

A Micro-Mechanics Based Corrosion Model for the Prediction of Service Life in Reinforced Concrete Structures

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Reinforcing steel bars in reinforced concrete structures are protected from corrosion by passive film on the steel surface inside concrete with high alkalinity. However, when the passive film breaks down due to chloride ion ingressed into the RC structures, a corrosion initiates at the surface of steel bars. Then, internal pressure by volume expansion of corrosion products in reinforcing bars induces cracking and spalling of cover concrete, which reduces not only durability performance but also structural performance in RC structures. In this paper, a service life prediction of RC structures is carried out by using a micro-mechanics based corrosion model. The corrosion model is composed of a chloride penetration model to evaluate the initiation of corrosion and an electric corrosion cell model and an oxygen diffusion model to evaluate the rate and the accumulated amounts of corrosion. Then, a corrosion cracking model is combined to the models to evaluate critical amount of corrosion product for initiation cracking in cover concrete. By implementing the models into a finite element analysis program, a time and space dependent corrosion analysis and a service life prediction of RC structures due to chloride attack are simulated and the results of the analysis are compared with test results. The effect of crack width on the corrosion and the service life of the RC structures are analyzed and discussed.

Keywords : reinforced concrete structures, corrosion, chloride ions, crack, service life

1. Introduction

Steel corrosion is a major deterioration in reinforced concrete (RC) structures. Volume expansion due to the rust in reinforcing bars occurred by the corrosion induces cracking and spalling of the cover concrete so that both durability performance and structural performance in RC structures are degraded. For the accurate prediction of service life of RC structures, it is necessary to develop an analytical model of steel-corrosion for the prediction of corrosion initiation as well as corrosion induced cracking.

This paper focuses on corrosion analysis of RC structures due to chloride attack at different environmental exposures. Chloride ions attack the passive layer of the steel surface and makes the corrosion to occur quickly. In order to predict the service life of RC structures due to the corrosion, we develop a corrosion model based on micro-mechanics, which considers micro-structure characteristics, cover concrete quality and pre-existing early-age crack. Using the proposed model, a corrosion analysis on the initiation of micro-cell corrosion, cracking due to

corrosion and service life prediction of RC structures considering different crack widths of cover concrete is carried out.

2. Chloride diffusion-penetration model

Chloride ions inside concrete transports as bulk movement of pore solution due to difference of ion concentration. For analysis of the chloride transport, a governing equation of mass transfer can be expressed as Eq(1).

$$\alpha_i \frac{\partial C_{cl}}{\partial t} + \text{div} J_{cl} + Q_{cl} = 0 \quad (1)$$

where, α_i is specific capacity, C_{cl} is amount of chloride ions, J_{cl} is diffusion flux of chloride ions and Q_{cl} is sink term.

The diffusion flux of chloride ions in unsaturated concrete, J_{cl} , can be represented as the sum of capillary absorbed flux, J_{ca} , and diffusion flux by concentration gradients, J_{df} , as expressed as Eq(2). The chloride diffusion coefficient, D_{cl} , can be expressed as Eq(3) by considering the effects of temperature, aggregate and humidity based

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on the Nernst-Planck's equation and the Debye-Hückel's theory.

$$J_{cl} = J_{ca} + J_{df} \quad (\text{mol}/\text{m}^2 \cdot \text{s}) \quad (2)$$

$$D_{cl} = D_{cl,ref} \cdot f_1(g_i) \cdot f_2(T) \cdot f_3(h) \quad (3)$$

where, $D_{cl,ref}$ is a referential chloride diffusion coefficient, $f_1(g_i)$ is a function of the aggregate, $f_2(T)$ is a function of temperature and $f_3(h)$ is a function of humidity.

In order to consider the crack effects on D_{cl} , the equivalent chloride diffusion coefficient D_{cl}^{eq} is obtained as Eq(4) by applying an averaging method on REV(Representative Elementary Volume) with crack model.¹⁾

$$D_{cl}^{eq} = \left(\frac{\Omega D_{crack}}{R_a \theta} + D_{cl} \right) \quad (4)$$

where, $R_a (=A_o / A_{cr})$ is ratio of total area and crack area in the REV, D_{crack} is diffusion coefficient in crack element, Ω is tortuosity of pore-structures, and $\theta (= \phi S)$ is volume

ratio of liquid state (multiply of porosity and saturation).

The chloride ion in cementitious materials have free and bound components. The bound components are fixed chlorides such as Friedel's salt. Only the free chlorides in the pore solution are related to the corrosion. The fixed and the free chloride contents can be calculated by fixed chloride factor and the free chloride content is an indicator of corrosion generation or corrosion rate.²⁾ Also the chloride threshold is specified in terms of the amount of the free chlorides in pore solution.

Fig. 1 shows the overall scheme of a chloride diffusion-penetration model for early-age concrete based on the framework³⁾ of early-age behaviors including heat of hydration, pore structure and moisture transfer.

3. Steel corrosion model

In this study, the corrosion is assumed as the micro-cell corrosion, in which the corrosion occurs uniformly over the surface of steel bar. A corrosion-cell model and an oxygen diffusion model are used to explain corrosion of the steel bars in the concrete at splash zone and at submerged zone, respectively, as shown in Fig. 2, based on

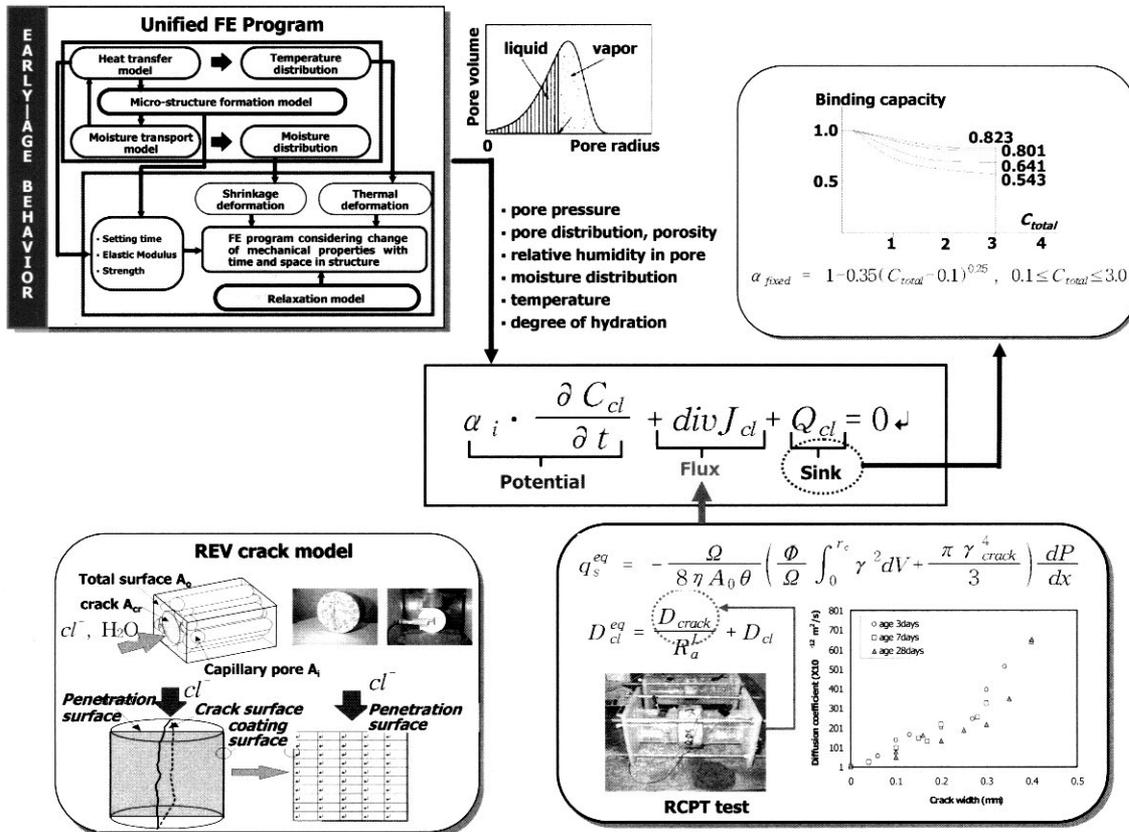


Fig. 1. Chloride diffusion- penetration model

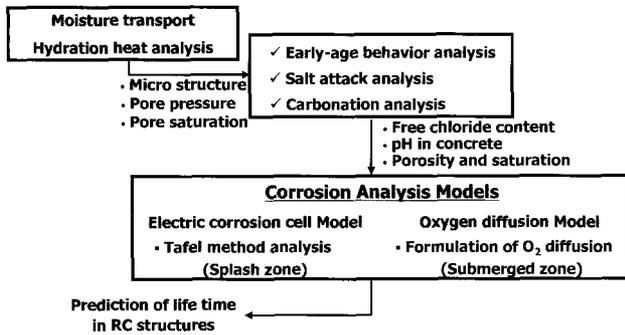


Fig. 2. Computational flow of steel corrosion model

the analyses transport of moisture, hydration heat, salt attack and carbonation. The polarization is classified into an activation polarization and a concentration polarization according to the amount of oxygen supplied from the environment. Fig. 2 shows a computational flow of the corrosion analysis combined with the corrosion-cell model and the oxygen diffusion model.

3.1 Electric corrosion-cell model

When the amount of supplied oxygen is enough, the corrosion rate is controlled by formation of passive layers, pH of pore water, and free chloride contents. Then, the corrosion rate is calculated by Tafel's method. The states of passive layers are shown in 3 stages according to free chloride contents as shown in Fig. 3 ; (1) When the passive layer on the surface of reinforcing bars is existed, the corrosion does not occur. This stage is described by

changing the Tafel gradient. In this stage, the cathodic Tafel gradient becomes double and the anodic Tafel gradient becomes infinite. Therefore, the corrosion rate for this stage is assumed to be the exchange current density of iron. (2) When the free chloride contents exceeds a critical chloride threshold (Fig. 3), the corrosion of reinforcing bars is initiated due to the breakdown of passive layers. Since the anodic Tafel gradient becomes decreasing with higher concentration of chlorides, the corrosion current density is increasing. (3) When enough chlorides is accumulated, the rate of corrosion does not increase any more even with new chlorides from the environment. In case of total break-down of passive layers, we assumed that the corrosion current density is only controlled by the pH of pore water.⁴⁾

In this study, the critical chloride threshold for initiation of corrosion is assumed to be 1.2 kg/m³ and it is also assumed that the passive layers are not existed when chloride contents exceeds to 2.4 kg/m³.⁵⁾ The critical values of total chloride contents are converted into the free chloride contents per unit cement weight as explained in Fig. 3. Only the free chloride ions is related to the corrosion of reinforcing bars.

When the passive layers are destroyed, the corrosion current density is determined by a relationship between electric potential and activation overcharge. As shown in Table 1, the corrosion current density is changing according to the condition of the passive layers in the electric corrosion-cell model. The corrosion rate, R_{corr} , which

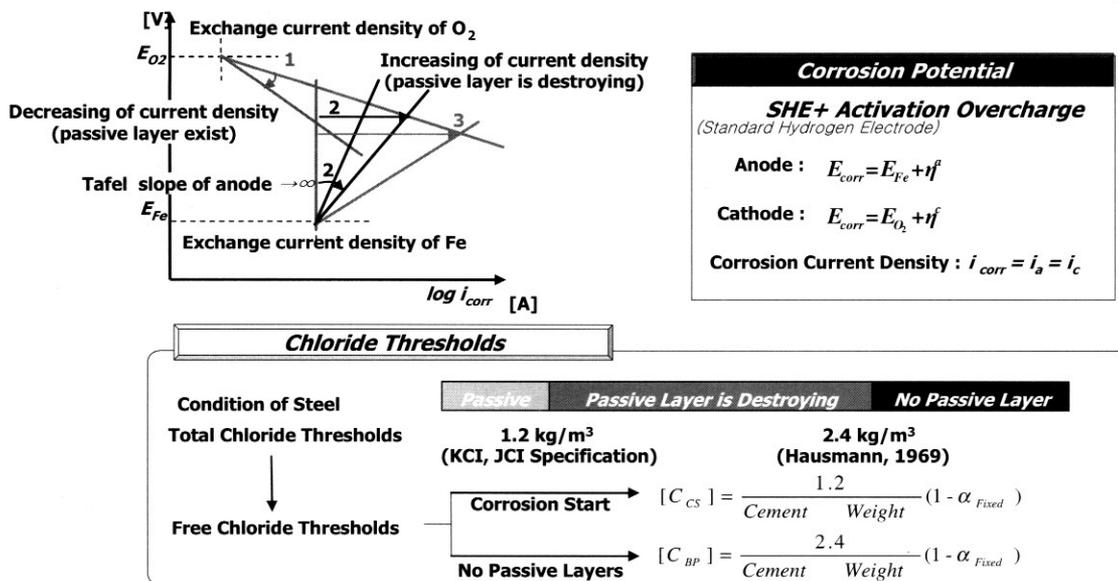


Fig. 3. Electric corrosion cell model

Table 1. Corrosion current density with condition of the passive layers

Condition of the passive layers	Corrosion current density (A/m ²)
Exist	$\log i_{corr} = \log i_{O_{Fe}}$
Being destroyed	$\log i_{corr} = \frac{0.998 - 0.06 pH - 0.059 \log i_{O_{O_2}} + \beta \log i_{O_{Fe}}}{\beta + 0.059}$ $\beta = \frac{0.059 \times (BPF - CSF)}{[Cl^-] - CSF}$ <p>CSF : Free chloride contents(% wt of cement) for the stage of corrosion BPF : Free chloride contents(% wt of cement) for the stage of no passive layers</p>
No exist	$\log i_{corr} = 8.458 - 0.508 pH + 0.5 \log i_{O_{O_2}} + 0.5 \log i_{O_{Fe}}$

defines as the amount of corrosion products, is determined by Faradays law as in Eq(5).⁶⁾

$$R_{corr} = \phi S \frac{M_{Fe} i_{corr}}{z_{Fe} F} \quad (kg/m^2 \cdot s) \quad (5)$$

3.2 Oxygen diffusion model

Corrosion requires the oxygen, O₂, which is consist of gaseous oxygen and dissolved oxygen, supplied from exposed environment. When the amount of oxygen supplied for the corrosion is not enough, the corrosion of reinforcing bars does not propagate although free chloride contents exceeds the critical value. This phenomenon can be seen in RC structures at submerged zone where the oxygen supplied from environment is not enough. In this case, the rate of corrosion is limited by slow diffusion of oxygen. Therefore, when the oxygen supplied is not enough, the corrosion current density is assumed to be a limit current density, which is obtained from oxygen diffusion model. A governing equation of the oxygen diffusion model based on conservation law of oxygen in concrete is as follows.⁶⁾

$$\frac{\partial}{\partial t} \{ \phi [(1-S) \cdot \rho_{gO_2} + S \cdot \rho_{dO_2}] \} + \text{div} J_{O_2} - Q_{O_2} = 0 \quad (6)$$

where, ϕ is porosity of the porous media, S is degree of saturation of the porous media, ρ_{dO_2} is density of dissolved O₂ in pore water (kg/m³), ρ_{gO_2} is density of gaseous O₂ (kg/m³), J_{O_2} is total flux of dissolved and gaseous O₂ (kg/m²s), and a sink term Q_{O_2} , which represents the rate of O₂ consumption due to corrosion (kg/m³s), is calculated by Faraday's law as shown in Eq(7).

$$Q_{O_2} = -\phi S \frac{M_{O_2} i_{corr}}{z_{O_2} F} \cdot \frac{A_{bar}}{V_{elem}} \quad (7)$$

where, M_{O_2} is molecular weight of O₂, i_{corr} is corrosion current density, z_{O_2} is the number of electric charge of O₂, A_{bar} is surface areas of reinforcing bars in a referential finite volume, V_{elem} is referential finite volume.

By considering tortuosity and connectivity of pores in concrete, the diffusion coefficient of gaseous O₂, D_{gO_2} , and the diffusion coefficient of dissolved O₂, D_{dO_2} , respectively, can be written as Eq(8). Then, a total flux of dissolved and gaseous O₂, J_{O_2} , can be expressed as Eq(9) with the molecular diffusion and the Knudsen diffusion. Besides, equivalent diffusion coefficient for cracked concrete, D_{eq} , is proposed as Eq(10), which is based on the 1-D isotropic crack model.⁷⁾

$$D_{gO_2} = \frac{\phi D_O^g}{\Omega} \frac{(1-S)^4}{1 + l_m / 2(r_m - t_m)}, \quad D_{dO_2} = \frac{\phi S^4}{\Omega} D_O^d \quad (8)$$

$$J_{O_2} = -(D_{gO_2} \nabla \rho_{gO_2} + D_{dO_2} \nabla \rho_{dO_2}) = -(D_{gO_2} K_{O_2} + D_{dO_2}) \nabla \rho_{dO_2} \quad (9)$$

$$D_{eq} = -\frac{1}{L_1} [\{ (L_1 - 0.5L_4)(D_{gO_2} K_{O_2} + D_{dO_2}) \} + 0.5L_4 D_O^d] \quad (10)$$

where, Ω is a parameter for tortuosity of pores, r_m is average radius of unsaturated pores, t_m is thickness of absorbed water layer in the pore whose radius is r_m , and D_O^d is diffusion coefficient of dissolved O₂ ($=1.0 \times 10^{-9}$ m²/s). Fig. 4 shows an outline of the aforementioned oxygen diffusion model.

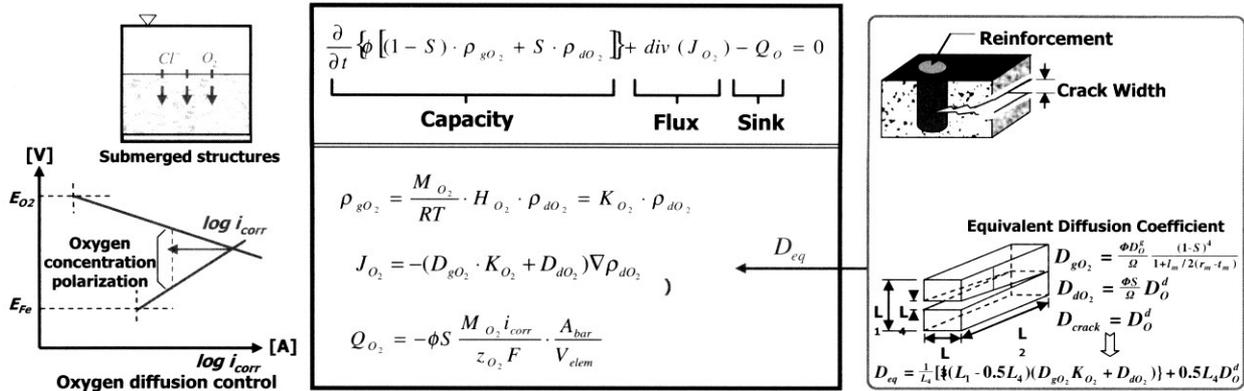


Fig. 4. Oxygen diffusion model

4. Service life and corrosion cracking

The process of the deterioration in concrete structures due to corrosion can be classified into four periods with time as shown in Fig. 5 ; initiation period, propagation period, acceleration period and deterioration period. In this study, the service life is defined as a time for the corrosion

initiation, i.e., when a chloride concentration reaches to the critical chloride threshold value (1.2 kg/m³ of total chloride content) at surface of rebar. Also the cracking time of structures is defined as a time interval from the initiation of corrosion to corrosion cracking in concrete cover. Then, the service life of RC structures can be predicted by the aforementioned chloride diffusion-

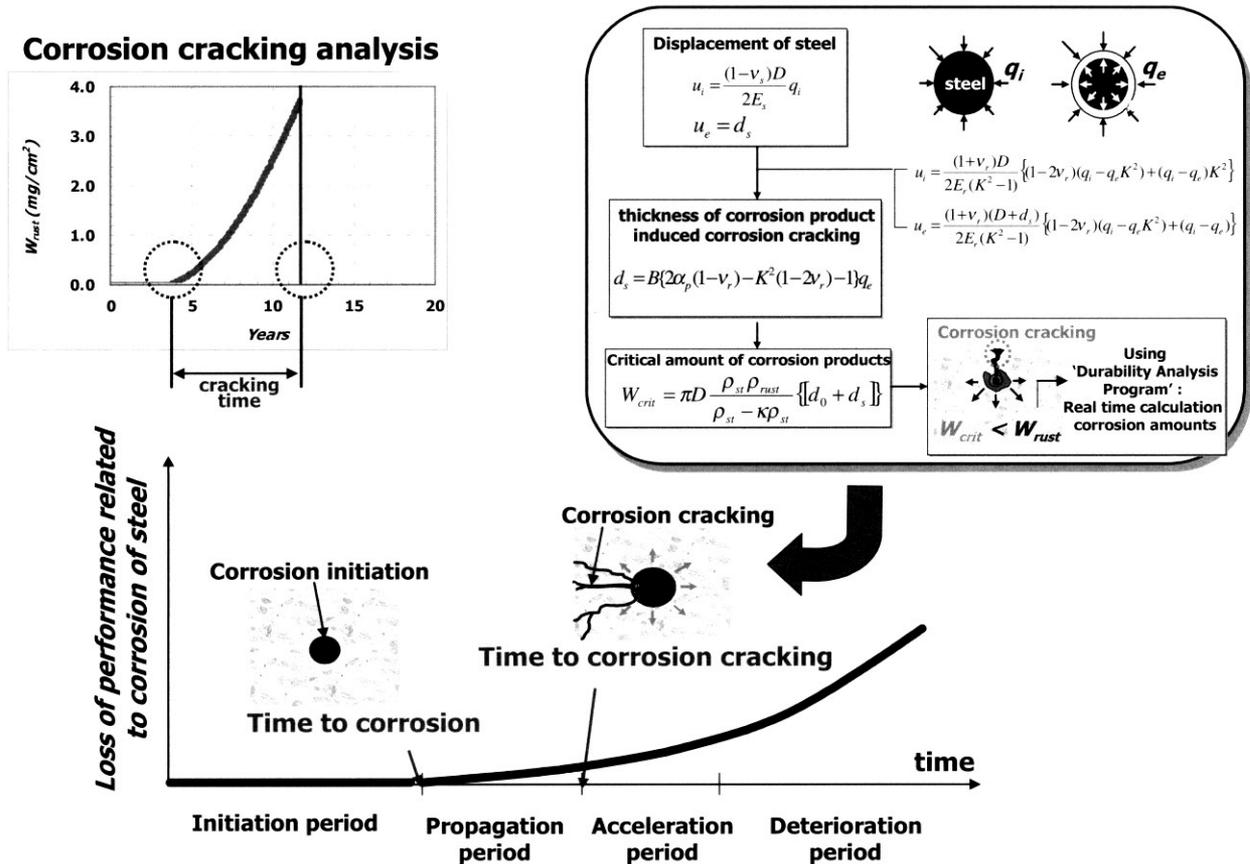


Fig. 5. Service life and corrosion cracking due to corrosion in concrete structure

penetration model. In order to predict the cracking time in the RC structures, a corrosion cracking model is also necessary for calculation of the critical amount of corrosion product, W_{crit} , at any given cover depth. For that purpose, the corrosion cracking model by Liu and Weyer⁸⁾ based on internal pressure q and radial displacement u of steel is modified as shown in Fig. 5. From the corrosion cracking model, $3 \text{ mg/cm}^2 \sim 10 \text{ mg/cm}^2$ of W_{crit} is calculated.⁹⁾ The model assumes that the corrosion cracking occurs when accumulated corrosion amount, W_{rust} , reaches to the W_{crit} .⁸⁾

Verification of the chloride diffusion-penetration model was carried out first by considering the variation of diffusion coefficient with time and existing cracks. Table 2 shows conditions for laboratory test and the analysis. The analysis results using the model were compared with the test results.

Fig. 6(a) shows that the analysis predicts the variation of free chloride contents according to the distance from surface of concrete cover with different crack widths. Fig.

Table 2. Conditions for laboratory test and analysis

Binding condition			Initial condition		
Temp	Relative humidity	Surface chloride content	Temp.	Relative humidity	Surface chloride content
20°C	Salt spray : RH = 90%	0.5mol/l	20°C	RH = 100%	0mol/l

6(b) shows the analysis predicts penetration depth comparably well according to different crack widths. Fig. 6(c) shows a comparison of the analysis with the results by the Fick's equation and the well-known Life365 program to see the effect of the chloride diffusion coefficients. For the cases with high cover depths, the Fick's equation overestimates chloride contents twice as much. For a verification of the analysis with data for long-term exposed RC structures, the analysis for an RC pier of bridge at submerged zone (Fig. 7(a)) exposed to marine environment for 10 years is carried out and the result is compared

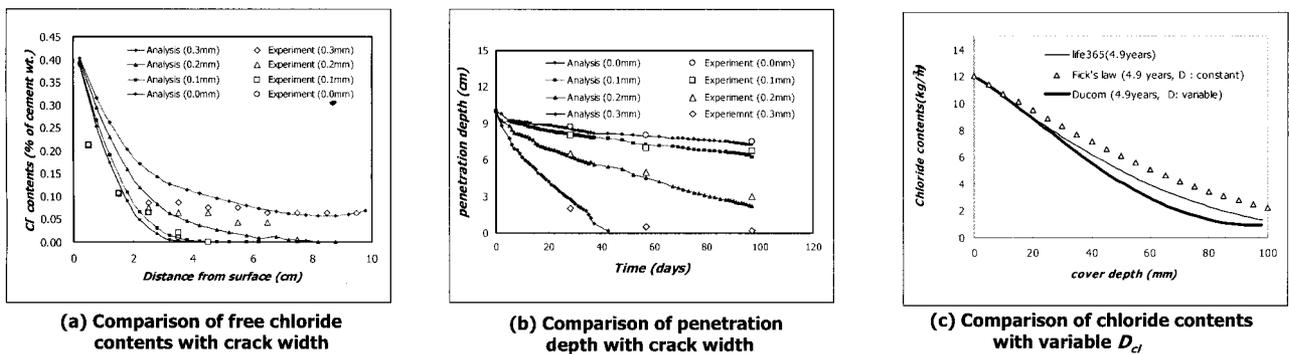


Fig. 6. Chloride contents with variable diffusion coefficient

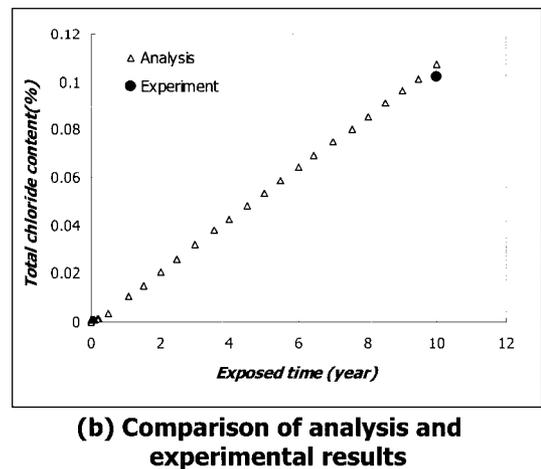
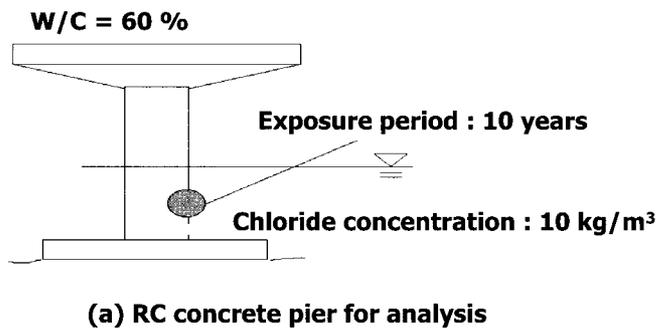


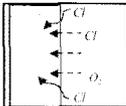
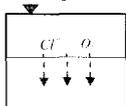
Fig. 7. Verification of the analysis for long term exposed structure

with experimental one (Fig. 7(b)). Fig. 7(b) shows a good agreement between the results.

The simulation of corrosion for concrete structures both at splash area and at submerged area are also carried out. Table 3 shows mix proportions and environmental conditions used for analysis. Fig. 8 shows results of the simulation on corrosion rate and accumulated corrosion amounts. The structures in splash zone are defined as RC structures which are exposed to an environment of constant supply of chloride and ample supply of oxygen.

As shown in Fig. 8(a), the structures in splash zone have a tendency to corrode at higher rates than the structures in submerged zone. Under the condition of splash zone, corrosion initiation of the structures is calculated to be occurred within 10 years and corrosion cracking is also simulated to be occurred within 20 years. As shown in Fig. 8(b), there is not enough oxygen for corrosion to propagate for the structures in the submerged zone. Hence, the structures are simulated to corrode but at lower rate of propagation with late corrosion cracking than the structures in splash zone. It is also shown that the decrease of the pH of pore water and the increase of the water to cement ratio of concrete directly affect fast corrosion. The results show that reduction of the pH accelerates slope of corrosion rate and makes corrosion cracking earlier. In the case of pH = 9, the corrosion rate is evaluated as high corrosion condition of 0.07 A/m².

Table 3. Mix proportions and environmental conditions for analysis

Mix proportions					
W/C	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)		
45	365	735	1102		
65	246	867	1059		
Environmental conditions					
Location	W/C	pH	External chloride concentration (mol/l)	Relative humidity (%)	Temperature (°C)
Splash zone 	45, 65	9~11	0.35	70	20°C
Submerged zone 	45, 65	10, 11	0.50	100	20°C

For cracked concrete, about 2~4 times of higher chloride penetration was analyzed than that of sound concrete, so that the service life is shortened to about a half. Especially, significantly rapid propagation of corrosion is observed

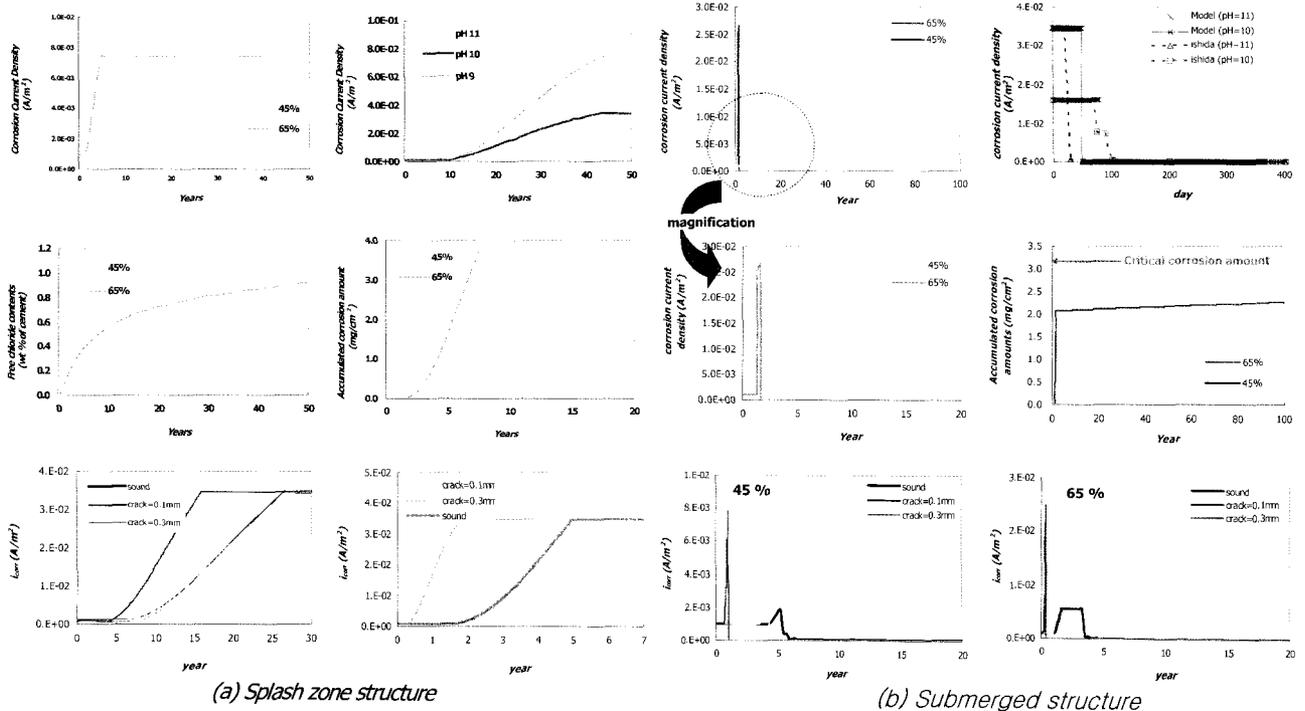


Fig. 8. Simulation of corrosion rate and accumulated corrosion amounts

when crack width is larger than 0.1mm for the case of higher water to cement ratio concrete. Since the structures in splash or submerged zone are in high chloride attack condition, it was found that the service life is generally very short.

5. Conclusions

The chloride diffusion coefficient of concrete and the amount of supplied oxygen to the concrete are major important factors affecting the service life of reinforced concrete structures. Since, existing service life prediction models do not consider those factors, the chloride content to be penetrated to the RC structures are overestimated so that the service life of concrete structures is sometimes underestimated. In this paper, a chloride penetration model which considers the early-age behavior of concrete and time/space dependent chloride diffusion coefficient of concrete and an oxygen diffusion model which considers amount of supplied oxygen as in submerged structures is proposed. In order to predict the service life of RC structures under chloride attacks, a microscopic steel corrosion model as well as a corrosion cracking model are also proposed and implemented into a finite element analysis program. From the corrosion analysis for cracked concrete structures both at splash zone and at submerged

zone, it was found that the service life of RC structures become shortens with increasing crack width, increasing water to cement ratio, and decreasing pH of pore water.

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