SERVICE LIFE PREDICTION OF CONCRETE STRUCTURES UNDER CHLORIDE ENVIRONMENT BASED ON MONTE CARLO METHOD

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Abstract

Transport of chlorides is one of the most critical factors determining the service life of concrete structures under ocean environments, and diffusion is usually regarded as the major mechanism for the transport of chloride ions into concrete. As chloride diffusivity is affected by temperature, most existing service life prediction models use the Arrhenius equation to describe the relationship between temperature and chloride diffusivity; however, the variability of activation energy values have rarely been considered. In this investigation, a statistical model using Monte Carlo method is established for the prediction of concrete's service life considering the temperature effect on chloride diffusivity, in which the values of activation energy for diffusivity was determined based on an empirical correlation between diffusivity and activation energy value. The proposed model could theoretically provide a more suitable method for the prediction of concrete's service life under various temperatures.
Keywords: Chloride diffusivity, Activation energy, Monte Carlo method, Service life

1. INTRODUCTION

Corrosion of reinforcing steel is the major cause to the deterioration of concrete structures under marine environment. According to Tutti's model, the service life of reinforced concrete is generally composed of the corrosion initiation period (t_i) and the propagation period (t_p)[1]. The initiation period is the time it takes for the chloride ion to reach the steel surface to a critical value. Most service life prediction models take the initiation period as the dominant factor determining concrete's service life. Compared with traditional service life prediction method, the reliability assessment of structural durability takes into account the randomness of parameters and its necessity has been accepted by many researchers.[2]Based on the statistical properties of the parameters used for service life prediction, Sagues proposed the distributed variables approach.[3] Hartt used this method to explore the evaluation of time-to-corrosion for chloride-exposed reinforced concrete with an admixed corrosion inhibitor, and considered it provided a more realistic representation of what actually transpires.[4] Monte Carlo method is a kind of stochastic simulation method which use random numbers and statistical experiments both based on probability and statistical theory to solve approximate solutions. Due to the accuracy and effectiveness of the calculation results, Monte Carlo based approach has become one of the most popular methods to solve reliability problems. Before using it to solve stochastic problems, a corresponding probability model should be established according to the characteristics of the stochastic process. And then based on the distribution of random variables in the model, random numbers are generated and a large number of statistical experiments are carried out. The estimate values are calculated from these random numbers and a statistical distribution is obtained in the end [5].

The initiation period is primarily determined by the chloride diffusivity of concrete, therefore, Fick's 2nd law is the most widely used model to calculate initiation period. Diffusion is regarded as the major mechanism for the transport of chloride ions in concrete. It is commonly accepted that chloride diffusivity is affected by temperature and the Arrhenius law is usually employed to describe the correlation between chloride diffusivity and temperature.[6] For example, the activation energy value in the Life-365 model is 35 kJ/mol.[7] Although most service life model employ a constant value of activation energy, researches have shown that the activation energy value is not constant but varies with the diffusivity of concrete.[8] Therefore, using a constant value of activation energy may cause misleading results of service life prediction. In this investigation, a service life prediction model is proposed based on Monte Carlo method considering the variation of activation energy values. The model may theoretically provide a more suitable method for predicting the service life of concrete under various temperatures.

2. MODELS AND METHODS

2.1 Corrosion model

The diffusion of chloride ions in concrete follows Fick's 2nd law, as shown in Eq. (1):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C is the chloride concentration at depth x and exposure time t, and D is the chloride diffusion coefficient. Assuming the surface chloride content and chloride diffusivity as constants, the solution of Fick's second law is given in Eq. (2):

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{2}$$

where *erf* is the error function, C_s is surface chloride content, D is chloride diffusivity, x is depth of rebar and t is the exposure duration.

When the chloride concentration reaches the chloride concentration threshold (C_T), $C(x,t)=C_T$, the steel passive layer is destroyed and steel is corroded. The time of corrosion initiation can be determined by formula Eq. (3) as follows:

$$t_i = \frac{x^2}{4D\left[erf^{-1}\left(1-\frac{C_T}{C_S}\right)\right]^2} \tag{3}$$

2.2 Monte Carlo method

The reliability analysis of structures is focused on evaluation and the prediction of the probability of reaching certain investigated limit states, which is called failure probability.[9] Monte Carlo method is a popular methods to solve the failure probability of concrete structures. The basic step is to take a large number of random samples of the variables that affect its reliability, and then take these sampling values into the performance function to determine whether they are invalid or not, and the failure probability and the reliability index of structures are obtained in the end. Song used the Monte Carlo simulation technique to analyze the reliability of the concrete tunnel box structure directly exposed to seawater with regard to the time to corrosion initiation of steel embedment.[10] In addition, Monte Carlo method is also used to build corrosion models. Kirkpatrick developed a Monte Carlo-based approach to modeling corrosion damage to explore the service life of bridge decks under chloride-induced corrosion and achieve better results.[11]

In this paper, it is assumed that C_T is constant, x, C_S and D all obey the probability distribution. According to the known distribution conditions, N random sampling tests are carried out for x, C_S and D. One random number is generated for each parameter in each test, and the service life of concrete structure is calculated by these generated random numbers. At the same time, the number of the initiation period (t_i) appearing in time t and expressed in n, is recorded. Ratio of n to N (the total number of tests) is the probability of concrete structures reaching service life at time t.

2.3 Distribution variables approach

A study [3] reported an approach to corrosion damage forecasting of the parallel twin-Escambia bay bridges. The deterioration model, which is the ratio of corrosion elements to total number, can be expressed as Eq. (4).

$$\frac{Nd(t)}{N} = \frac{1}{\sum_i N_i} \sum_i N_i \int_{Dli}^{Dhi} \int_{Csli}^{Cshi} P_{cumli}\left[2\sqrt{D(t-t_{pi})}erf^{-1}\left(1-\frac{C_T}{C_S}\right)\right] P_{Csi}(C_S)\, P_{Di}(D)\, dC_S dD \quad (4)$$

Where D_{li}, C_{Sli} and D_{hi}, C_{Shi} represent the lowest and highest values. Nd(t) is the number of units whose chloride concentration achieves C_T in time t. The tidal range area (i=1) with the most serious corrosion damage to the substructure of the bridge round piles is calculated in this investigation. A summary of the random variables for the model is given in Table 1.[3]

Table 1: Escambia Bay Bridges Parameters

Parameter	Distribution	Mean	Standard Deviation
D,m^2/s	Normal	2.13×10^{-13}	1.4×10^{-13}
C_S,kg/m^3	Normal	25.02	12.1
x,m	Normal	0.0279	0.0063
C_T,kg/m^3	Determine	4.8	

Fig. 1 shows a comparison of damaged probability based upon the above two approaches and the Table 1 parameters. It indicates that predict results from Monte Carlo method are basically consistent with the distributed variables approach. Moreover, 100,0000 of random variables for each parametric value were achieved through the Monte Carlo Simulation. A large number of random experiments make the prediction results more accurate.

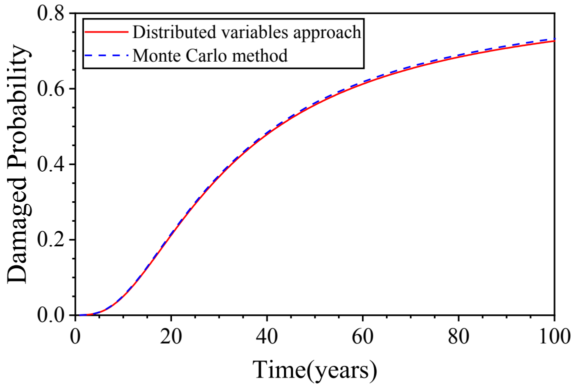


Figure1: Comparison between the results of two approaches

2.4 Statistical model

The relationship between temperature and chloride diffusion is usually described by the Arrhenius equation, as shown in Eq. (5):

$$D(T)=D_0\exp\left[\frac{E_a}{R}\left(\frac{1}{T_0}-\frac{1}{T}\right)\right] \tag{5}$$

where $D(T)$ is the diffusion coefficient at temperature T and D_0 is the diffusion coefficient at the reference temperature T_0. R is the gas constant and E_a is the activation energy of the diffusion process. E_a is treated as a constant and its value is 35kJ/mol in Life-365's service life prediction model.[7] Liu developed the correlation between non-steady-state migration coefficients (D_{nssm}) at 21℃ and E_a ,[12] as given in Eq. (6):

$$E_a=-4.46\ln\left(D_{nssm,\,21°C}\right)+27.92 \tag{6}$$

The chloride diffusion coefficient usually is regarded as a time dependent random variable and Life-365 uses the following relationship to account for time-dependent changes in diffusion [9]:

$$D(t)=D_0\left(\frac{t_0}{t}\right)^m \tag{7}$$

where D_0 is diffusion coefficient at reference time t_0 (usually 28 days) and m is attenuation coefficient. However, it is unreasonable for the chlorine diffusion coefficient to decrease with time indefinitely. Therefore, it is usually assumed that the diffusion coefficient will not decrease when the exposure time is longer than n years. For example, Life-365 states that the relationship shown in Eq. (7) is only valid up to 25 years. Beyond this time, the value of chlorine diffusion coefficient at 25 years calculated from Eq. (7) is assumed to be constant throughout the rest of the analysis period.[7] For durability design in the Hong Kong-Zhuhai-Macao (HZM) Bridge project, the power law in the above equation is truncated at the end of 30 years and it is assumed that the chloride diffusion coefficient will be stable after 30 years' exposure.[13] so the value of n is 30. In this case, Eq. (7) can be expressed as:

$$D(t)=\begin{cases} D_0\cdot\left(\dfrac{t_0}{365\cdot n}\right)^m, n<30 \\ D_0\cdot\left(\dfrac{t_0}{365\cdot 30}\right)^m, n\geq 30 \end{cases} \tag{8}$$

The value of non-steady-state migration coefficients (D_{nssm}) is considered equal to the value of diffusion coefficient (D).Based on the relationship shown in Eq. (2), a statistical model introducing temperature variable is obtained from Eq. (5), Eq. (6) and Eq. (8), as given in Eq. (9).

$$t_i=\frac{x^2}{4\cdot D_{21°C}\cdot\left(\dfrac{t_0}{365\cdot 30}\right)^m\cdot\exp\left[\dfrac{\left[-4.46\ln\left[D_{21°C}\cdot\left(\dfrac{t_0}{365\cdot 30}\right)^m\right]+27.92\right]\cdot 1000}{R}\left(\dfrac{1}{T_{21°C}}-\dfrac{1}{T}\right)\right]\cdot\left[erf^{-1}\left(1-\dfrac{C_T}{C_S}\right)\right]^2} \tag{9}$$

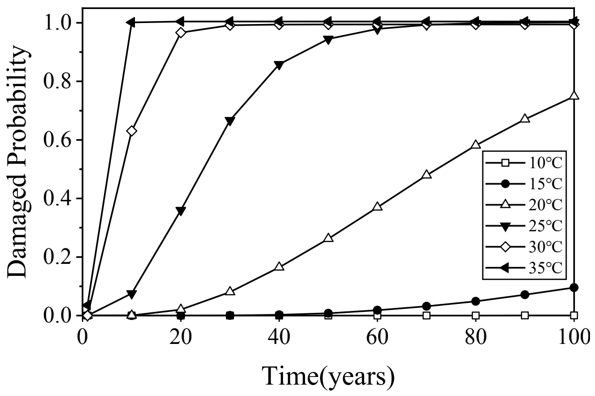
3. RESULTS AND DISCUSSION

This paper takes the HZM project as an example to predict the service life of concrete structure in splash zones at different temperatures. The reference temperature is assumed to be 21℃. Studies have reported that temperature range of this sea area is between 15℃ and 29℃.[14] In order to explore the effect of temperature in a wider range, 5℃ is taken as an interval to take values ranges from 10℃ to 35℃. A summary of the random variables for the corrosion models adopted in this work is listed in Table 2[14]. The length of the initiation period of concrete is predicted by using the model of introducing temperature variable.

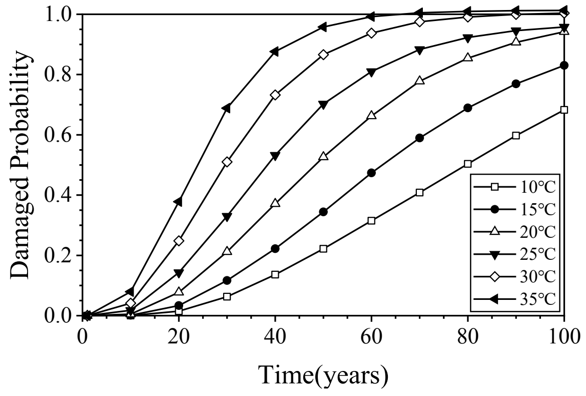
Table 2: Distribution Parameters for Variables

Parameter	Distribution	Mean or α	Standard Deviation or β
D_{28d} ,m^2/s	Normal	3.0×10^{-12}	0.6×10^{-12}
C_S,%	Lognormal	5.76	0.87
C_T,%	Beta	0.22	0.36
x,mm	Normal	80	0.00526
m	Normal	0.471	0.0286

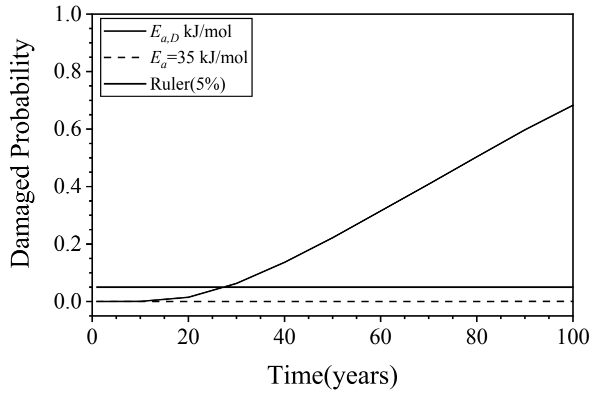
Fig. 2 shows comparisons of damaged probability, which is the probability of concrete structures reaching service life in time t, at different temperature based upon the Life-365 model and the statistical model both using Monte Carlo method and the parameter values from Table 2.



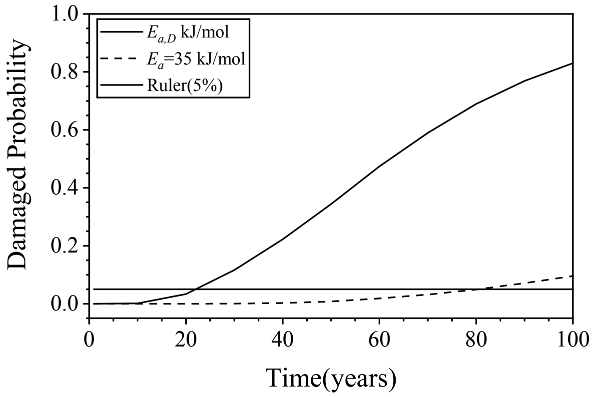
(a) E_a=-4.46ln($D_{nssm,21}$)+27.92



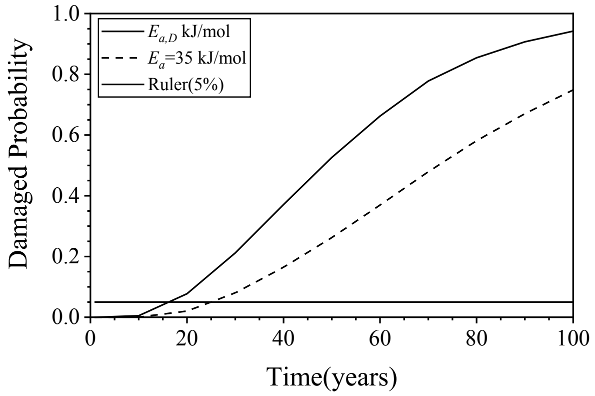
(b) E_a=35kJ/mol



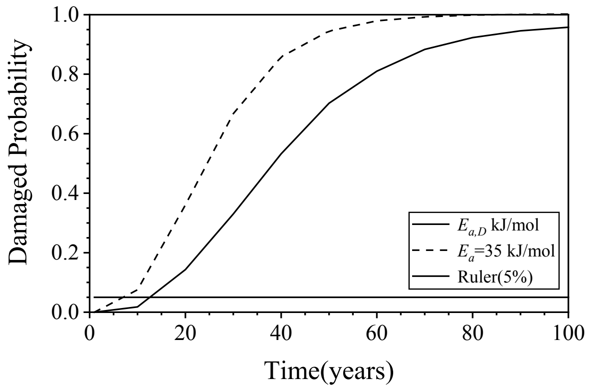
(c) 10℃



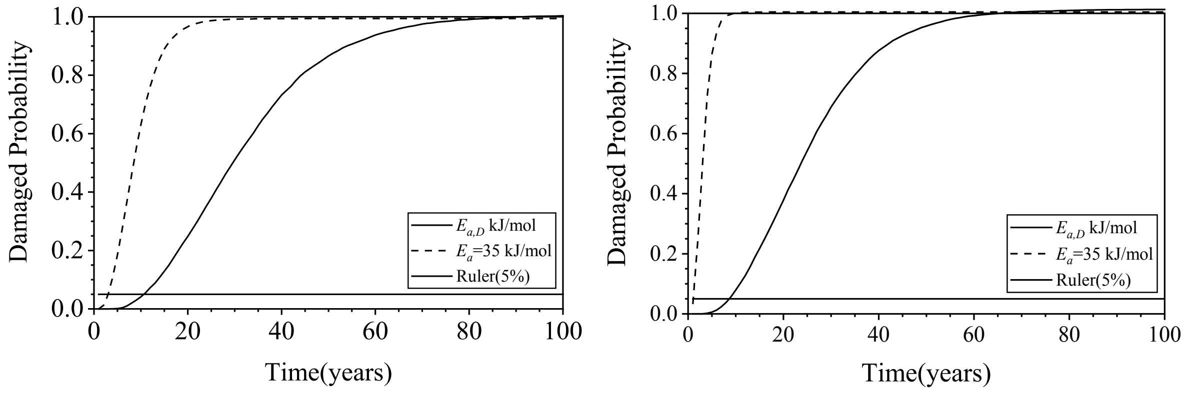
(d) 15℃



(e) 20℃



(f) 25℃



(g) 30℃ (h) 35℃

Figure 2: Comparison of damaged probability at different temperatures

5% is assumed to be the maximum probability that concrete structures are allowed to reach the chloride concentration threshold within time *t* in this paper, which is called the probability limit. Fig.2 (a) and Fig.2 (b) show the variation trend of the probability of reaching service life of two models with time at different temperatures. It is found that there is a difference in time t between the statistical model and the Life-365 prediction model, in which E_a is 35 kJ/mol, when the probability is the same. Likewise, the slopes of both probability curves are markedly elevated as the temperature increases. The comparison of probability changes at different temperatures are shown in Fig.2 (c) to Fig.2 (h). It appears to suggest that with the temperature rising, the time to reach the probability limit decreases, which illustrates the service life of concrete structures is shorten with increasing temperature, and when the ambient temperature is 10 ℃, the service life predicted by the above two models are the longest in this investigation. The time gap between these two models to reach the probability limit reduces first and then increases with the rise of temperature, and the predicted results are basically the same at a certain temperature between 20 ℃ and 25 ℃. This is because E_a at various temperatures calculated by Eq. (6) differ from that in Life-365 life prediction model, which results in a large difference between the mean value and standard deviation of chloride diffusion coefficient of the two models calculated by Arrhenius equation. Therefore, the time for structures to reach the probability limit of service life are also not same. This illustrates that the temperature sensitivity of this model is greater than that of the Life-365 model, which may provide a reference for predicting the service life of concrete structures under different temperatures theoretically.

4. CONCLUSIONS

- The results predicted by Monte Carlo method fit well with those predicted by distributed variable method, and are more accurate and easier to understand.
- The service life of concrete is affected by temperature, and the service life of concrete structures is shortened with increasing temperature
- There is a difference between the service life predicted by the model in the paper and the life-365 life prediction model and with the increase of temperature, the difference decreases and then increases.

- Based on the model developed in this study which introduces the correlation between $D_{nssm,21℃}$ and E_a, it will provide a reference for the durability design to extend the service life of marine concrete structures.

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