A Micro-mechanics Based Corrosion Model for Predicting the Service Life of Reinforced Concrete Structures

Ha-Won Song*, Ho-Jin Kim, Velu Saraswathy and Tae-Hwan Kim

School of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, KOREA
*E-mail: song@yonsei.ac.kr

In reinforced concrete structures, the steel rebars embedded in concrete are protected from corrosion by passive film on the steel surface due to high alkalinity. Corrosion is initiated by the ingress on chloride ions which leads to the break down of passive film formed on the steel surface. Once corrosion has initiated accumulation of corrosion products occurs on the steel surface. Since these products occupy a volume several times larger than that of the original steel, the result is thus an increase of the internal tensile stresses leading to cracking and spalling of cover concrete, which not only reduces the durability performance but also affect the structural properties of reinforced concrete(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 consists 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 products. Then, a corrosion cracking model is combined with the above models to evaluate the critical amount of corrosion product required 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 the results. The effect of crack width the corrosion and the service life of the RC structures are analyzed and discussed.

1.0 INTRODUCTION

Corrosion of reinforcing bars is one of the main causes which induce an early deterioration of concrete structures, reducing their residual service life. The resistance to corrosion initiation and further propagation is provided by two barriers: a) the resistance of the concrete cover to chloride

penetration which depends on its thickness, and permeability and b) the resistance of the reinforcement bars to corrosion which in turn depends on the type of steel and the alkalinity of the surrounding concrete and the composite action of both concrete and steel, due to the bond deterioration [1],[2],[3],[4]. Corrosion damage in concrete structure is usually manifested by rust-staining of the surface and by cracking and spalling of the concrete cover due to the expansion of the corrosion products and thereby affecting the durability performance and structural performance of RC structures.

In order to predict the service life of RC structures accurately, it is necessary to develop an analytical model of steel-corrosion for the prediction of corrosion initiation as well as corrosion induced cracking. Most of the research has been concerned with modeling the diffusion of chloride ions through un-cracked concrete based on Fick's second law [5]. However, in practice, it is very common to have cracks in concrete structures in chloride environments. In cracked concrete, corrosion initiation takes place much faster than the uncracked concrete [6]. The initiation of steel corrosion in cracked concrete is dependent on the surface crack width [7]. Wider crack widths have been found to induce corrosion much faster than relatively smaller ones [8],[9],[10]. It has been reported that, increased cover thickness in cracked concrete, reduced the corrosion initiation time [11,12]. This is because corrosion of steel depends on the availability of oxygen. Thus it is recognized that both crack width and cover thickness do affect the initiation of steel corrosion in concrete.

This paper focuses on corrosion analysis of RC structures due to chloride attack at different environmental exposures. In order to predict the service life of RC structures due to the corrosion, a model is developed 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 were carried out.

1.1. 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).

$$\alpha_i \frac{\partial C_{cl}}{\partial t} + div J_{cl} + Q_{cl} = 0 \tag{1}$$

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

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

$$D_{cl} = D_{cl_{ref}} \cdot f_1(g_i) \cdot f_2(T) \cdot f_3(h)$$ (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 [13].

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

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

The chloride ion in cementitious materials has 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 [14]. 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 framework [15] of early-age behaviors including heat of hydration, pore structure and moisture transfer.

1.2. 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 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.
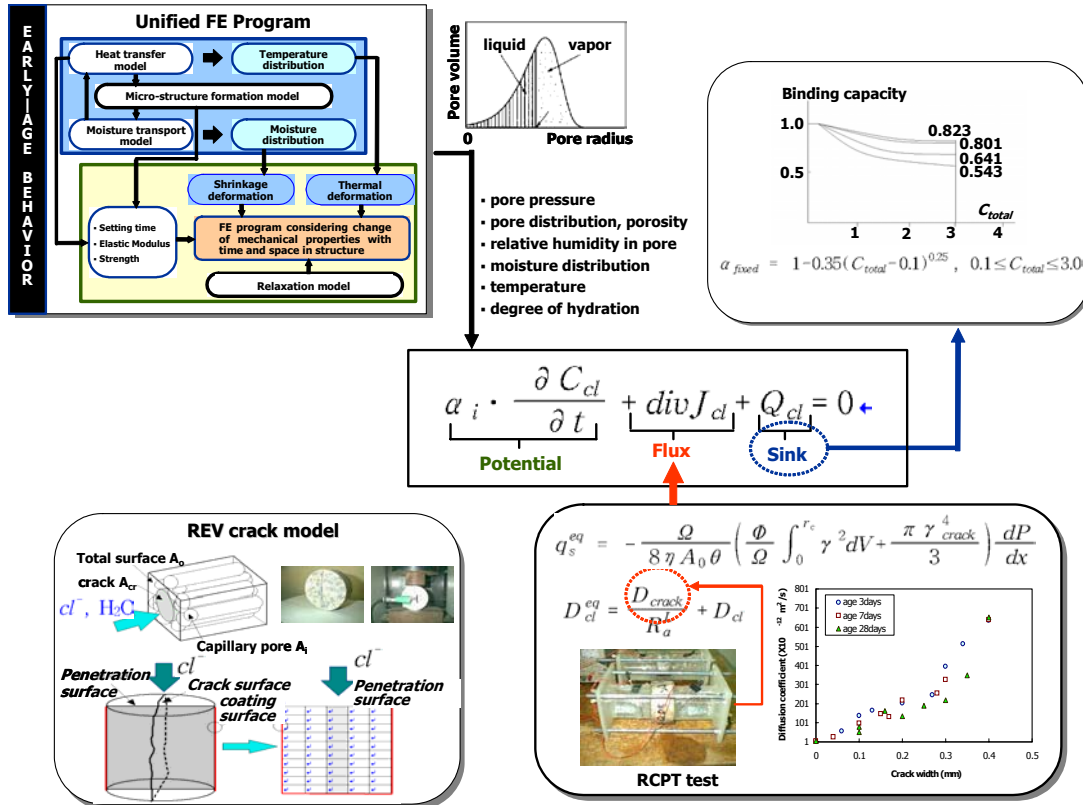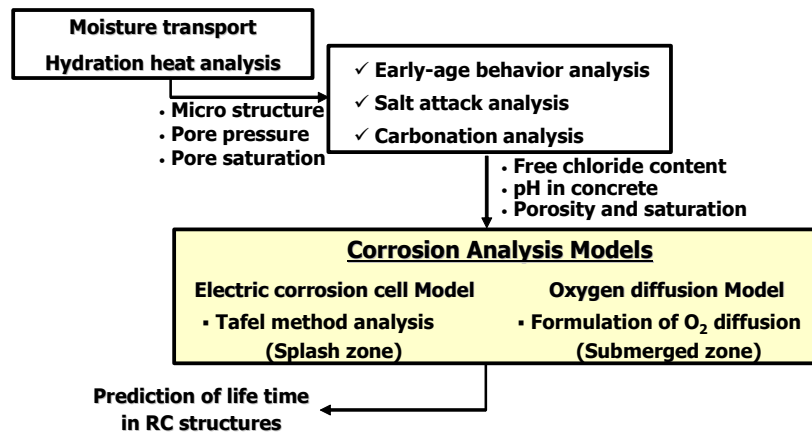

Figure 1. Chloride diffusion- penetration model

Figure 2. Computational flow of steel corrosion model

1.2.1. Electrochemical 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 exist on the surface of reinforcing bars, 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 content exceeds a critical threshold value (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 chloride 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, the authors assumed that the corrosion current density is only controlled by the pH of pore water [16].
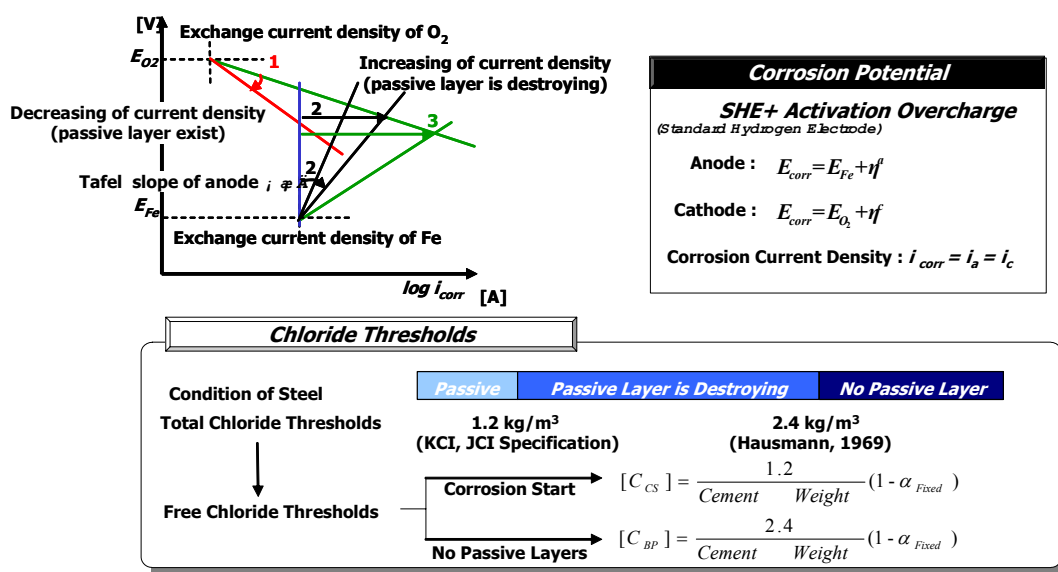

Figure 3. Electrochemical corrosion cell model

In this study, the critical chloride threshold value for initiation of corrosion is assumed to be $1.2 kg/m^3$ and it is also assumed that the passive layers are not existing when chloride contents exceeds $2.4 kg/m^3$ [17]. 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 are 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 defines as the amount of corrosion products, is determined by Faradays law as in Eq.(5) [18].

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

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	$\log i_{corr} = \dfrac{0.998 - 0.06 pH - 0.059 \log i_{O_2} + \beta \log i_{O_{Fe}}}{\beta + 0.059}$ $\beta = \dfrac{0.059 \times (BPF - CSF)}{[Cl^-] - CSF}$ 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
Not exist	$\log i_{corr} = 8.458 - 0.508 pH + 0.5 \log i_{O_2} + 0.5 \log i_{O_{Fe}}$

1.2.2. Oxygen Diffusion Model

Corrosion requires oxygen, which consist of gaseous oxygen and dissolved oxygen, supplied from the environment. When the amount of oxygen supply is not enough, the corrosion of reinforcing bars does not propagate although free chloride content exceeds the critical value. This phenomenon can be seen in RC structures at submerged zone where the oxygen supplied from the environment is not enough. In this case, the rate of corrosion is limited by slow diffusion of oxygen. Therefore, when the oxygen supply is not enough, the corrosion current density is assumed to be a limiting 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 [18].

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

where, ϕ is porosity of the porous media, S is degree of saturation of the porous media, ρ_{dO_2} is density of dissolved O_2 in pore water (kg/m^3), ρ_{gO_2} is density of gaseous O_2 (kg/m^3), J_{O_2} is total flux of

dissolved and gaseous O_2 (kg/m^{2}s), and a sink term Q_{O_2}, which represents the rate of O_2 consumption due to corrosion (kg/m^{3}s), is calculated by Faraday's law as shown in Eq(7).

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

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

By considering tortuority and connectivity of pores in concrete, the diffusion coefficient of gaseous O_2, D_{gO_2}, and the diffusion coefficient of dissolved O_2, D_{dO_2}, can be written as Eq.(8). Then, the total flux of dissolved and gaseous O_2, 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 [19].

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

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

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

where, Ω is a parameter for tortuority 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 O_2 ($=1.0 \times 10^{-9}$ m^2/s). Fig. 4 shows an outline of the aforementioned oxygen diffusion model.

2. SERVICE LIFE AND CORROSION CRACKING

The deterioration process 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 the time for the corrosion initiation, i.e., when a chloride concentration reaches the critical threshold value (1.2kg/m^3 of total chloride content) at

surface of rebar. Also the cracking time of structures is defined as the 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-penetration model. In order to predict the cracking time in RC structures, a corrosion cracking model is also necessary for calculation of the critical amount of corrosion product, W_{crit}, at any cover depth. For that purpose, the corrosion cracking model by Liu and Weyer [20] based on internal pressure q and radial displacement u of steel is modified as shown in Fig. 5. From the corrosion cracking model, $3mg/cm^2 \sim 10mg/cm^2$ of W_{crit} is calculated [21]. The model assumes that the corrosion cracking occurs when accumulated corrosion amount, W_{rust}, reaches the W_{crit} [20].
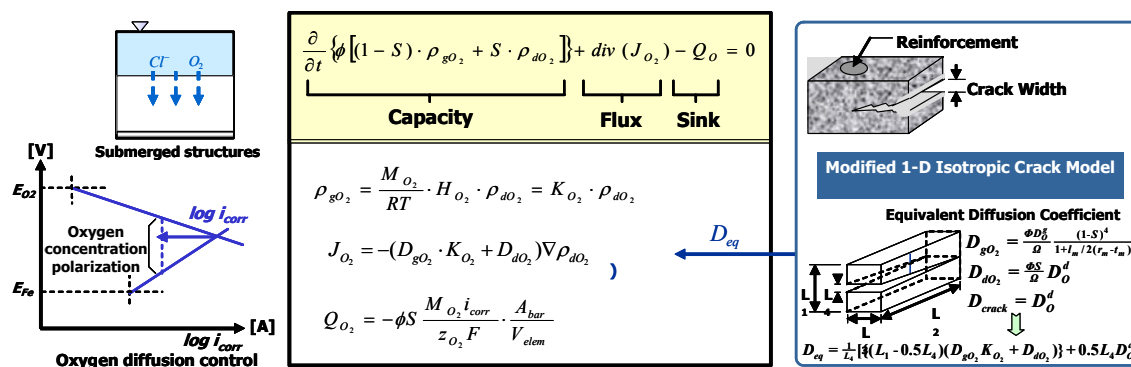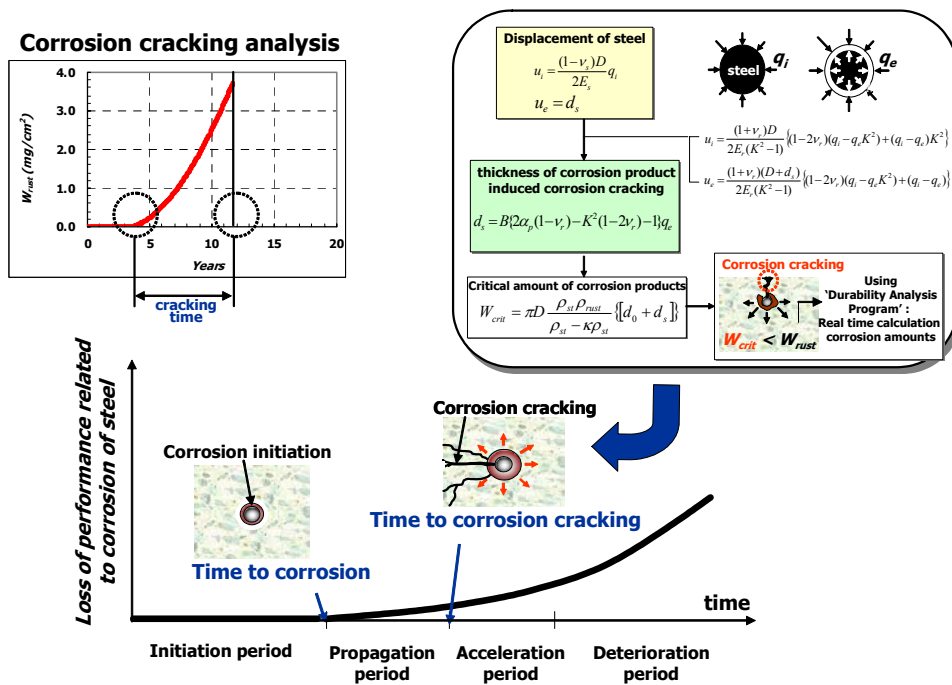

Figure 4. Oxygen diffusion model

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

Initially verification of the chloride diffusion-penetration model was carried out by considering the variation of diffusion coefficient with time and existing cracks. Table 2 shows laboratory exposure conditions of the test and analysis carried out. The results obtained from the analysis model were compared with the test results.

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 $^{\circ}$C	Salt spray : RH = 90%	0.5mol/l	20 $^{\circ}$C	RH = 100%	0mol/l

Fig.6(a) shows that the analysis predicts the variation of free chloride contents according to the distance from the surface of concrete cover with different crack widths. Fig.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. In the case of high cover depths, the Fick's equation over estimates the chloride contents by two times. For verification of the data analysis with long-term exposed RC structures, the analysis of a RC pier of a bridge at submerged zone (Fig. 7(a)) exposed to marine environment over a period of 10 years is carried out and the result is compared with experimental (Fig. 7(b)). Fig. 7(b) shows a good agreement between the results.
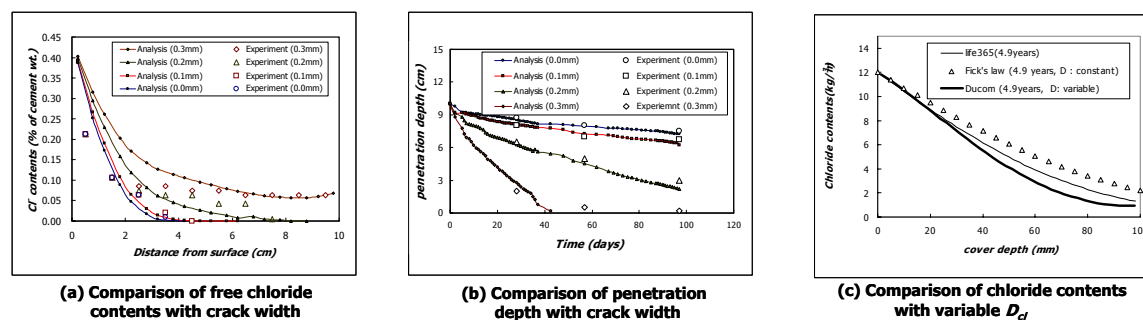

(a) Comparison of free chloride contents with crack width

(b) Comparison of penetration depth with crack width

(c) Comparison of chloride contents with variable D_{cl}

Figure 6. Chloride contents with variable diffusion coefficient

The simulation of corrosion in 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 the results of the simulation on corrosion rate and accumulated amount of corrosion product.

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.
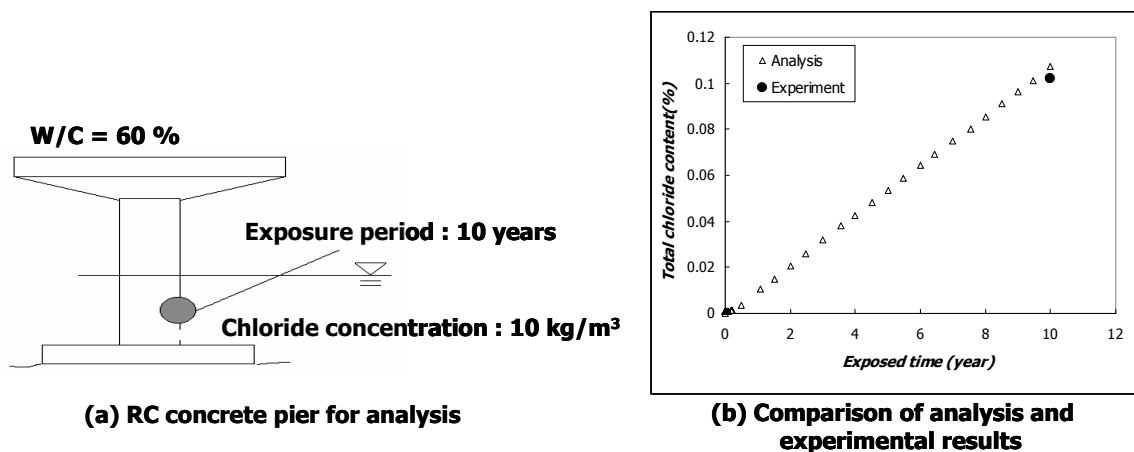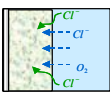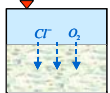
W/C = 60 %

Exposure period : 10 years

Chloride concentration : 10 kg/m³

(a) RC concrete pier for analysis

(b) Comparison of analysis and experimental results

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

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					

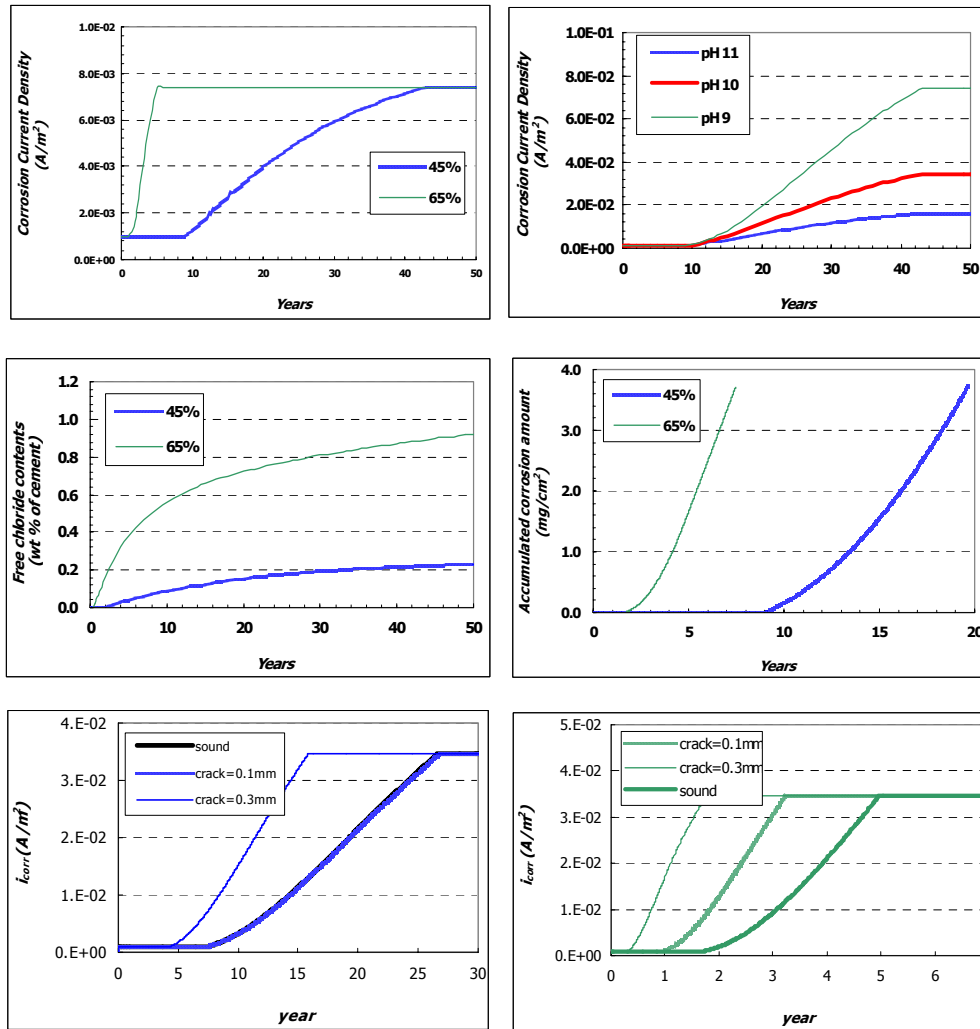| Location	W/C	pH	External chloride concentration (mol/ℓ)	Relative humidity (%)	Temperature (^{o}C)
Splash zone	45, 65	9~11	0.35	70	20 ^{o}C
Submerged zone	45, 65	10, 11	0.50	100	20 ^{o}C

Figure 8(a). Simulation of corrosion rate and accumulated corrosion products – Splash zone structure

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 splash zone condition, corrosion initiation of the structures is calculated to be occurred within 10 years and corrosion cracking is also to be occurred within 20 years. As shown in Fig. 8(b), there is not much oxygen available for corrosion propagation for the structures exposed to the submerged zone. Hence, the structures are subjected to corrode but at lower rate of propagation with slow corrosion cracking than the structures in splash zone. It is also shown that the decrease in pH of pore water and increase in water to cement ratio of concrete accelerates corrosion. The result shows that reduction in pH accelerates corrosion and makes corrosion cracking earlier. In the case of pH = 9, the corrosion current density is found to be as high as $0.07 \, A/m^2$.

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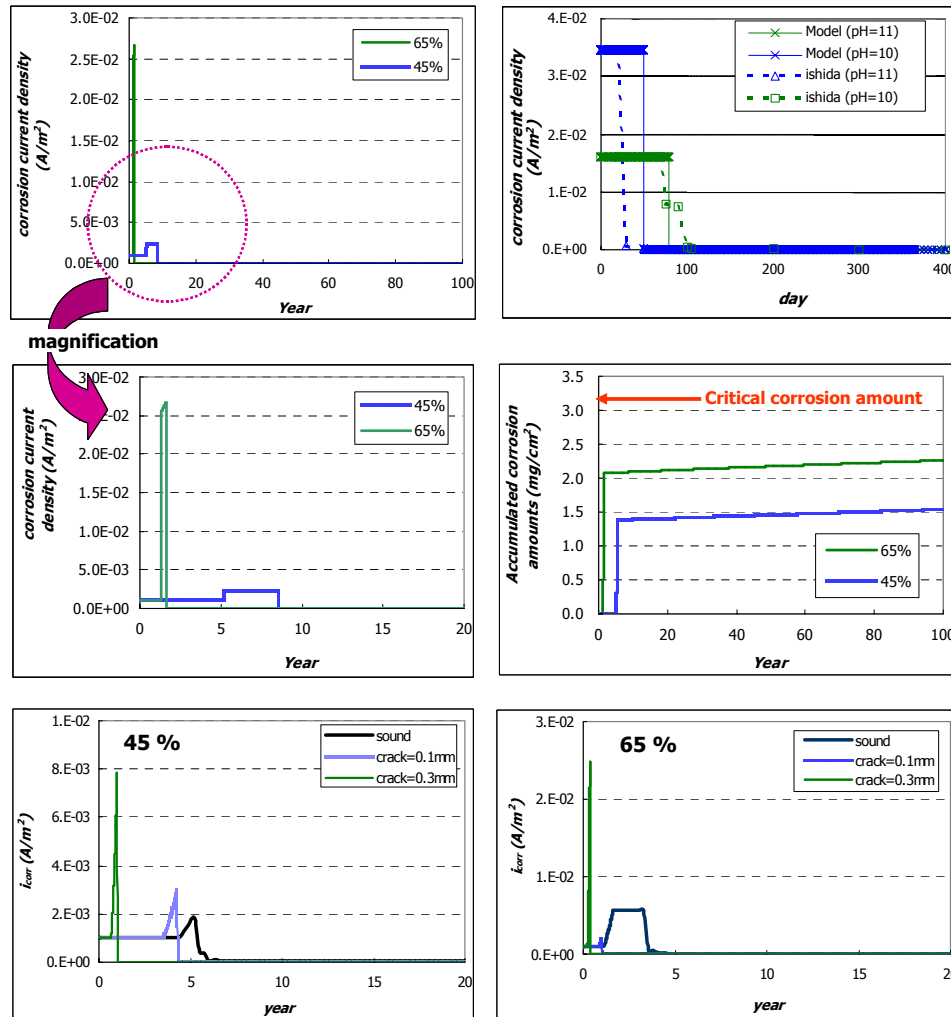

Figure 8(b). Simulation of corrosion rate and accumulated corrosion products – Submerged structure

4. CONCLUSIONS

The following conclusions are drawn form the above investigation:

1. The chloride diffusion coefficient of concrete and the amount of oxygen supplied to the concrete are major important factors affecting the service life of reinforced concrete structures.

2. Since, existing service life prediction models do not consider the above factors, the chloride content to be penetrated to the RC structures are overestimated so that the service life of concrete structures is sometimes underestimated.

3. 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.

4. 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.

5. From the corrosion analysis of 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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