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Probability-Based Durability Design for Concrete Structure with Crack: Bimodal Distribution of Chloride Diffusion

Ung-Jin Na[1] · Seung-Jun Kwon[2]*

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Chloride ions in RC (Reinforced Concrete) structures can cause very severe corrosion in reinforcement steel. It is generally informed that chloride penetration can be considerably accelerated by enlarged chloride diffusion due to cracks. These cracks play a role in main routes through which chloride ions penetrate into the concrete, and also lead to steel corrosion in RC structures exposed to chloride attack, such as port and ocean structures. In this paper, field survey including evaluation of crack and chloride concentration distribution in concrete is performed to investigate an effect of crack on chloride diffusion. The service life of cracked concrete exposed to the marine environmental condition is estimated considering the crack effect on chloride diffusion. For this purpose, diffusion coefficients in cracked concrete are obtained based on the field survey. Using the relationship between diffusion coefficients in the cracked concrete and the crack widths, service life of the cracked concrete is predicted in a probabilistic framework. A bimodal distribution with two peaks, consisting of a weighted sum of two normal distributions is introduced to describe chloride diffusion of the concrete wharf with crack.

Keywords : Chloride diffusion, Crack width, Service life, Probability, Bimodal distribution

1. INTRODUCTION

Deterioration in RC structures is identified as one of the main issues related to concrete materials and structures. RC structure is vulnerable to the damaging effects of corrosion induced by chlorides, so that the service life is significantly affected. As chloride ion rapidly penetrates into the concrete and it directly affects steel corrosion, it is very important to investigate the overall phenomena of chloride behavior. In addition, the corrosion of the steel results in cracking, delamination, and spalling of the concrete cover. It also leads to the reduction of the strength of concrete members and the safety of the structures. Many researches have been conducted focusing on the chloride behavior in concrete (Broomfield 1997; CEB 1989; RILEM 1994; Song et al. 2006). For the chloride behavior in sound concrete, various models and analysis techniques have been proposed (Ishida et al. 2003; Somg et al. 2005; Andrade 1993; Song et al. 2009). A lot of improvements have been achieved in modeling and analysis techniques for chloride behavior. Advanced techniques for chloride behavior are also introduced considering porosity and saturation in early-aged concrete (Maekawa et al. 2009; Song et al. 2001). Recently, the influences of cracks on chloride diffusion and water transport are studied considering the behavior in early-aged concrete (Park et al. 2012; Vesikari 1998).

Cracks in RC structures provide a main route for chloride ions to reach reinforcement steel and can accelerate corrosion. On the view of the crack effect on the chloride penetration, it is informed that cracks on the concrete surface play a role in maintaining the chloride concentration from rain and drainage (CEB 1989). Even though there is no external applied load, the crack width on concrete usually decreases by auto-

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* Corresponding author E-mail: jjuni98@hannam.ac.kr

[1]Ministry of Land, Infrastructure and Transport. Division of Airport, Sejong, 339-012, Korea
[2]Hannam University, Civil and Environmental Eng., Daejeon, 306-791, Korea

healing action caused by rehydration of unhydrated cement paste or calcium based chemical compositions. These kinds of various features make it very difficult to quantitatively evaluate the characteristics of the time–dependant chloride diffusion considering crack effect. On the view of the design concept, probability–based durability design has been recently attempted to consider the uncertainties of input variables such as material properties and geometry. Related with the chloride penetration, many probabilistic design models have been proposed (RILEM 1994; Vesikari 1998; Ferrera et al. 2004; Gjorv 1994). New procedures for probability–based durability design have been proved to give more realistic basis for the analysis. In this methodology, several parameters such as surface chloride content, cover depth, and diffusion coefficient are considered as random variables through statistical distributions. For the numerical technique, Monte Carlo Simulation (MCS) technique has been generally used (Gjorv 2004; Koyama and Hanada 1998). MCS provides a predicted probability distribution of the output variables by repeated calculation using values randomly sampled from pre–defined probability distribution function of variables. In this paper, Fick's second law is simulated as the physical phenomenon for describing the chloride diffusion process. Several input parameters in Fick's second law are described by a probability density function (PDF). Once the PDFs of the input parameters are assumed, the probability of failure can be obtained from the evaluation of the limit state function with a large number of trials.

However, these applications using probabilistic approach are limited to the sound concrete structures without considering crack effects since it is very difficult to evaluate the crack effect on the chloride diffusion characteristics.

To consider the crack effects on chloride diffusion, field survey to the wharf structures is performed. Through the survey, diffusion coefficients in cored concrete with different crack width (0.1~0.3mm) are evaluated. Using the diffusion coefficients which can consider the crack effect, the service life is predicted. For the probabilistic analysis, critical chloride content, cover depth, and time–dependant diffusion coefficient are considered as random variables. Finally, to demonstrate the crack effect on the probability distribution for chloride penetration, bimodal distribution having two peaks is introduced and comparative studies considering the variation of crack width and cracked area are conducted.

2. PROBABILISTIC APPROACH FOR THE SERVICE LIFE PREDICTION

2.1 Chloride penetration and steel corrosion

For chloride–induced corrosion, the corrosion initiation time is defined as the time when chloride concentration at the outer steel surface reaches a critical value. The propagation stage corresponds to the period during which accumulated corrosion products initiate cracking due to corrosion swelling. In general, the durability of concrete structures depends on the duration of the initiation stage. The basic concept of durability design for chloride intrusion is that the induced chloride concentration within intended service life should not exceed the critical chloride concentration (i.e., 1.2kg/m^3 = 0.051% of weight ratio to concrete weight) at the location of embedded steel reinforcement (Liang et al. 2002). For the simple presentation, the durability failure is assumed to occur when the chloride concentration at the steel location has reached the critical chloride level, C_{cr}. In general, one–dimensional chloride diffusion models based on the Fick's second law in steady state have been used for describing chloride behavior. The chloride ion concentration, C(x,t), at distance x and the period of exposure t is given by the following equation:

$$C(x,t) = C_s[1 - erf(\frac{x}{2\sqrt{Dt}})] \qquad (1)$$

where D is chloride diffusion coefficient to the time t, C_s is the surface chloride content, and erf is error function.

2.2 Probabilistic approach

During the last decade, a lot of researches have been conducted to predict the chloride behavior. In many cases, a deterministic approach characterized by a fixed single value for each model parameter has been adopted. However, it is not easy to find reliable and accurate prediction model because there exist so many uncertain factors in chloride penetration behavior. The uncertain parameters related to stochastic nature of the material properties and exposure environment can be accounted by adopting a probabilistic approach. In this case, each model parameter is represented by a mean value, a standard deviation, and a type of statistical distribution (i.e., normal or lognormal). The basic concepts of durability design are briefly explained in Table 1 (RILEM 1994).

In the view of a probabilistic approach, the induced chloride concentration at the steel location and critical chloride concentration can be expressed as exterior deterioration load $[S(t)]$ and interior resistant load $[R(t)]$, respectively. The probability of durability failure and service life can be determined through Eq. (2a and 2b).

Table 1. Design concept for durability

Design method	Governing Equation	Note
Deterministic design method	$R(t)-s(t)>0$ $R(t)$:resistance at intended service life t $S(t)$:deterioration at intended service life t	time-dependant $R(t)$ and $S(t)$ obtained from mean values of design parameters
Probabilistic design method	$P(f)_t = P(R-S)_t < P_{fmax}$ $P(f)$:probability of durability failure at intended service life t P_{fmax}:maximumprobabilityofdurabilityfailure	Time-dependant probability distribution

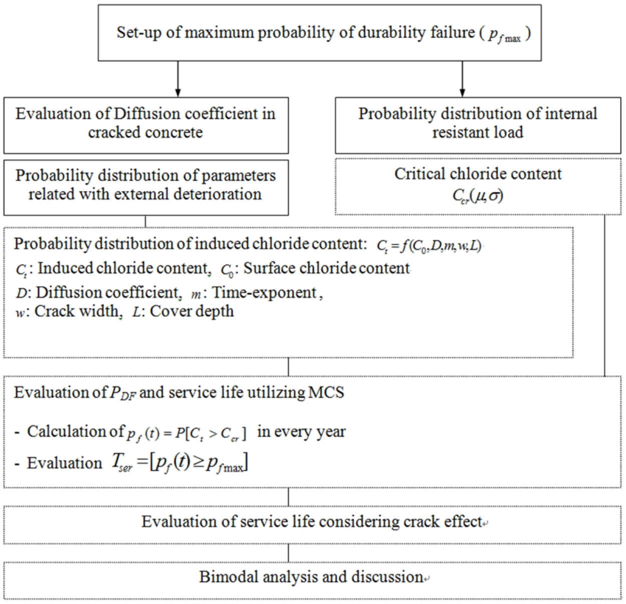


Fig. 1. Flowchart of the methodology in this paper

$$p_f = P[C_t > C_{cr}] \tag{2a}$$

$$p_f(T_{ser}) \geqq p_{fmax} \tag{2b}$$

where p_{fmax} is the maximum probability of durability failure. $p_f(t)$ indicates the probability that the chloride concentration at steel location exceeds the critical chloride concentration. When $p_f(t)$ is greater than p_{fmax}, service life can be determined as Eq. (2b). The flowchart of the methodology proposed in this paper is shown in Fig. 1.

3. CHLORIDE PENETRATION IN CRACKED CONCRETE

3.1 Crack effect on chloride diffusion

When concrete has crack on surface, cracks can be the main routes to transport aggressive substance into the concrete. It was informed that chloride diffusion in cracked concrete is proportional to crack width and crack density in the steady state and one-dimensional condition (Gérard 2000; Kwon et al. 2007; Yokozeki et al. 1998). And it was also reported that chloride diffusion is proportional to the square of the crack width (w^2) in non-steady state (Yokozeki et al. 1998). Even though chloride diffusion characteristics in cracked concrete may be affected by many parameters such as crack width, crack depth, auto-healing of the crack, change in surface chloride content due to rain, and local condensation of chloride, the effect of crack on chloride behavior mainly depends on the crack width and depth. Because most design codes adopt critical crack width for the durability design and crack width shows clear relationship with diffusion coefficient, only crack width is considered as a practical parameter to represent a significant crack effect in this paper.

3.2 Field survey

For the evaluation of the crack effect on diffusion, field investigations are carried out for two different port wharves constructed 8 and 11 years ago, respectively. The wharf structures and crack patterns on the slab are shown in Fig. 2.

For the evaluation of the crack effect, the crack widths are classified into 3 groups: 0.1mm, 0.2mm, and 0.3mm. For each group, 3 samples are cored from the concrete deck slab (loading platform and berthing dolphin) and tested. To avoid the crack density effect on diffusion, core samples (ø=50mm) are obtained from the area where only single crack exists. The cores of 50mm diameter with 50mm depth are obtained. The cores are sliced in 10mm depth, and each slice is crushed and grinded into small particles. Based on the AASHTO T 260, total chloride (acid soluble) concentration is evaluated by potentiometric titration using standard solution ($AgNO_3$). Diffusion coefficient is also determined through linear regression analysis (Kwon et al. 2007). Fig. 3(a) shows schematic drawing for core sample. General information on wharf structures such as crack depth, crack width, concrete strength, obtained from field investigation is summarized in Table 2. Crack width, crack depth, and concrete strength are evaluated by optical microscope, ultrasonic pulse velocity method, and rebound


(a) Wharf structure


(b) Crack pattern on slab

Fig. 2. Wharf structures and crack pattern on slab

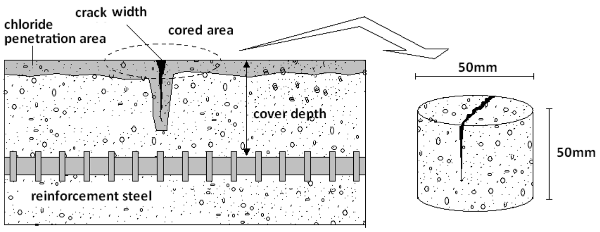


Fig. 3. Schematic drawings for core sample affected by crack

Table 2. General information for wharf structures

Member	Cover depth	Crack depth	Concrete strength	Carbonation depth
Loading platform	105~140 mm	50~120 mm	26.0 MPa	2.80~6.26 mm
Berth dolphin	100~150 mm	30~80 m	25.6 MPa	2.85~6.20 mm

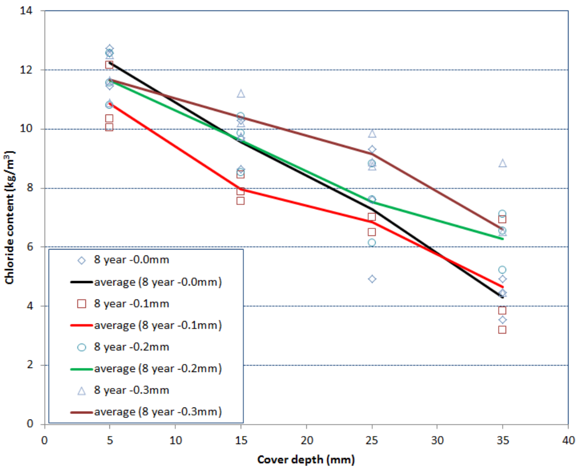


Fig. 4. Profiles of chloride concentration in core samples (WHARF-8)

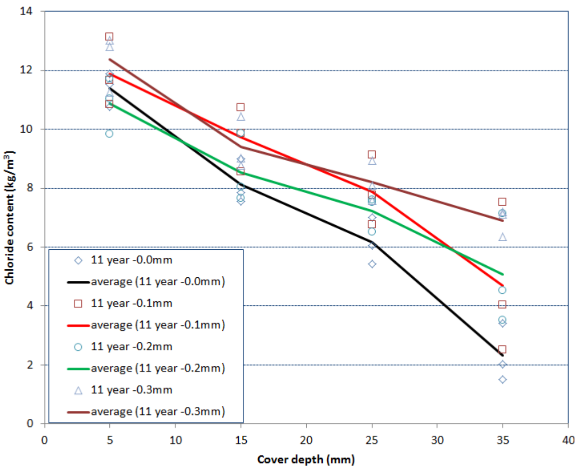


Fig. 5. Profiles of chloride concentration in core samples (WHARF-11)

hammer test, respectively (Bungey 1994).

The profiles of the chloride concentration in the core samples are shown in Fig. 4 and Fig. 5. Fig. 4 shows the results obtained from the wharf constructed 8 years ago (referred to WHARF-8) and Fig. 5 is for the wharf constructed 11 years ago (referred to WHARF-11).

As shown in Fig. 4 and Fig. 5, the chloride concentration decreases with concrete depth. It is also observed that the induced chloride concentration ($C(t)$) increases with crack width, however, clear relationship between surface chloride content and crack width cannot be found. Since age difference between field investigation data of WHARF-8 and WHARF-11 is relatively small, the averaged diffusion coefficient and surface chloride content are used in this paper. The results are listed in Table 3 and shown in Fig. 6.

In Fig. 6, it is observed that wider crack opening causes rapid chloride penetration into concrete. In the sound concrete, diffusion coefficient from the core can represent the entire diffusion characteristics, but in cracked concrete the crack effect on diffusion can be evaluated differently according to the represent volume size (core volume). Recently, several studies utilizing micro controlled cracking device have reported that chloride profile perpendicular-to-crack depth for crack width over 0.1mm are very similar to that of surface profile (Ismail et al. 2004; Ismail et al. 2008). It means the chloride diffusion perpendicular to crack plane (parallel direction to steel length in Fig. 3) increases significantly when crack width is wider than 0.1mm. In this paper, however, averaged diffusion coefficients in the core volume are obtained since 1) increased chloride concentration perpendicular to crack plane due to crack width is already considered in diffusion coefficient from chloride profiles (direction to crack depth) 2) In service life prediction, one-dimensional diffusion is generally assumed for the convenience. Several Concrete Specifications (KCI 2004; JSCE 2002) have suggested the crack effect on 1-dimensional diffusion for prediction of service life in RC structures. Furthermore, modeling for equivalent mass transfer and diffusion in representative element volume (REV) with crack can be found in several previous studies (Song et al. 2006; Song et al. 2007a,b). In this paper, conventionally used core with 50mm diameter is used and its equivalent diffusion coefficient is experimentally obtained.

Table 3. Results of the field investigation

Crack width(mm)	Averaged diffusion coeff. $\times 10^{-12}$ (m^2/sec)	Surface chloride concentration (% of concrete weight)
Sound concrete	1.46	0.602
0.1	3.02	0.551
0.2	4.27	0.527
0.3	7.82	0.553

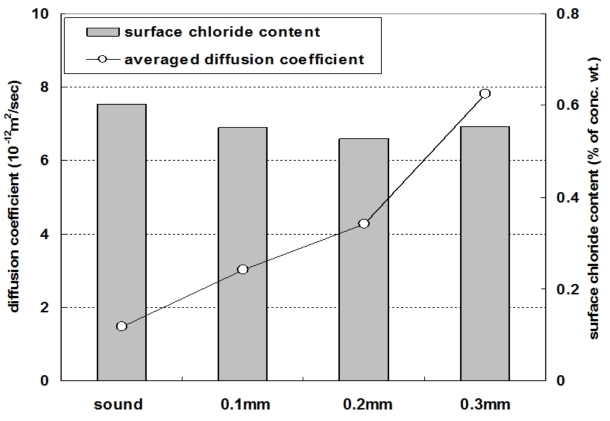


Fig. 6. Averaged diffusion coefficient and surface chloride content with crack width

3.3 Effect of crack width on diffusion coefficient

In order to consider crack effect on diffusion phenomena, several assumptions are needed. If crack width and its effect on chloride penetration keep constant from the initial stage and they are independent on the time, the chloride concentration in cracked concrete can be calculated from Eq. (1) based on the Fick's second law (Tang and Joost 2007; Poulsen 1993). To obtain the diffusion coefficient considering crack effect, the diffusion coefficient, D in Eq. (1), can be rewritten as Eq. (3).

$$D=\overline{D(t)}f(w) \tag{3}$$

where $\overline{D(t)}$ is diffusion coefficient in sound concrete considering time effect and $f(w)$ is a function of crack width (w)

considering crack effect obtained from field investigations. $\overline{D(t)}$ can be expressed as Eq. (4) and (5) considering time effect (Poulsen 1993).

$$\overline{D(t)} = \frac{1}{t}\int_0^t D_{ref}(\frac{t_{rde}}{\tau})^m d\tau = D_{ref}\frac{t_{ref}^m}{t}[\frac{\tau^{1-m}}{1-m}]_o^t = \frac{D_{ref}}{1-m}(\frac{t_{ref}}{t})^m \quad (4)$$

$$\overline{D(t)} = D_{ref}[1+\frac{t_R}{t}(\frac{m}{1-m})](\frac{t_{ref}}{t_R})^m \quad (5)$$

where t_r is the time when diffusion coefficient is changed to be constant and is generally assumed as 30 years (Thomas and Bentz 2002), D_{ref} is diffusion coefficient in reference time (t_{ref}: 28days), and m is a time–exponent parameter depending on mix proportions (Thomas and Bentz 2002).

Based on field survey, the relationship function–$f(w)$ is obtained through the regression analysis. To obtain this relationship, square function in terms of the crack width (w) is assumed and diffusion coefficients are used for data–fitting. As it can be indicated in Fig. 6, the diffusion coefficient of cracked concrete (D) can be expressed using $f(w)$and $\overline{D(t)}$. From the regression analysis, $f(w)$ can be written as Eq. (6).

$$f(w) = 31.63w^2 + 4.73w + 1,\ (w > 0.1, R^2 = 0.984) \quad (6)$$

Considering the crack effect in Eq. (6), the governing equation for chloride concentration can be rewritten as Eq. (7). In addition, the PDF in cracked concrete can be calculated through the comparison of $C(x,t)$ of Eq. (7) and critical chloride concentration, C_{cr}. Finally, service life of the structures can be determined through Eq. (8).

$$C(x,t) = C_s[1 - erf(\frac{x}{2\sqrt{\overline{D(t)}f(w)t}})] \quad (7)$$

$$p\left\{[C_{cr}(\mu,\sigma) < C_s(1 - erf(\frac{x}{2\sqrt{\overline{D(t)}f(w)t}}))]\right\} > p_{f\max} \quad (8)$$

4. PROBABILITY–BASED SERVICE LIFE PREDICTION IN CRACKED CONCRETE

4.1 Probabilistic modeling of chloride diffusion

For the probability analysis, the intended safety index (ϕ_f) should be designated to define the maximum probability of durability failure p_{fmax} [i.e., ϕ_f=2.2 (CEB–FIP 2006)]. A safety index of 2.2 means that the service life can be determined when the predicted PDF exceeds p_{fmax} of 10.0%. As mentioned previously, a considerable level of uncertainty is associated with the prediction of chloride penetration in concrete and corrosion in reinforcement steel. For the probabilistic approach, several parameters affecting and controlling the durability of concrete structures are used to demonstrate the stochastic nature of concrete durability and environmental exposure. All parameters, introduced in Eq. (4) and Eq. (5), such as cover depth, surface chloride content, diffusion coefficient corresponding to crack width, time–exponent parameter, and critical chloride content, are considered as random variables in this probabilistic approach. Table 4 lists each parameter with its mean and coefficient of variation (standard deviation/mean, COV) with the related references. The parameters for cover depth and surface chloride content are obtained from field investigation, however, it is very difficult to obtain COVs of m–exponent and critical chloride content, so that appropriate level (0.2) is

Table 4. Random variables in service life prediction

External deterioration load		
Variables	(mean, C.O.V)	Reference
Cover depth (mm)	(121, 0.23)	Field test
Diffusion coeff. at 28days (m^2/sec)	(3.87×10^{-12},0.28)	Field test
Surface chloride concentration (kg/m^3)	(13.1, 0.103)	Field test
m-exponent	(0.2, 0.2)	OPC concrete (Thomas and Bentz, 2002)
Internal resistant load		
Variables	(mean, C.O.V.)	Reference
Critical chloride concentration (kg/m^3)	(1.2, 0.2)	Specification (KCI, 2004; JSCE, 2002)

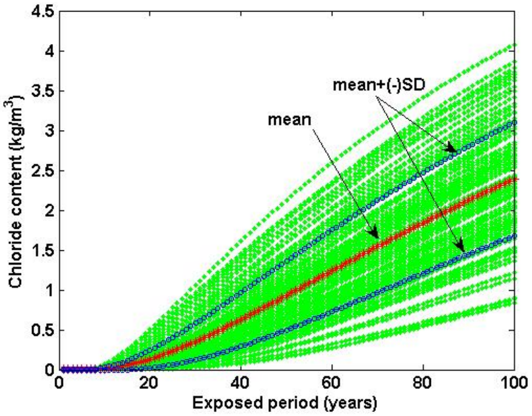


Fig. 7. Simulation results of chloride concentrations at the steel location

adopted from the previous research (Stewart and Mullard 2007). The COV for diffusion coefficient is assumed as 0.28 since the number of samples used in this paper is not sufficient.

Using the probabilistic information in table 4, 1000 samples of the chloride concentrations at the reinforcement steel are simulated with the exposed period and the results are shown in Fig. 7.

4.2 Service life prediction

Based on Table 4, the service life is evaluated using the MCS. With increased crack width, diffusion coefficient increases according to Eq. (6). The changes in the PDF with exposed period and crack width are shown in Fig. 8. The case with crack of 0.3mm width shows PDF of 10.0% within exposed period of 3.5 years, while the case without crack comes to durability failure after 21.5 years. The induced chloride concentration obtained from Eq. (7) are shown in Fig. 9, which is so called deterministic method.

For the comparative study, analysis results obtained from deterministic and probabilistic method are listed in Table 5 and also shown in Fig. 10. The results of probabilistic approach show that the service life decreases from 21.5 years to 3.5 years as the crack width increases from 0.0 to 0.3mm (p_{fmax}: 10.0%).

In case of the deterministic method using the mean values of each parameter, the service life decreases from 61.0 years

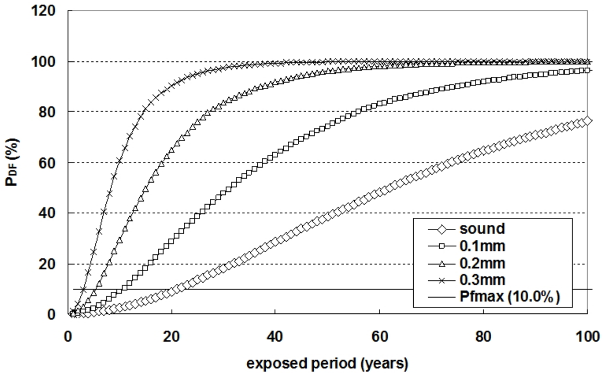


Fig. 8. Variation of PDF with exposed period

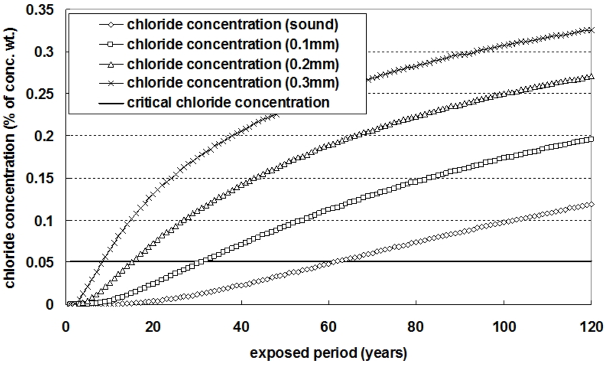


Fig. 9. Induced chloride concentration with exposed period

Table 5. Predicted service life corresponding to crack width

Crack width (mm)	Evaluated service life (years)			
	Probability method (MCS)	Limit state	Deterministic method	Limit state
Sound concrete	21.5	P_{fmax} : 10.0 %	61.0	Critical chloride concentration : 0.051% of concrete wt.

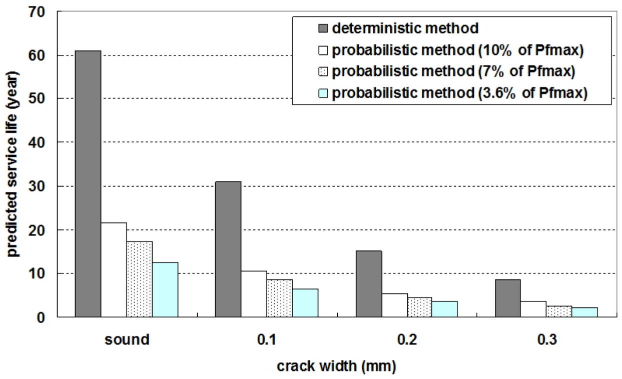


Fig. 10. Predicted service life considering crack effect

to 8.5 years under the same condition. For the probabilistic method, 3 cases with different p_{fmax} are demonstrated in Fig.10. For all cases of p_{fmax} of 3.6% (KCI 2004), 7.0% (CEN 2000), and 10.0% (JSCE 2002), the results from probabilistic method are smaller than those from the deterministic method. The maximum probability of durability failure have been proposed in several Concrete Specifications. It should be noted that the concrete with cracks over 0.2mm has to be carefully monitored and repaired with corrosion protect system since service life is significantly reduced when crack width increases over 0.2mm.

To demonstrate the influence of cover depth on the service life, three different cover depths (100mm, 150mm, and 200mm) are considered in the evaluation process of the service life in cracked concrete. Based on 10% of Pfmax, service life corresponding to each cover depth is plotted in Fig. 11. The service life is reduced significantly with decreased cover depth. For the case with the larger crack width (0.3mm), the positive effect of increasing cover depth seems to be small.

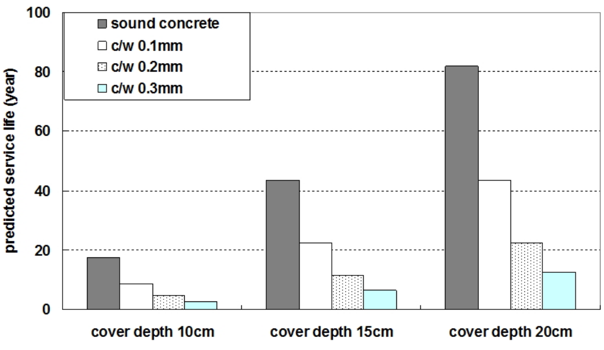


Fig. 11. Effect of cover depth on service life in cracked concrete

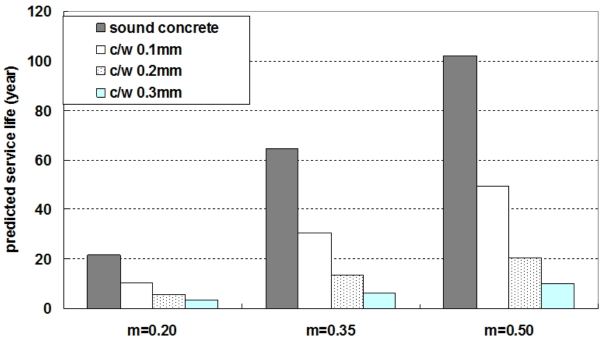


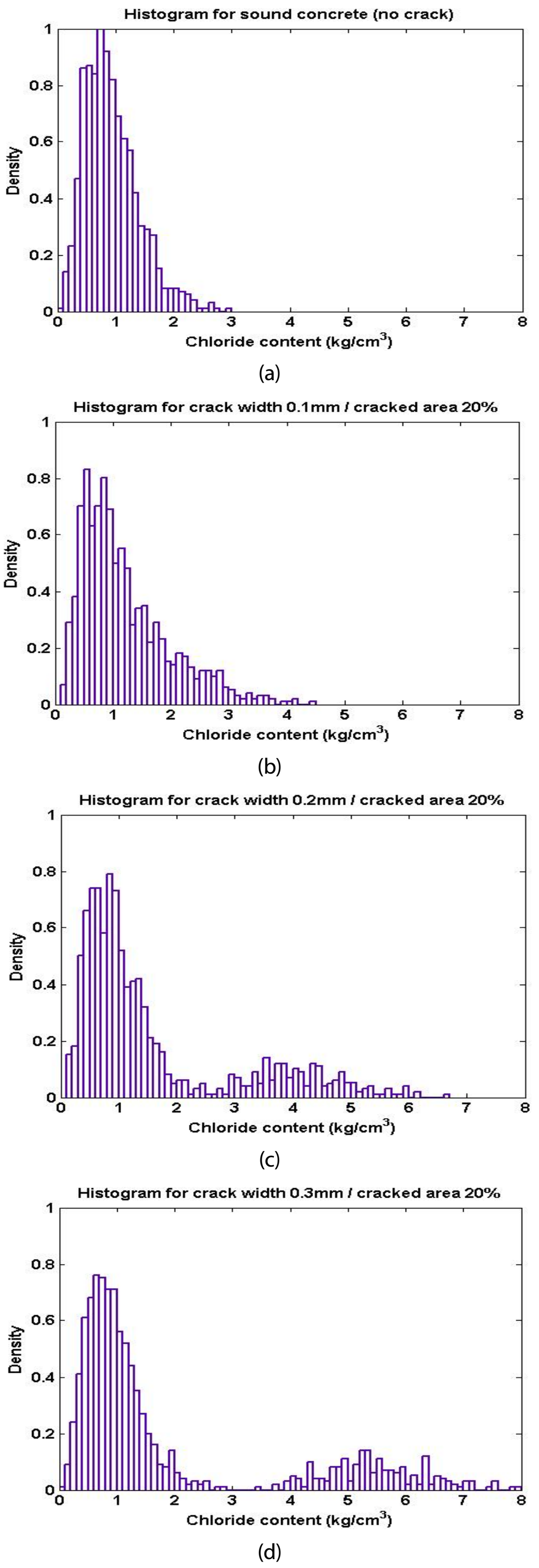
Fig. 12. Effect of time-exponent parameter on service life of cracked concrete

In addition to the cover depth, time-exponent parameter (m) is also used to demonstrate the influence of the input parameter. In this part, the service life of the structures with different time-exponent parameters(m=0.20, 0.35, and 0.50) is predicted. The mean values of surface chloride concentration and cover depth are assumed to be 13.1kg/m^3 and 121mm, respectively. And COVs of each parameter are assumed as 0.103 and 0.23 shown in Table 4. The service life based on 10% of P_{fmax} is plotted in Fig. 12.

From Fig. 12, it can be indicated that the service life significantly increases with an increase in the time-exponent parameter m. This parameter can increases through mineral admixtures like slag, fly ash, and silica fume (Thomas and Bentz 2002).

4.3 Demonstration of bimodal distribution for cracked concrete

The example for numerical demonstration is for concrete wharf with crack which is subjected to chloride attack. The concrete slab of the wharf contains both cracked and uncracked area. As shown before, the sound concrete with proper cover depth shows serviceable condition for many years after construction. But, in case of the cracked concrete, the service life decreases depending on the crack width. For a simple demonstration, it can be assumed that some part of the concrete slab is influenced by the crack and the other part is not affected. To build the probability function representing all concerned area considering both characteristics of cracked and uncracked sections, one can apply bimodal distribution which is combined with the probability distributions of the cracked and uncracked sections. To investigate the effect of crack width on the probability function, at first, crack width is concerned as a variable parameter. 1000 samples of the chloride concentrations at the steel location are simulated through MCS. For four cases with different crack width (no crack, 0.1mm, 0.2mm, and 0.3mm), the histograms for the chloride concentrations are shown in Fig. 13. Each case having different crack width shows different shape of probability



(a)

(b)

(c)

(d)

Fig. 13. The histograms for the chloride concentrations with different crack width

distribution. In case of Fig. 13(c) and Fig. 13(d), one can find the probability distributions have two peaks. In this demonstration, the cracked area is assumed as 20% of the whole area. In statistics, this kind of a probability distribution having two separated peaks is called a bimodal distribution (Schilling et al. 2005; Mei et al. 2004). A bimodal distribution commonly arises as a mixture of two different unimodal distributions (i.e., distributions with only one peak such as normal or lognormal). In case of Fig. 13(d), the chloride concentrations mostly locate at two regions centered at 0.8 and 5.2kg/cm^3.

Based on these histograms, it can be concluded that the chloride concentration at the concrete slab with crack shows a bimodal distribution with two peaks. The bimodal distribution can be written as Eq. (9) using the weight factor p and two unimodal distributions $Y_1(X)$ and $Y_2(X)$.

$$Y(X) = p \times Y_1(X) + (1-p) \times Y_2(X) \tag{9}$$

In this study, it is assumed that a bimodal distribution consists of a weighted sum of two normal distributions as Eq. (10).

$$Y(X) = \frac{p}{\sqrt{2\pi}\,\sigma_1}\exp(-\frac{X-\mu_1}{2\sigma_1^2}) + \frac{1-p}{\sqrt{2\pi}\,\sigma_2}\exp(-\frac{S-\mu_2}{2\sigma_2^2}) \tag{10}$$

Two unimodal distributions, Y1(X) and Y2(X), and the sum of these two, Y(X), are schematically drawn in Fig. 14. One can

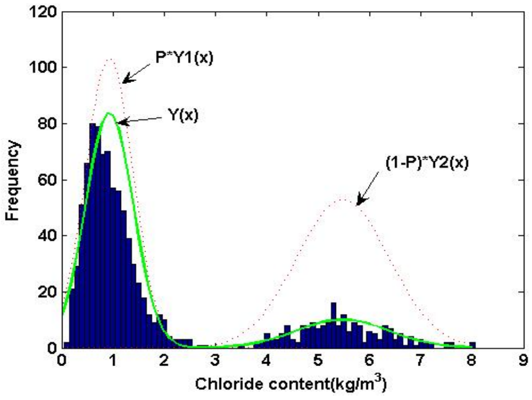
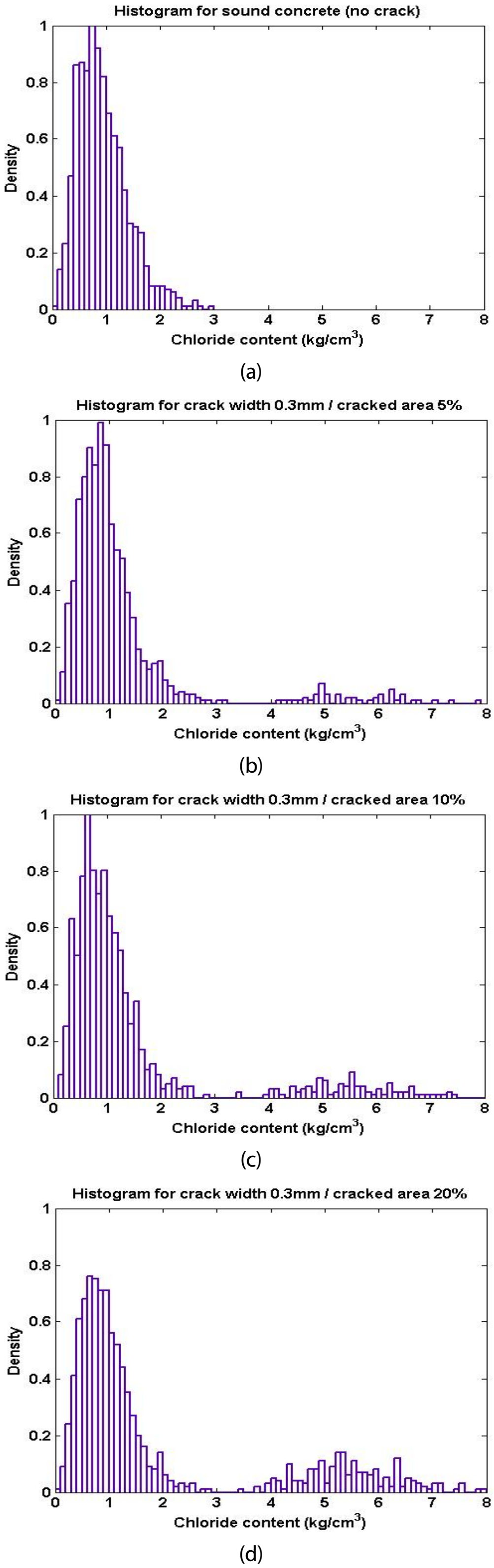


Fig. 14. Bimodal distribution Y(X) combined with two weighted unimodal distribution

indicate that bimodal distribution Y(X) can be constructed using the weighted sum of Y1(X) and Y2(X). In case of Fig. 14 representing the case with 0.3mm crack width, the parameters, p, $\mu1$, $\sigma1$, $\mu2$, and $\sigma2$ in Eq. (10) are obtained as 0.81, 0.93, 0.46, 5.48 and 0.90 using likelihood estimation.

For another comparative study, three cases with different cracked area (5%, 10%, and 20%) are tested. For all cases, it is assumed crack width is 0.3mm. In Fig. 15, one can indicate that the locations of two peaks are changed depending on the percentage of cracked area.



(a)

(b)

(c)

(d)

Fig. 15. The histograms for the chloride concentrations with different cracked area

5. CONCLUSIONS

Deterioration of RC structures due to chloride attack is an important issue in concrete engineering. In this study, in order to investigate the crack effect on the service life of concrete exposed to marine environment conditions, field survey is conducted for the wharf structures with crack. Based on the field survey results, probabilistic methodology is applied to develop reasonable analysis framework for the service life prediction considering crack effect. The results would be improved if field survey data is collected more and the advanced numerical modeling techniques are introduced. Some important conclusions obtained from this paper are listed below.

1. The service life of cracked concrete is predicted in the probabilistic methodology framework using Monte Carlo Simulation. Governing parameters of chloride penetration, such as cover depth, surface chloride content, diffusion coefficient corresponding to crack width, time-exponent parameter, and critical chloride content, are considered as random variables. Using the crack function between crack widths and diffusion coefficients in cracked concrete, the service life is predicted. Since crack width over 0.2mm causes rapid reduction of service life from the analysis, it should be monitored and repaired carefully.
2. For the demonstration of the probability function of chloride concentrations considering the crack effects, a bimodal distribution with two peaks is introduced. Using a bimodal distribution consisting of a weighted sum of two normal

distributions, chloride penetration phenomenon of cracked concrete is presented in the probabilistic framework. Bimodal distribution function can be effectively used to represent this kind of phenomenon.

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