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INFLUENCE OF DIFFUSION PROPERTIES ON THE SERVICE LIFE OF CONCRETE STRUCTURE UNDER CHLORIDE EXPOSED ENVIRONMENT

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ABSTRACT

Recently, a variety of studies has been carried out to predict or design service life of concrete. To obtain a controlled durability and long-term performance of concrete structures under chloride attacking environments, durability analysis on chloride diffusion needs to be conducted with major design variables such as the diffusion coefficient, chloride corrosion threshold value, and chloride ion content at surface as random variables. Therefore, this study has explored the influence of diffusion properties on the service life of concrete structures.

Keyword: Durability, Service life, Chloride, Concrete

I. INTRODUCTION

Although concrete is believed to be a durable material, concrete structures have been degraded by severe environmental conditions such as the effects of chloride and chemical, abrasion, and other deterioration processes. Therefore, durability evaluation has been required to insure the long term serviceability of structures located in chloride exposed environments. Traditionally, the durability design of concrete structures is based on implicit rules for materials, material compositions, working conditions, structural dimensions, etc. Generally, the minimum requirements that can satisfy the durability have been used such as minimum concrete cover, maximum water/cement ratio, minimum cement contents, crack width limitations, and so on. The purpose of all these rules has been to secure robustness for structures, although no clear definition for service life has been presented.

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As new methods for more accurate durability design of structures have been demanded, a lot of research on concrete durability has produced reliable information on deterioration process [1, 2], which makes it possible to incorporate durability even in the mechanical design of concrete structures. In these days, a new method based on probability theory is established to overcome the above problems in durability design of concrete structures. With this, the service life of concrete structures in respect to the durability can be predicted with a probability. This study has explored the influence of diffusion properties of concrete on the service life of concrete structures.

II. ANALYSIS MODELS AND METHODS

In the deterministic approach, only average properties are used in the prediction of service life. However, concrete structures in actual condition behave different from the idealized condition which is assumed in the prediction. The region where the concrete quality is the poorest is supposed to corrode earlier than elsewhere.

In order to consider the variations of properties, the probabilistic approach should be adapted in the diffusion analysis. There are several prediction methods including Monte Carlo Simulation (MCS) methods, the first-order reliability method (FORM), the second-order reliability method (SORM) [1], and the other [12]. In this study, a MCS method has been used.

A. Serviceability Limit States

The durability design concerns serviceability limit states such as corrosion due to chloride penetration, corrosion due to carbonation, surface deterioration, frost attack, etc. For concrete structures located near seashore, the most significant durability problem is the chloride penetration which results in a corrosion of reinforcing steel embedded in concrete. After depassivation or onset of steel corrosion, it may take several years before any visual sign of deterioration such as cracking and spalling will occur, and it may still take a very long time before the structural capacity or integrity becomes significantly reduced. However, since the time to depassivation, that is when the chloride ion concentration at steel reaches the critical value and the corrosion may start, represents both a reasonable and well defined stage of deterioration process, it appears appropriate to define this stage as the serviceability limit state in the durability analysis [3,4]. With this definition, the limit state function can be written as equation (1).

$$g(\mathbf{X},t) = R(t) - S(t) \tag{1}$$

in which, **X** is the design variable vector defining limit state function *g*, *t* is time, *R(t)* and *S(t)* are time dependent variables representing resistance and load, respectively. In chloride penetration problems, resistance and load are defined as steel cover and chloride ion penetration depth whose concentration reaches critical value, respectively.

B. *Durability Model*

The rate of chloride penetration into concrete as a function of depth is normally modeled by using Fick's Second Law of Diffusion.

$$\frac{\partial C(x,t)}{\partial t} = D(t)\frac{\partial^2 C(x,t)}{\partial x^2} \tag{2}$$

where, *C(x,t)* is chloride ion concentration at a distance *x* from the concrete surface after being exposed for a time *t*, and *D(t)* is the chloride diffusion coefficient dependent on the time *t*. Because the diffusion coefficient varies with ages, the aging effect can be considered as follows,

$$\frac{\partial C(x,t)}{\partial T} = \frac{\partial^2 C(x,t)}{\partial x^2} \quad , \quad T = \int_0^t D(\tau)d\tau \tag{3}$$

Generally, the time dependent function *D(t)* can be written as equation (4). [6]

$$D(t) = D_0\left(\frac{t_0}{t}\right)^n \qquad (t < t_c) \tag{4a}$$

$$D(t) = D_0\left(\frac{t_0}{t_c}\right)^n = const. \qquad (t > t_c) \tag{4b}$$

where, D_0 is the diffusion coefficient at time t_0 and the exponent represents the ability of the concrete to increase the resistance against chloride penetration with time. In order to prevent the diffusion coefficient decreasing with time indefinitely, the relationship shown in equation (4) is expressed by decreasing limit time t_c (= 30 years). Beyond this time, the value at time t_c calculated from equation (4b) is assumed to be constant throughout the rest of the analysis period. By substituting equation (4) into equation (3), T is obtained as

$$T = D_m t = \frac{D_0}{1-m}\left(\frac{t_0}{t}\right)^m t \qquad (t < t_c) \tag{5a}$$

$$T = D_m t = D_0\left[1+\frac{t_c}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_0}{t_c}\right)^m t \qquad (t < t_c) \tag{5b}$$

where, D_m is the mean diffusion coefficient from initial time 0 to analysis time *t*. From appropriate initial and boundary conditions and by substituting equation (5) into equation (3), an expression is obtained that permits the prediction of chloride levels based on time-dependent diffusion coefficient

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_m t}}\right)\right] \tag{6}$$

where C_S is the chloride ion concentration on the concrete surface and erf is the error function.

C. *Probabilistic Analysis*

In this study, the probabilistic analysis was carried out by using a Monte Carlo Simulation Method (MCSM). The limit state function was derived from equation (6) by defining the depth of chloride penetration at time t when the Cl^- concentration reaches pre-defined threshold value. The depth can be written as follows;

$$x(t) = 2erf^{-1}\left(1 - \frac{C_{cr}}{C_s}\right)\sqrt{D_m t} \tag{7}$$

where, C_{cr} is the threshold value of chloride ion concentration at which the depassivation of the steel reinforcement occurs and D_m is defined by equation (5).

The resistance *R(t)* in equation (1) is defined as the concrete cover. At every simulation, the input variables are randomly generated according to the given probabilistic distributions and the value of the limit state function is calculated. If it is positive, the case is counted as SAFE, if not FAIL. The probability of failure is defined by equation (8).

$$p_f = \frac{1}{N}\sum_{j=1}^{N} I\left[g\left(r_j, s_j\right)\right] \tag{8}$$

where, N is the number of simulations, $g(r_j,s_j)$ is limit state function, and $I(\cdot)$ is indicator function. The design with structural reliability theory requires to meet the target reliability level or the reliability index can be calculated from equation (8).

III. PARAMETER ANALYSIS

A. *Comparison of deterministic and probabilistic analysis*

As a first study, the deterministic and probabilistic analysis methods are compared with the parameters shown in Table 1. In order to vary the diffusion coefficients, water-binder ratio was changed from 0.25 to 0.40, which correspond to the diffusion coefficient 3.4674×10^{-12} to 7.9433×10^{-12} m^2/s. The aging coefficient 0.4 was used assuming fly-ash replaced cement by 25 %.

Table 2 shows the results obtained using the deterministic and probabilistic methods. The corrosion initiation time of the probabilistic method represents when the corrosion initiation probability is equal to the targeted value (i.e. 10, 25, or 50%). From the results, it can be known that the prediction results using the deterministic method correspond to probabilistic prediction with 50% of the corrosion initiation probability.

TABLE I. Parameters Used in the Analysis

Parameters		**Average**	**COV (%)**
Surface chloride concentration, C_s(%)		0.8	20
Critical chloride concentration, C_{cr} (%)		0.05	10
Cover depth, x (mm)		75	10
Diffusion coefficient, D_0 ($\times 10^{-12}$ m^2/s)	Analysis A.	3.47 – 7.94	20
	Analysis B.	4.57	10, 20, 30
Aging coefficient, m	Analysis A.	0.4	20
	Analysis B.	0.4	10, 20, 30
Time to build up (yrs)		0	
Time to propagate (yrs)		0	

TABLE II. Comparison between deterministic and probabilistic analysis

Mixtures	**D_0 ($\times 10^{-12}$ m^2/s)**	**Corrosion initiation time (years)**			
		Deterministic method	**Probabilistic method - Corrosion initiation probability**		
			10%	25%	50%
W/B=0.25, FA 25%	3.47	60.3	26.0	38.7	59.8
W/B=0.30, FA 25%	4.57	41.8	17.0	25.9	41.3
W/B=0.35, FA 25%	6.03	27.8	10.3	16.4	27.3
W/B=0.40, FA 25%	7.94	17.6	6.19	10.1	17.1

B. *Influence of material property distributions*

Since only average properties are used in the deterministic analysis method, distributions of the diffusion properties do not influence the service life prediction at all. However, in the probabilistic analysis method, the distributions influence the prediction results. In this section, the influence of material property's distributions has been investigated on the service life of concrete structures. Table 1 lists the parameters used in the analysis. The COVs of the diffusion and aging coefficients are varied from 10% to 30%.

Analysis results are shown in Figure 1 and Table 3 with respect to the COVs of diffusion and aging coefficients. At a glance, it can be noticed that the COVs influence the corrosion initiation probability a lot. The corrosion probability, especially for within 30 years, increases with an increase in COVs of D_0 and m. For an example, corrosion probability at 20 years varies from 6.1% to 21.4% as the COVs changes from 10% to 30%. The results also show that the corrosion imitation time can vary with the changes of the distributions even though the average values are not changed. This can imply that the poor quality control of concrete material can cause a decrease in the service life of the concrete structures.

TABLE III. Corrosion initiation probabilities with respect to the time and COVs

Time (years)	**COVs of D_0 and m**		
	10%	**20%**	**30%**
10	0.1	2.1	7.0
20	6.1	14.8	22.4
30	24.7	32.2	36.9
40	47.4	48.2	48.7

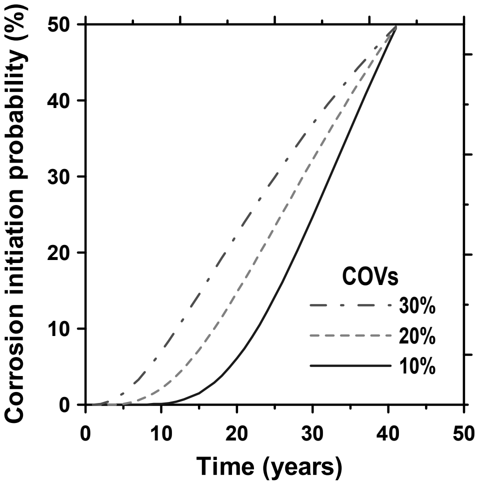

Fig.1. Corrosion initiation probability with respect to COVs of diffusion properties

IV. CONCLUSIONS

This study shows the influence of diffusion properties on the service life of concrete structures.

(1) The influence of material property distribution has been investigated using the probabilistic diffusion analysis method. The results show that the deterministic prediction corresponds to probabilistic analysis results with 50% of the corrosion initiation probability. The results also show that the corrosion imitation time can vary with the change of the property distributions even though the average values are not changed.

(2) The distribution of diffusion properties is one of the important factors influencing the service life of concrete structure under chloride exposed environment. The diffusion property distributions do not influence the deterministic predictions. However, the probabilistic analysis results conducted considering the distributions of the parameters shows the importance of the distribution of diffusion properties. As the COVs of diffusion properties increase, the corrosion initiation probability increases. This implies that proper quality control, which can guarantee small variations of material properties, must be fulfilled in order to insure the service life of concrete structures.

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