RESEARCH ON PREDICTION OF THE INITIATION TIME OF CARBONATED INDUCED STEEL CORROSION IN REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Reinforced concrete is a popular material for civil works due to its conveniences and cost. Along with the influence of environment, reinforced concrete structures will gradually deteriorate due to the penetration of chloride and CO_2 into the concrete and cause corrosion on reinforcement. Currently, due to climate change resulting to sea level rising up and so the CO_2 concentration in the atmosphere. Those factors accelerate the degradation of reinforced concrete structures and reduce their service life. Extending the service life of reinforced concrete structures exposed CO_2 is a task that must be put in place to ensure the long-term durability of the structure. This paper presents a method to predict the initiation time of carbonated - induced steel corrosion in reinforced concrete structures by considering the increase of the concentration of CO_2 in the atmosphere due to climate change.

Keywords: reinforced concrete, initiation, carbonated induced steel corrosion, climate change.

Cite this Article: Dao Van Dinh, Research on prediction of the initiation time of carbonated induced steel corrosion in reinforced concrete structures, International Journal of Civil Engineering and Technology, 9(9), 2018, pp. 1747–1754.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=9&IType=9

1. INTRODUCTION

Reinforced concrete structures will gradually deteriorate due to the negative effects of environment. The popular deteriorations include reinforcement corrosion, sulfate attacks, alkaline aggregate reaction, creep and shrinkage and temperature effects. Among the above effects, carbonated induced steel corrosion is a cause of deterioration in concrete structure. Corrosion of reinforcement leads to cracking, spalling and delamination of the concrete cover [5], reducing the area of the reinforcement section, loss of adhesion between the

reinforcement and concrete, and then reducing the strength and plasticity. The result is the safety and serviceability reduction of concrete structures and shortening of their service life

Carbonation refers to a series of processes involving the diffusion of atmospheric carbon dioxide into concrete, which then react with the alkaline products of hydrated cement resulting in a reduction in the pH of water in the pore from a value greater than 12.6 (13.5 in the OPC case) to a level below 9.0 and thus lead to breaking of reinforced passive membrane and causing corrosion of the reinforcement[2]. The carbonation process depends not only on the composition of the concrete, temperature and humidity but also on the concentration of CO_2 in the air. Climate change scenarios predict that CO_2 concentrations in the air will increase over the years.

This paper proposes a model for predicting the beginning time of carbonated-induced corrosion of reinforced concrete structures exposed to CO_2, considering the increase of CO_2 concentration in the air caused by climate change.

2. PREDICTION THE INITIATION TIME OF CARBONATED-INDUCED STEEL CORROSION

Model for predicting the beginning time of carbonated-induced steel corrosion is based on diffusive Fick law No1. Volume of CO_2 enters into the concrete due to the difference CO_2 concentration between the outside air and the concrete is shown as follow:

$$dQ = D_{CO_2} A \frac{\Delta C_{CO_2}}{x} dt$$

(1)

Where: dQ = Diffusive volume of CO_2 (kg);

A = Penetrated area(m^2);

ΔC_{CO_2} = Difference CO_2 concentration (kg/m^3)

x = Distance between carbonation front and concrete surface(m);

dt = Time step(s);

D_{CO_2} = Diffusion coefficient of CO_2 (m^2/s).

Carbon dioxide diffuses into reaction with calcium hydroxide, potassium hydroxide and sodium hydroxide in concrete. In simple form, this process is simulated by equation 2.

$$dQ = a.A.dx$$

(2)

Where: a is carbon dioxide binding capacity of concrete (kg/m^3);

From equation (1) and (2) we have:

$$x.dx = \frac{D_{CO_2}}{a} \Delta C_{CO_2} dt$$

(3)

In case D_{CO_2} ; ΔC_{CO_2} are constant with t, integration of two sides of equation 3 we obtain:

$$X_c = \sqrt{\frac{2D_{CO_2}}{a} \Delta C_{CO_2}} . \sqrt{t}$$

(4)

X_c is cacbonated depth;

a is carbon dioxide binding capacity of concrete (kg/m^3);

In fact, according to climate change scenario, CO_2 concentrations in the air increase year by year.

2.1. CO₂ concentration of the environment

A historical study of CO_2 concentration of the IPCC (Intergovernmental Panel on Climate Change) indicates that during the period prior to 1750, CO_2 concentration were relatively stable from 260 to 280 ppm, but from 1750 to 2005, the CO_2 concentration increased from 280 ppm to 380 ppm [3]. Under the average emission scenario A1B, the amount CO_2 is shown in Figure 1
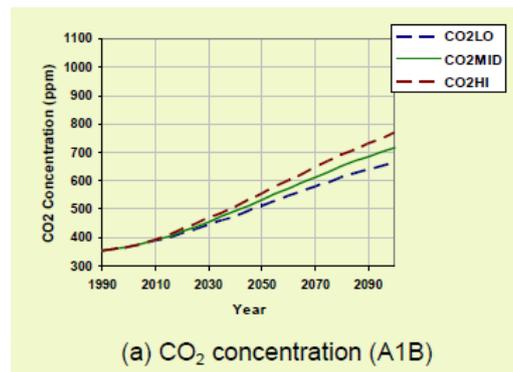

(a) CO₂ concentration (A1B)

Figure 1 CO₂ concentration increase by time [3]

Assume that the concentration CO_2 in 2017 is 400ppm and increases linearly by time:

$$CO_2(t) = (400 + p.t) \times 0.0019 \times 10^{-3} \quad (kg/m^3)$$

(5)

Where

p = The average increase of CO_2 by per year (ppm/year);

(0.0019×10^{-3}) = Constant to change from ppm to kg/m^3

2.2. Parameters to determine the initiation time of carbonated corrosion

2.2.1. Diffusion coefficient of CO₂ in concrete

Diffusion coefficient CO_2 in concrete was determined by standard experiments such as accelerated carbonation experiments. Diffusion coefficient can also be predicted according to the concrete composition as suggested by Vagelis G. Papadakis as follow [4]:

$$D_{CO_2} = 6.1 \times 10^{-6} \left(\frac{\varepsilon_c}{\dfrac{w_c}{\rho_c} + \dfrac{w_p}{\rho_p} + \dfrac{w_w}{\rho_w}} \right)^3 \cdot \left(1 - \frac{H}{100}\right)^{2.2}$$

(6)

Where

ε_c = The porosity of concrete;

w_c; w_p; w_w = The content of cement, additives and water, respectively;

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ρ_c; ρ_p; ρ_w =The density of cement, additives and water, respectively;

H =Humidity of the environment when the standard test, (H = 65%).

2.2.1.1. Effects of maintenance

Maintenance time affects diffusion CO_2 into the concrete. The influence coefficient of the maintenance symbol is k_c and will be taken according to Fib 2006 [1] as follow:

$$k_c = \left(\frac{t_c}{7}\right)^{b_c}$$

(7)

t_c = Number of days of concrete maintenance (day);
b_c = The exponent of regression, $b_c = -0,567$;

2.2.1.2. Effects of temperature

The temperature environment affects the diffusion speed, the higher the temperature, the faster diffusion. Arrhenius equation is a simple but quite accurate formula for the temperature dependence of the reaction rate. The equation was proposed by Svante Arrhenius in 1889. Based on the Arrhenius equation the relationship between the chlorine diffusion coefficient and the temperature is described by the following equation:

$$D(T) = D_{t0}.\exp\left[\frac{U}{R}\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T_{td}}\right)\right] = D_{t0}.f(T)$$

(8)

$$f(T) = \exp\left[\frac{U}{R}\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T_{td}}\right)\right]$$

(9)

Where:

D(T) = The diffusion coefficient at time t at the temperature T;
D_{t0} = The diffusion coefficient at time t_0 at the temperature Ti=293.15K (20°C) ;
U = Energy that activates the diffusion process (U = 35.000 J/mol);
R = Air constant (= 8,314 JK^{-1}mol^{-1});
T_{td} = Absolute temperature (K);
T_{ref} = Reference temperature =293.15K ;

2.2.1.3. Effects of humidity

Quantification of relative humidity coefficient can be determined by comparing the data obtained under real climate conditions H with a test climate (typically T = 20 ° C and relative humidity reference H_ref=65%).

Humidity coefficient is obtained as follow [1]:

$$f(H) = \left(\frac{1 - H^5}{1 - H^5_{\text{ref}}}\right)^{2.5}$$

(10)

Where:

H = Relative humidity of cacbonated layer (%)

H_{ref} = Humidity reference (H_{ref}=65%).

So the diffusion coefficient at the temperature T and the humidity H of environment is:

$$D_{CO_2,T,H} = D_{CO_2} \times k_c \times f(T) \times f(H)$$

(11)

2.2.2. The carbon dioxide binding capacity of concrete

The carbon dioxide binding capacity of concrete, the parameter in equation (8), was determined in equation (12), according to Yoon and his associates [6], as follow:

$$a = 0.75.C_{CaO}.C_c.\alpha_h \frac{m_{CO_2}}{m_{CaO}}$$

(12)

Where:

C_{CaO} = content of calcium oxide in cement;

C_c = volume of cement in the concrete;

α_h = level of hydration;

m_{CO_2} = the molecular mass of carbon dioxide;

m_{CaO} = the molecular weight of calcium oxide;

The binding or absorption capacity CO_2 of the concrete is denoted by a and porosity ε_c of the concrete is given by Papadakis then a is calculated as [4]:

$$a = 0,33C_{CH} + 0,214C_{CSH}$$

(13)

- For silica fume cement ($w_{SF} < 0,18w_C$)

$$C_{CH} = 0,29w_C - 1,62w_{SF}$$

(14)

$$C_{CSH} = 0,57w_C + 2,49w_{SF}$$

(15)

$$\varepsilon_c = (w_W - 0,267w_C - 0,0278w_{SF})/1000$$

(16)

- For low fly ash cement ($w_{FA} < 0,23w_C$)

$$C_{CH} = 0,30w_C - 1,30w_{FA}$$

(17)

$$C_{CSH} = 0,57w_C + 1,25w_{FA}$$

(18)

$$\varepsilon_c = (w_W - 0,268w_C - 0,177w_{FA})/1000$$

(19)

- For high fly ash cement ($w_{FA}<0,58w_C$)

$$C_{CH} = 0,29w_C - 0,50w_{FA}$$

(20)

$$C_{CSH} = 0,57w_C + 0,79w_{FA}$$

(21)

$$\varepsilon_c = \left(w_W - 0,267 w_C - 0,203 w_{FA} \right) / 1000 \tag{22}$$

Where

C_{CSH} = content of calcium silicate hydrate;

C_{CH} = content of $Ca(OH)_2$;

w_c; w_{SF}; w_{FA}; w_w = content of cement, silica, fly ash and water in 1 m^3 of concrete;

2.3. Prediction the Initiation time of steel corrosion

Replace Equations 5 and 10 in Equation 3 and take the differential equation, we have as follow:

$$\frac{x^2}{2} = \frac{D_{CO_2} k_c f(T) f(H)}{a} \times 0.0019 \times 10^{-3} \left(400t + \frac{p}{2} . t^2 \right) \tag{23}$$

Solve the equation (23) with $p > 0$, $x = L_c$, we obtain t by year as follow:

$$t = \frac{-B_1 + \sqrt{B_1^2 - 4A_1 C_1}}{2A_1} \tag{24}$$

Where:

$$A_1 = 1.9 \frac{p}{2} \frac{D_{CO_2} k_c f(T) f(H)}{a} \times 10^{-6} \times 365 \times 24 \times 3600 \quad (m^2/year) \tag{25}$$

$$B_1 = 0.76 \frac{D_{CO_2} k_c f(T) f(H)}{a} \times 10^{-3} \times 365 \times 24 \times 3600 \quad (m^2/year) \tag{26}$$

$$C_1 = -\frac{L_c^2}{2} \quad (m^2) \tag{27}$$

L_c - Clear concrete cover (m);

For outdoor structures subjected to wet-dry cycles, start-up time corrosion will be extended by the c influence coefficient due to the wet-dry cycle. This coefficient will be taken according to Fib [1] as follow:

$$k = \frac{1}{w(t)} \tag{28}$$

$$W(t) = \left(\frac{t_0}{t} \right)^{\frac{(p_{sR} T_0 W)^{b_w}}{2}}$$

3. EXAMPLE

3.2. Investigation on the effect of increase CO_2 concentration

Composition of concrete: Cement $380 kg/m^3$; Water: $180\ l/m^3$; Cement density: $3100 kg/m^3$; maintenance time: 2 days;

Environment conditions: Everage temperature by year: 26°C; Humidity: 75%;

Type of structure: Covered;

The start-up time corrosion is calculates by $p = 2; 3; 4\ ppm/năm$, thick of concrete cover $L_c = 25, 30, 35, 40, 45mm$. The results are as in the following graph:
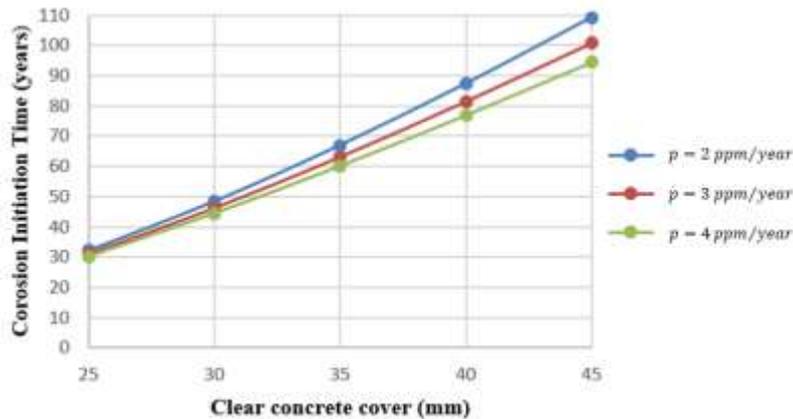

Figure 2 Effect of clear concrete cover on the innitiation corrosion

3.2. Investigation on the effect of water on cement ratio

Composition of concrete: Cement $380kg/m^3$; Cement density: $3100kg/m^3$; maintenance time: 2 days

Environment conditions: Everage temperature by year: 26^oC; Humidity: 75%;

Type of structure: Covered; Concentration increase of CO_2 là $p = 3ppm/year$, clear concrete cover $L_c = 30\ mm$;

The start-up time corrosion is calculates by $w/c = 0.35; 0.4; 0.45; 0.5$ and the results are as in the following graph:
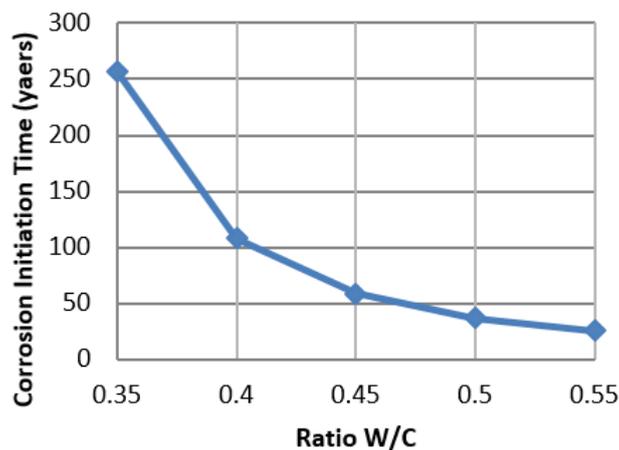

Figure 3 the effect of water on cement ratio to start-up time corrosion

4. CONCLUSION

The Initiation time of corrosion of reinforced concrete in reinforced concrete structure depends on three basic factors: Properties of concrete are characterized by two parameters: diffusion coefficient CO_2 (D_{CO_2}) and linkage abilityCO_2 of concrete (a); concrete layer thickness protection (L_c); Concentration of CO_2 in the air.

1. When the thickness of the concrete layer is small, the effect of increasing CO_2 concentration in the air is not much (Ex: $L_c = 25mm$: $p = 2; 3; 4\ ppm/year$, The initiation time of corrosion are $T = 32.14; 31.1; 30.17\ year$, respectively).

2. When the thickness of the concrete layer is quite thick the effect of increasing CO_2 concentration in the air is significant (Ex: $L_c = 45mm$: $p = 2; 3; 4\ ppm/year$, The initiation time of corrosion are $T = 109.12; 100.8; 94.37\ year$, respectively).

3. The initiation time of corrosion increases sharply when the cement ratio decrease (Ex $L_c = 30mm$: $p = 3\ ppm/year$, $w/c = 0.35; 0.40; 0.45; 0.50; 0.55$, The startup time of corrosion $T = 257.07; 108.23; 58.54; 36.70; 25.4\ year$, respectively).

4. It is recommended that the thickness of the protective concrete layer should be equal or greater than to 30mm and water-to-cement ratio of 0.30-0.40 should be used.

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