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CORROSION INITIATION AND SERVICE LIFE OF CONCRETE STRUCTURES

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ABSTRACT

The Corrosion of steel reinforcements in concrete is of great concern in the view of safety and durability of reinforced concrete structures. The reinforced concrete structures exposed to sea environments suffer from corrosion of steel bars due to chloride ingress. The chloride penetration into concrete is influenced by many parameters such as type of cement, mixture proportions and existence of rebars. The conventional diffusion analyses have neglected the existence of steel bar in concrete. The purpose of the present paper is, therefore, to explore the effects of reinforcement on the chloride diffusion in concrete structures by incorporating realistic diffusion models. To this end, the nonlinear binding isotherm which includes the effects of cement types and mixture proportion has been introduced in the chloride diffusion analysis. The effects of reinforcements on the chloride penetration have been analyzed through finite element analysis. The present study indicates that the chlorides are accumulated in front of a reinforcing bar and the accumulation of chlorides is much more pronounced for the case of larger-size bars. The higher accumulation of chlorides at bar location causes faster corrosion of reinforcing bars. The corrosion initiation time reduces by about 30-40 percent when the existence of rebar is considered in the chloride diffusion analysis.

Keywords: chloride diffusion, corrosion, critical chloride concentration, reinforced concrete

1. INTRODUCTION

The reinforced concrete structures exposed to sea environments suffer from corrosion of steel bars due to chloride ingress. Therefore, the chloride penetration is a major factor that affects the durability of concrete structures. The durable life (or service life) of those structures has been determined conventionally based on the initiation time to corrosion of steel bars, which is caused by penetrated amount of chlorides (Broomfield, 1997 and Tang, 1993). The chloride diffusion analysis is required to determine the penetrated amount of chlorides at the location of steel bars. If the amount of penetrated chloride at the steel reinforcement reaches the limiting threshold value for corrosion, then the reinforcing bar starts to corrode. Many researchers have studied and reported on the chloride threshold values which cause corrosion of steel bars (Xi, 1999; Bazant, 1979; Hussain, 1996). In the chloride diffusion analysis, the existence of steel bars in concrete has been neglected so far and the effect of steel bars on the chloride penetration has not been studied. However, the penetrated chloride profiles in concrete may be greatly influenced by the existence of steel bars because the chloride diffusion cannot occur through the reinforcing bars. The purpose of the present study is, therefore, to explore the effects of steel bars on the chloride penetration and to determine realistically the time to corrosion considering the existence of steel bars. The chloride binding in concrete has been also modeled reasonably for more realistic chloride diffusion analysis. Many design variables including rebar diameter, cover thickness of rebar, and water-cement ratio have been

considered in the analysis to see the effects of those variables on the chloride penetration. The threshold values for steel corrosion were also studied in the present study.

2. CHLORIDE DIFFUSION MODEL

2.1 Diffusion Equation

The diffusion of chloride ions is generally assumed to follow the Fick's second law. The general diffusion equation can be written as follows.

$$\frac{dC_f}{dt} = \frac{dC_f}{dC_t} div\left[D_{cl}\, grad\left(C_f\right)\right] \tag{1}$$

where C_t = total chloride ions (per concrete weight, g/g) , C_f = free chloride ions(per concrete weight, g/g), t = time, D_{cl} = diffusion coefficient , and dC_f / dC_t = binding capacity. The binding capacity is here defined as the ratio between the free chloride and total chloride ions and can be written as follows.

$$C_t = C_f + C_b, \quad \frac{dC_f}{dC_t} = \frac{1}{1 + \left(dC_b / dC_f\right)} \tag{2}$$

Here C_b = bound chloride ions (per concrete weight, $g_{cl} / g_{concrete}$), and dC_b / dC_f represents binding isotherm. The binding isotherm is usually affected by concrete mixture characteristics and those features have been considered in the present study.

2.2 Binding Isothern

Some parts of chloride ions penetrated into concrete are bound and do not affect directly the corrosion of steel bars. The chloride binding is directly related to the amount of calcium silicate hydrate(C-S-H) which are formed during hydration process of cement. The modified Powers model proposed by Jennings is employed in the present study to model the binding isotherm (Xi, 1999). The following nonlinear binding isotherm was used in this study, (Tang, 1993 and Xi, 1999)

$$C_b{}' = \left(C_f{}'\right)^A 10^B \tag{3}$$

where, $C_b{}'$ =bound chloride ions (per gel weight, mg_{cl} / g_{gel}), $C_f{}'$ =free chloride ions (per one liquid liter, mol / l), and A, B are constants.

It is necessary here to introduce some converting factors (i.e., β_{sol} and β_{CSH}) to express the values $C_b{}'$ and $C_f{}'$ in the unit of concrete weight. The factor β_{sol} represents the ratio of pore liquid volume to concrete weight (i.e., $L_{total\ pore} / g_{concrete}$) and the factor β_{CSH} represents the ratio of C-S-H gel weight to concrete weight (i.e., $g_{CSH\ gel} / g_{concrete}$) (Xi, 1999).

$$\beta_{sol} = \frac{L_{total\ pore}}{g_{concrete}} = \frac{V_{total\ pore}}{1{,}000} \cdot \frac{g_{cement\ paste}}{g_{concrete}}, \quad \beta_{CSH} = \frac{g_{CSH\ gel}}{g_{concrete}} = V_{CSH\ solid}\, \rho_{CSH} \cdot \frac{g_{cement\ paste}}{g_{concrete}} \tag{4}$$

The values $V_{total\ pore}$ and V_{CSH} in Eq.(4) can be obtained from Jennings and Tennis' model as follows

$$V_{total\ pores} = V_{CSH\ pores} + V_{capillary\ pores}, \quad V_{CSH\ pores} = 0.620\, V_{CSH\ solid} \tag{5}$$

$$V_{CSH\ solid} = c\left(0.347\, \alpha_1 p_1 + 0.461\, \alpha_2 p_2\right), \quad V_{capillary\ pores} = \left(1 - c\right) - \sum_{i=1}^{4}\left(\alpha_i p_i \Delta_i\right) \tag{6}$$

$$c = \frac{1}{1 + w/c} \tag{7}$$

Other components in Fig. 1 are also expressed as follows.

$$V_{unreacted\ \ cement} = c\left(1 - \alpha_{total}\right)\left(\frac{1}{\rho_{cement}}\right), \quad V_{CH} = c\left(0.189\, \alpha_1 p_1 + 0.058\, \alpha_2 p_2\right) \tag{8}$$

$$V_{AFm} = c\left(0.849\, \alpha_3 p_3 + 0.472\, \alpha_4 p_4\right), \quad \alpha_i = 1 - exp\left[-a_i\left(t - b_i\right)^{ci}\right] \tag{9}$$

where, t=age in days, and the coefficients a_i, b_i and c_i are summarized in Table 1. where, c =cement content

used in the cement paste of 1g, α_i =degree of hydration for i-th hydration compound, p_i =proportion of i-th hydration compound in cement, i=1 for C_3S, i=2 for C_2S, i=3 for C_3A, i=4 for C_4AF, ρ =cement unit weight, and Δ_i =volume change for i-th hydration compound after hydration.

Several concrete mixtures have been modelled to explore the variation of predicted chloride binding. Table 2 shows the mixture proportion of concrete used in the prediction. Major variables include water-cement ratio and the type of cement.

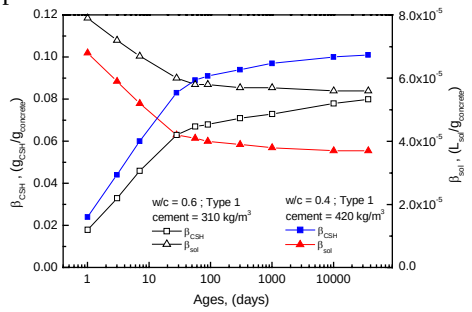


Fig. 2 Three dimensional stresses acting on element

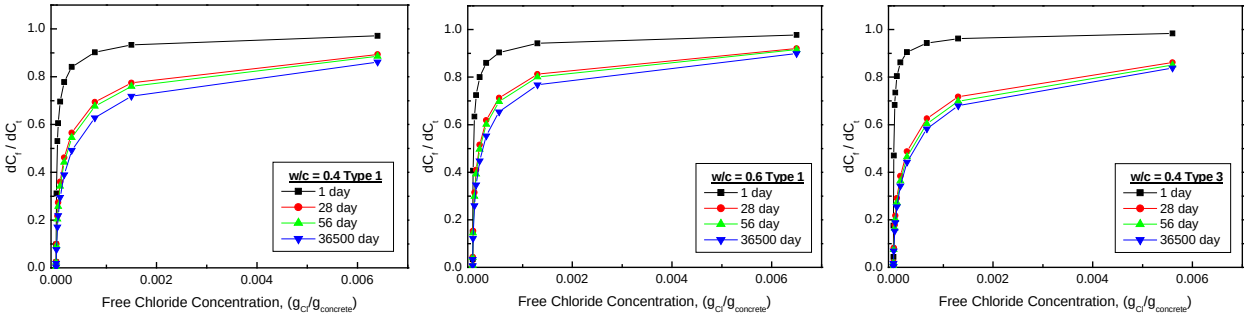
Table 1 Coefficients used in Avrami equations

compound	a_i	b_i	c_i
C_3S	0.25	0.90	0.70
C_2S	0.46	0.90	0.12
C_3A	0.28	0.90	0.77
C_4AF	0.26	0.90	0.55

Table 2 Mixture proportion of concrete (kg/m3) and major constituent phases of cement(%)

w/ c	cement type	cement content	water	fine agg.	Coarse agg.		alite (C_3S)	belite (C_2S)	aluminate (C_3A)	ferrite (C_4AF)
0.4	Type 1	420	168	602	1088	Type I	49	25	12	9
0.6	Type 1	310	186	687	1046	Type 3	65	11	12	8
0.4	Type 3	420	168	602	1088					

Fig.1 shows the variation of β_{CSH} and β_{sol} according to age. It is seen that the value β_{CSH} increases rapidly up to the age of about 56 days and then increase slowly after that age. The reverse is true for the value of β_{sol}. Fig. 1 also indicates that the water-cement ratio and cement content affect greatly the values of β_{CSH} and β_{sol}. The value of β_{CSH} increases with a decrease of water-cement ratio and the value of β_{sol} decreases with a decrease of water-cement ratio. Therefore, the effects of ages and mixture proportions must be considered appropriately to calculate the binding isotherm properties. The binding capacity, dC_f / dC_t, has been also determined using the previously defined material properties. Fig.2 describes the variation of dC_f / dC_t according to free chloride concentration for various ages. It can be seen that the values of dC_f / dC_t are much larger at very young ages compared with those of mature concrete at older ages. This is because the free chlorides are reduced with increasing age. Fig. 2 also indicates that the binding capacity does not change much after the age of 28 days for a specified mixture of concrete. Fig. 3 shows the relation between bound chlorides and free chlorides for various water-cement ratios and cement types. Fig. 3 indicates that the amount of bound chlorides decrease with an increase of water-cement ratio. This means that the binding capacity is lower for concrete with higher water-cement ratio. It can be also seen from Fig. 3 that the binding capacity is different for different cement types. The binding capacity of type 3 cement is higher than that of type 1 cement at the same water-cement ratio. Fig.4 shows the comparison of proposed binding isotherm with Tang's results. Fig.5 indicates that the current binding isotherm correlates fairly well with existing data.



(a) type 1 cement, w/c=0.4 (b) type 1 cement, w/c=0.6 (c) type 3 cement, w/c=0.4

Fig.2 Variation of β_{CSH} and β_{sol} according to age

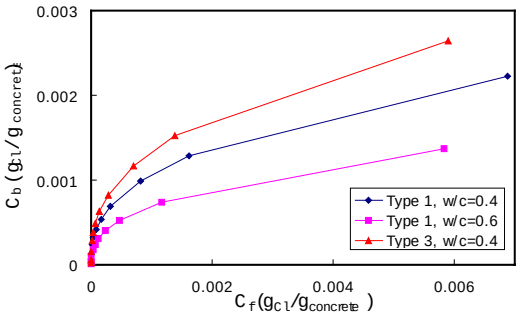


Fig. 3 Binding isotherm relation between bound and free

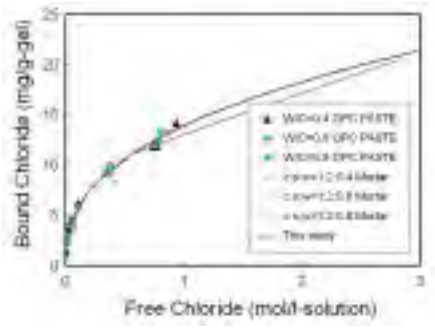


Fig. 4 Comparison of present binding isotherm with Tang's results

2.3 Diffusion Coeffcient

The diffusion coefficient is one of the most important parameters that affect the chloride penetration into concrete. Many researchers studied on the diffusivity of chloride ions in concrete. Table 3 gives the effective diffusivity of chloride ions reported by Page et.al. (1981) and Table 4 summarizes the diffusivity values given by Sharif, Loughlin, Azad, and Navaz (1997).

Table 3 Effective diffusivity of chloride ions by Page, Short, El Tarras, and Holden

Cement type	$D_e\left(\times 10^{-8}\, cm^2 / sec\right)$
OPC	4.47
OPC / 30% FA	1.47
OPC / 65% FA	0.41
SRPC	10.0

Table 4 Effective diffusivity of chloride ions by Sharif, Loughlin, Azad, and Navaz

Cement content Kg/m^3	w/c	$D_e\left(\times 10^{-8}\, cm^2 / sec\right)$ chloride ponding test
300	0.40	10.32
	0.55	33.90
350	0.40	8.28
	0.55	28.10
400	0.40	7.63
	0.55	16.46

In the present study, the common value of $1.0\times 10^{-8}\, cm^2 / sec$ has been used for normal strength concrete and a smaller value of $0.1\times 10^{-8}\, cm^2 / sec$ was used for high performance concrete.

2.4 Chloride Threshold Values and Surface Chloride Concentration

The threshold value represents the required amount of chloride that induces the initiation of steel corrosion in concrete. Many investigators reported the chloride threshold values indicates that the threshold values in total chlorides range from 0.2 to 1.2 percent by cement weight depending upon the researchers. This wide range in threshold values comes probably from the fact that the constituent materials such as cement and aggregates are different for different researchers. In the present study, the average threshold value of 1% by cement weight proposed by Hussain, Al-Gahtani, and Rasheeduzzafar, and Page and Havdahl has been used in the subsequent corrosion analysis. This value is equal to $0.0015\, g_{cl} / g_{concrete}$ if converted to chloride ion weight per concrete weight (Hussain, 1996). The value of surface chloride concentration C_s is also necessary in the chloride diffusion analysis. For reinforced concrete structures exposed to sea water, several researchers reported this value to be about $0.006\, g_{cl} / g_{concrete}$ (Bazant, 1979). This value was used in the present analysis.

3. CHLORIDE DIFFUSION ANALYSIS CONSIDERING BINDING AND REINFORCEMENTS

3.1 Major Variables

The major variables used in the diffusion analysis include bar diameter, cover thickness of rebar, and water-cement ratio. Fig. 5 shows the specimen identification which explains the analysis variables. The first variable indicates whether the reinforcing bar has been considered or not in the diffusion analysis. The second variable represents the diameter of reinforcing bars, i.e., 10mm, 20mm, and 40mm. The third variable

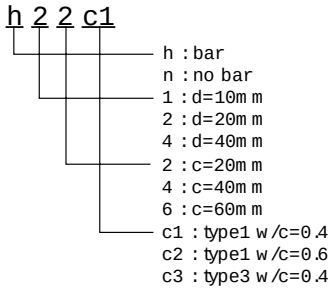


Fig. 5 Specimen identification with analysis variables

represents the cover thickness of rebar, i.e., 20mm, 40mm, and 60mm. The last variable shows water-cement ratio with cement type.

3.2 Finite Element Models for Diffusion Analysis

The chloride penetration into concrete wall or column members exposed to seawater can be analyzed by modeling the cross-section of the member in two dimensions. The finite element meshes for the cross-section of a member (a) with or (b) without considering reinforcing bar have been modeled. C_s represents the surface chloride concentration and C_0 is the initial chloride content contained in concrete. The value C_0 can be regarded as almost zero because the concrete has usually no chlorides initially in the mixture. The chloride diffusion analysis has been executed here based on the procedure described in the previous section.

3.3 Analysis of Results

The chloride diffusion analyses were implemented for various cases and the results are depicted in Fig.6-10. Fig.6 shows the chloride profiles penetrated into concrete for the member with rebar diameter d =10 mm and cover thickness c=20 mm. Fig.6 indicates that the penetrated chlorides increase with time. However, The most important finding here is that the chlorides accumulate in front of the reinforcing bar and that it shows much higher chlorides values at the location of rebar, compared with those without considering reinforcement. This is due to the fact that the chloride penetration can not take place through the rebar and the rebar plays a role to curb further penetration of chlorides locally. This higher accumulation of chloride in front of reinforcing bar may cause faster corrosion of reinforcing steel and thus reduce the lifetime of the structures.

Fig. 7 shows the chloride profiles for the case of increased rebar diameter d=20mm and same cover thickness c=20mm. It can be clearly seen from Fig. 7 that the chloride accumulation in front of the rebar is more pronounced for this case of larger size bar diameter with same cover thickness (See Fig. 6 with d=10mm for comparison). Fig. 8 again shows the chloride profiles for the case of d=40mm and c=20mm. Fig.8 indicates that the chlorides are accumulated further at the location of steel bar due to the increased bar size. This fact must be reasonably considered in the realistic corrosion analysis to obtain more accurate results in the lifetime prediction of the structures. Fig.9 shows the similar results for the case of rebar diameter d=20mm and cover thickness c=40mm. The similar trend is obtained for the chloride accumulation at the reinforcing bar. Fig.10 depicts the chloride profiles for the case of rebar diameter d=20mm and cover thickness c=60mm. The chloride accumulation in front of a rebar is relieved a little bit as the cover thickness increases.

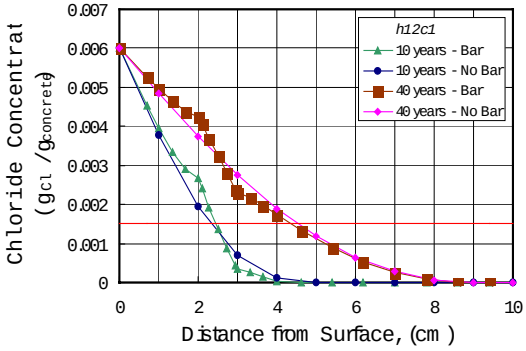


Fig.6 Effects of reinforcing bar on chloride diffusion (h12c1; 10,40year)

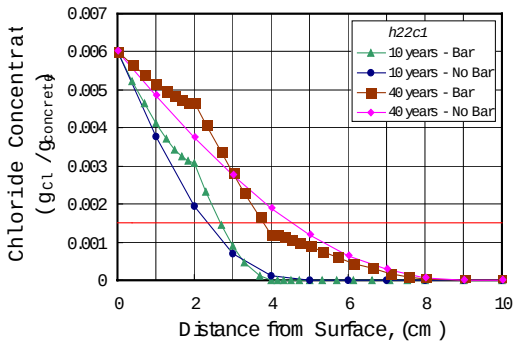


Fig. 7 Effects of reinforcing bar on chloride diffusion (h22c1; 10,40year)

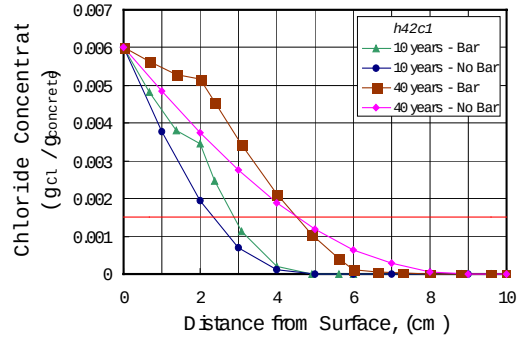


Fig.8 Effects of reinforcing bar on chloride diffusion (h42c1; 10,40year)

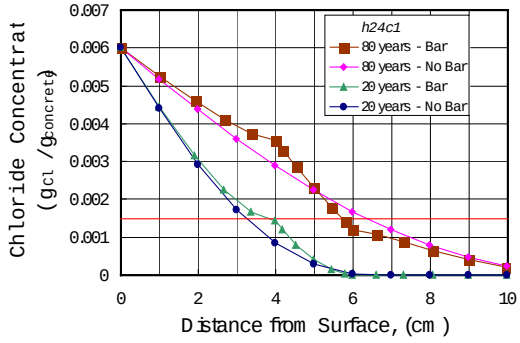


Fig.9 Effects of reinforcing bar on chloride diffusion (h24c1; 20,80year)

4. CORROSION INITIATION TIME FOR SERVICE LIFE

From the analysis results for penetrated amount of chlorides for various cases, there are great differences in chloride amounts at the bar locations. These differences will influence directly the estimated time for corrosion in concrete structures. The time to corrosion has been calculated here using the analyzed chloride profiles. The critical threshold value of 0.0015 $g_{cl} / g_{concrete}$ was used for the initiation of corrosion as mentioned in the previous section. The corrosion initiation time is much faster for the case of considering rebar than the case of neglecting rebar. Namely, the corrosion initiation time reduces by about 30-40 percent when the existence of rebar is considered in the chloride diffusion analysis.

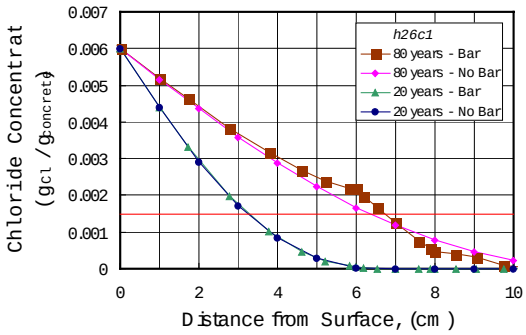


Fig.10 Effects of reinforcing bar on chloride diffusion (h26c1; 20,80year)

This fact is very important in estimating the durable or service life of concrete structures and therefore must be reflected correctly for more accurate and realistic durability design of such structures.

5. CONCLUSIONS

The threshold chloride concentration that causes the initiation of corrosion is of particular importance in view of service life prediction. The chloride penetration into concrete is also influenced by many parameters such as types of cement and mixture proportion. Therefore, the effects of these parameters on the chloride diffusion must be considered appropriately. The present study focused on the effects of reinforcing bar and binding isotherm on the chloride diffusion and also critical chloride concentration to initiate the corrosion of steel bars. The amount of bound chlorides decreases with an increase of water-cement ratio. The binding capacity of type3 cement is found to be higher than that of type1 cement at same water-cement ratio. The present study indicates that the chlorides are accumulated in front of a reinforcing bar and the accumulation of chlorides is much more pronounced for the case of larger-size bars. The major reason of chloride accumulation in front of a bar is due to the fact that the chloride diffusion does not occur through the reinforcing bars. The higher accumulation of chlorides at the bar location causes faster corrosion for reinforcing bars. The corrosion initiation time reduces by about 30-40% when the existence of rebars is considered in the accurate diffusion analysis. Therefore, realistic chloride diffusion analysis considering the effects of correct binding and reinforcing bars is required for more accurate determination of service life and realistic durability design of concrete structures.

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