the analytical solution from Eq.(1), and only the numerical solution can be used.

To the application of de-icing salts for concrete bridges, we still adopt a constant of $3.5 \text{kg}/\text{m}^3$ as the value of surface chloride content C_S due to the absence of relevant datum. And to chloride diffusion coefficient D_{Cl} , only the time factor is considered and Eq.(3) is used. Based on above demands, the numerical

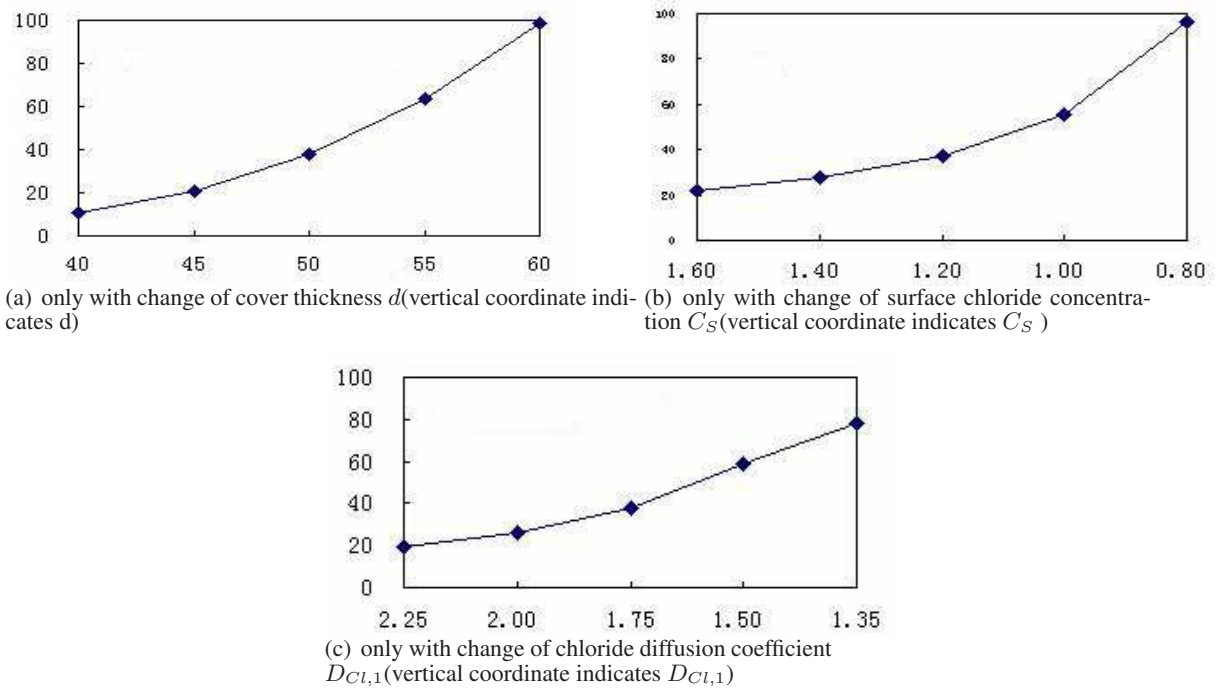


Figure 2: Service life analysis for PC structural durability suffering from marine chloride attack: at (a) change of d ; (b) change of C_S ; and (c) change of $D_{Cl,1}$. The horizontal coordinate indicates durability life.

simulations for de-icing salts are done with FEMLAB software and the results are shown in Fig.3, which presents the chloride content distribution situations at different depths in concrete every other year (first to tenth year) with distinct values of w/c . From Fig.3, it is obvious that the incremental speeds of chloride concentration at different depths will become gradual slowdown with the increment of time. And the chloride diffusion velocity in concrete member with higher w/c value ($w/c=0.55$) will be much larger and even several times than that with lower w/c value ($w/c=0.40$). So, it is very important to choose a suitable value of w/c in order to improve structural durability in chloride environment.

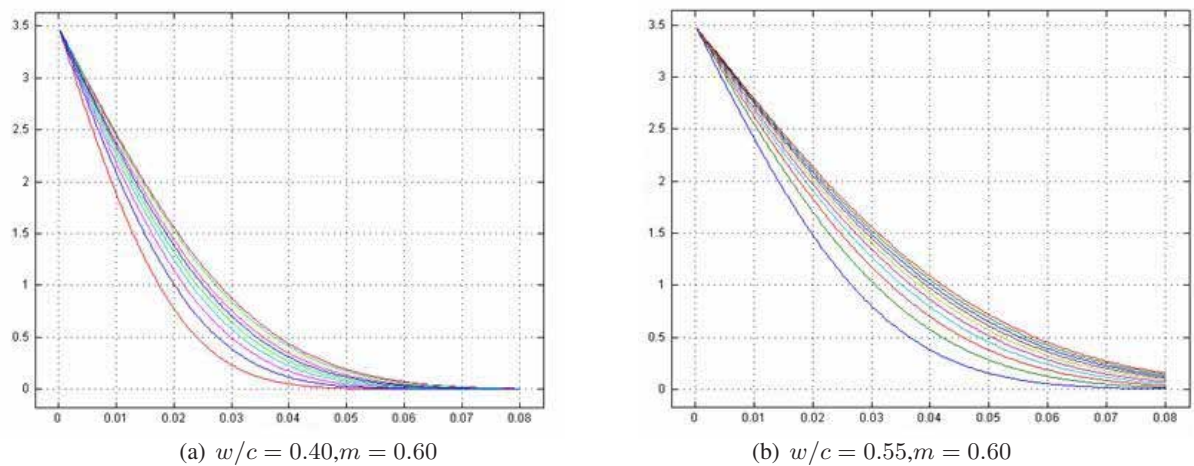


Figure 3: Chloride content distribution situations at different depths in concrete every other year in de-icing salt environment: at (a) $w/c = 0.40, m = 0.60$; (b) $w/c = 0.55, m = 0.60$. The horizontal coordinate indicates concentration and the vertical coordinate indicates depth.

In an atmospheric marine zone, water-borne chloride ions carried by the wind will accumulate on the concrete surface. And it has been proposed that surface chloride concentration C_S will increase with time at first and keep stable at certain time in service [14]. So its value we adopt here is

$$C_S = 0.4 \cdot t(\text{kg/m}^3) \quad (t \leq 10a)$$

$$C_S = 4.0(\text{kg/m}^3) \quad (t > 10a)$$

where t = structure service life (a). And in numerical simulations for marine chloride diffusion, only the time factor is considered and Eq.(3) is used for chloride diffusion coefficient D_{Cl} too. Based on above demands, the numerical simulations for marine zone are also done with FEMLAB software and the results are shown in Fig.4, which presents the chloride content distribution situations at different depths in concrete every five years (fifth to fiftieth year) with distinct values of factor m . From Fig.4, it is obvious that the incremental speeds of chloride concentration at different depths will become gradual slowdown with the increment of time. And the chloride diffusion velocity in concrete member with lower m value ($m = 0.30$) will be much larger and even several times than that with higher m value ($m = 0.60$). So, it is very important to establish a suitable value of m for certain concrete structure in order to improve structural durability in chloride environment.

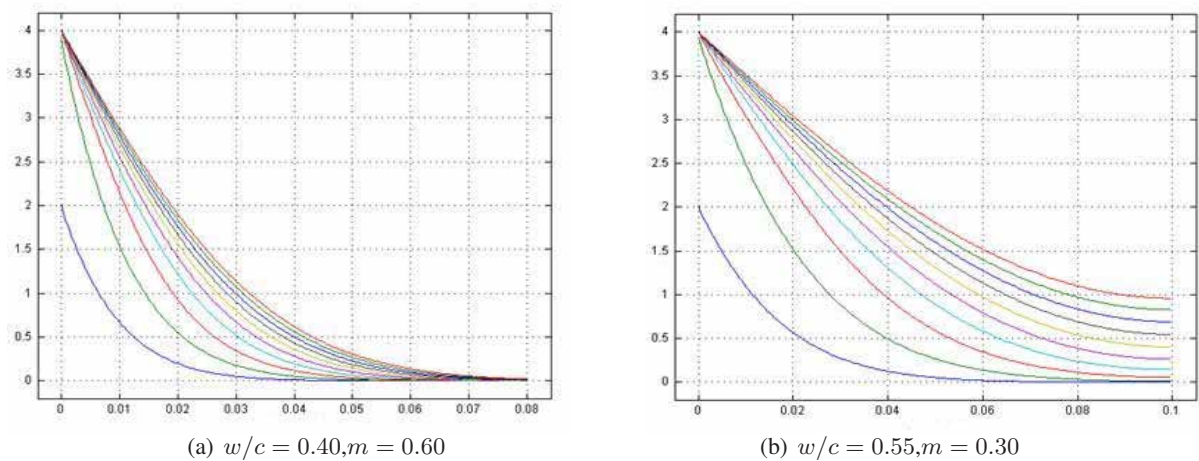


Figure 4: Chloride content distribution situations at different depths in concrete every other year in marine zone environment: at (a) $w/c = 0.40, m = 0.60$; (b) $w/c = 0.55, m = 0.30$. Horizontal coordinate indicates concentration and vertical coordinate indicates depth.

10 Conclusion

One of the major causes of deterioration of pre-stressed concrete structures is chloride-induced corrosion of the pre-stressing steel. The magnitude of the damage is especially large in structures exposed to marine environment and de-icing salts. In our paper, on the basis of the published mathematical models used to describe chloride transport in concrete, we build a diffusion model of chloride in pre-stressed concrete, which take stress level of concrete into account specially. And some parameters are got from our fast chloride test. Then, an analytical method of PC structural reliability in the chloride contamination environment has been put forwarded. Based on the reliability theory, we have evaluated the reliability index of PC structure in marine environment, which takes three parameters, including the concrete cover thickness, chloride diffusion coefficient and surface chloride concentration, as analytical variables. And, we have predicted structural durability life in chloride environment when the limit reliability index equals to zero. At last, the numerical simulations for chloride diffusion in de-icing salts and marine zone environments are done with the help of FEMLAB software.

From the result of the study, it is obvious that the thickness of concrete cover has a biggest influence on durability of PC structure in marine environment, and other two parameters (chloride diffusion coefficient and the surface chloride concentration) are second. And it is important to choose and establish suitable values of w/c and m in order to obtain better durability for PC structures in chloride environment.

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