

The effect of crack width on the service life of reinforced concrete structures

NGUYEN Van Hung¹, VU Viet Hung² and TRAN Bao Viet³

¹University of Transport and Communications– campus in Ho Chi Minh City, VietNam, Master student

²University of Transport and Communications– campus in Ho Chi Minh City, VietNam, Lecturer; email: vvhung@utc2.edu.vn

³University of Transport and Communications– campus in Hanoi, VietNam, Lecturer; email: baoviet.tran@gmail.com or viettb@utc.edu.vn

Abstract. Reinforced concrete has become a widely used construction material around the world. Nowadays, the assessment of deterioration and life expectancy of reinforced concrete structure is very important and necessary as concrete is a complex material with brittle failure. Under the effect of load and over time, cracks occur in the structure, significantly reducing its performance and durability. Therefore, a number of models for predicting the penetration of chloride ions into the concrete were proposed to assess the durability of the structure. In the study performed by T B Viet (2016) [1], the author proposed a new theoretical model, especially considering the effects of macro and micro cracking on the diffusion coefficient of chloride ion in the cracked concrete. The following experimental results, in term of electrical indication of concrete's ability to resist chloride ion penetration, are used to calculate the lifespan of a reinforced concrete structure according to Dura Crete approach [8] with different crack widths to evaluate the accuracy and reliability of the above model in the range of concrete compressive strength of 30-70MPa.

1. Introduction

The durability of reinforced concrete (RC) structures in the marine environment can be understood as the ability to resist the intrusion of harmful substances, especially chloride ions from the external environment, through a network of pore and cracks. This results in the reinforcement corrosion, and eventually destroying the entire structure. There have been several scientific researches to determine the chloride ion diffusion coefficient in cracked concrete and have concluded that the pore structure of concrete affects decisively the penetration mechanisms and further the durability of the building [2-6]. Besides the pore system, during the fabrication and exploitation, concrete structures are also suffered from cracks (practically crack is considered as one of the intrinsic characteristics of concrete structure). Over time, under the effects of loads and environmental factors, cracks tend to expand and develop. It is believed that cracks reduce mechanical properties and significantly increase the diffusion of deleterious materials [1]. However, predicting the effect of cracking on diffusion of harmful substances in concrete, especially chloride ions is complicated and difficult [7].

Normally, when the structure is subjected to a certain state of load, macro cracks appear, extending from the exposed concrete surface to the reinforcement. In addition, microcracks also occur in the voids, internal defects and the interfacial transition zone (ITZ) between the aggregate and the cement paste in concrete. As the applied load is large enough, microcracks and macro cracks will connect together to form a crack network, affecting substantially the average diffusion coefficient of the structure [1].

The following study showed the obtained experimental results of electrical indication of concrete's ability to resist chloride ion penetration, and then to calculate the service life of reinforced concrete structures according to Dura Crete approach [8], with different crack widths to evaluate the accuracy



and reliability of the model proposed by T B Viet [1] in the range of commonly used concrete compressive strength of 30-70MPa.

2. New approach for improving prediction of effective chloride diffusivity in cracked concrete structures [1]

With an isotropic material hypothesis, and on the basis of Fick's second law, the average chloride ion diffusion coefficient in the RC structure with parallel surface fracture is calculated as following:

2.1. Macroscopic structure model

The average diffusion coefficient of cracked concrete (D^e) is calculated based on the diffusion coefficient in the crack (D_1) and diffusion coefficient of the un-cracked concrete (D_0) as seen in Figure 1:

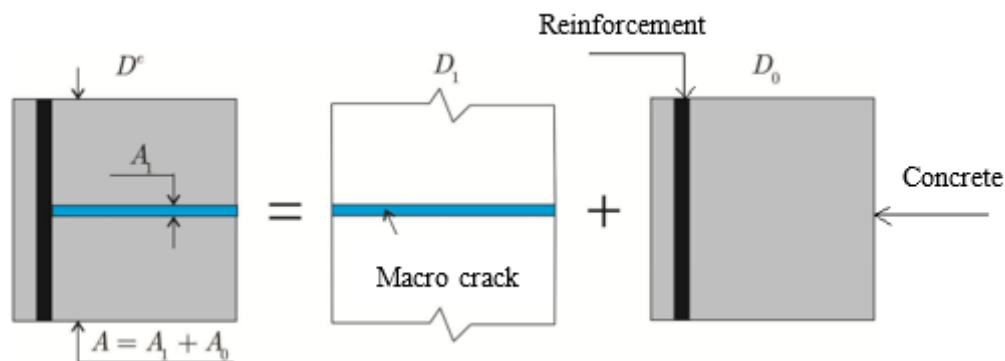


Figure 1. Illustration of the effect of macro cracking on the diffusion coefficient of concrete.

$$\frac{D^e}{D^b} = \frac{D_1}{D^b} \frac{1}{S} + K. \quad (1)$$

In which: D^e : Average chloride ion diffusion coefficient of cracked concrete.

D_1 : Chloride ion diffusion coefficient in crack.

$D_0 = D^b$: Chloride ion diffusion coefficient of concrete structure once only microcracks appear.

K : Coefficient depends on material characteristics.

$$S = \frac{A_0}{A_1} \quad \text{in which } A_0, A_1 \text{ are the cross-sectional areas of concrete structure and crack respectively.}$$

2.2. Microscopic structure model

It was hypothesized that a microscopic crack is formed in elliptical shape with two basic geometric features: $X=c/a$ (short axis and long axis ratio of the ellipse); The crack density parameter $e=N\alpha^3$ with N is the number of cracks per unit volume.

Eshelby tensor is a relevant mathematical solution of the elliptic problem in an infinite domain bearing a constant load. [2].

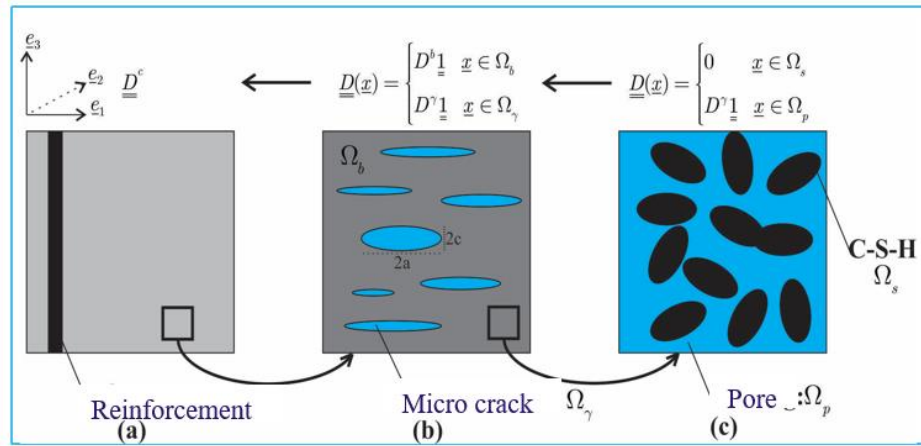


Figure 2. Illustration of the effect of micro crack on the diffusion coefficient of concrete structure.

$$K = \frac{D^e}{D^b} = 1 + f\left(\frac{D^g}{D^b}, e, X\right) \quad (2)$$

In which: D^g : Chloride ion diffusion coefficient of crack under saturated phase.

e : crack density parameter.

X : Short axis and long axis ratio of ellipse -shaped micro crack.

Thus, the chloride ion diffusion coefficient in the cracked concrete structure taking into account microcracks depends on not only the macro crack width (W), and depth (L), but also the pore structure characteristics, size and density of microcracks.

3. The service life of concrete structure according to Dura Crete [8]

According to Dura Crete approach [8], the initiation time of chloride induced corrosion of steel in concrete (t_1) is calculated as the following formula:

$$t_1 = \left[\left(\frac{2}{x^c - \Delta x} \operatorname{erf}^{-1} \left(1 - \frac{c_{cr}^c}{\gamma_{C_{cr}}} \frac{1}{A_{C_{s,cl}}^c \frac{W}{b} \gamma_{C_{s,cl}}} \right) \right)^{-2} \frac{R_{0,cl}^c}{k_{e,cl}^c \cdot k_{c,cl}^c \cdot t_0^{n_{cl}^c} \gamma_{R_{cl}}} \right]^{\frac{1}{1-n_{cl}^c}} \quad (3)$$

In which:

erf : error function, stemming from solving Fick's second law of diffusion

c_{cr}^c : characteristic value of critical chloride concentration.

$c_{s,cl}^d$: design value of surface chloride concentration.

x_d : design value of concrete cover thickness.

R_{cl}^d : design value of chloride resistance.

Δx : margin for concrete cover thickness.

x^c : thickness of concrete cover.

γ_{Cr} : partial coefficient for critical chloride concentration.

$A^c_{Cs,cl}$: regression parameter describing the relationship between chloride surface concentration and water & binder ratio (w/b).

$\gamma_{Cc,cl}$: partial coefficient for chloride surface concentration.

$R^c_{0,cl}$: resistance to chloride ingress determined on the basis of compliance trials.

$R^c_{cl,0} = \frac{1}{D_{0,cl}}$ in which $D_{0,cl}$: chloride ion diffusion coefficient.

$k^c_{c,cl}$: curing factor.

$k^c_{e,cl}$: environmental coefficient.

t_0 : age of concrete when testing.

n^c_{cl} : ageing exponent.

γ_{Rel} : partial coefficient of resistance for chloride intrusion.

4. Experiment to determine the effect of crack expansion on chloride ion diffusion coefficient

Due to time constraints and limited experimental conditions, as well as the difficulty in crack control, only one instance of artificial concrete cracks ($W = 2$ mm in width; $L = 20$ mm in depth) were conducted and compared to un-cracked concrete sample. Thus, it can be found that these test results investigate qualitatively the effect of crack expansion on chloride ion diffusion coefficient.

4.1. Testing sample preparation

To examine the effect of microcracks (porosity, internal defects, ITZ between cement paste and aggregates) on the chloride ion diffusion coefficient, three types of concrete with different compressive strengths ($f'_c = 30, 50, 70$ MPa) were used.

Moreover, in order to fully control the crack parameters and model evaluation, in this study an artificial cracking method was implemented by using a reciprocating saw machine to introduce a single parallel surface crack of 80 mm long, 2 mm wide and 20 mm deep.

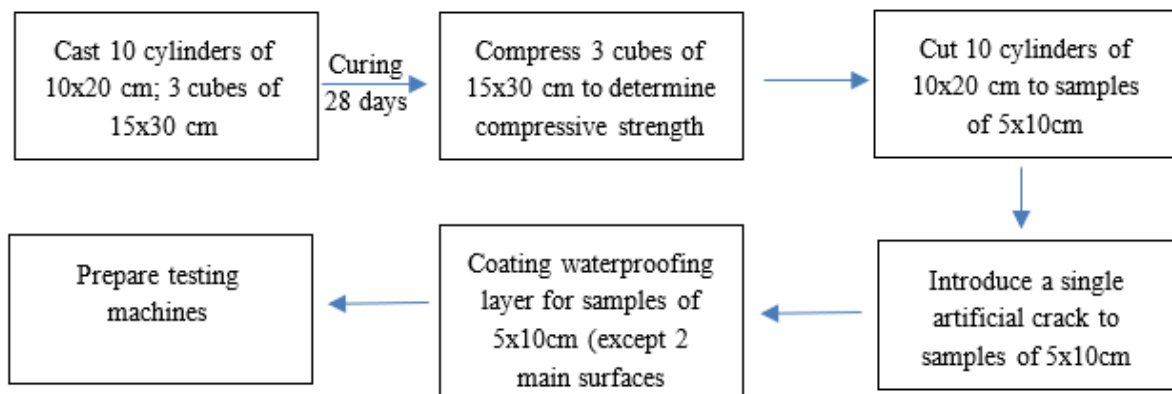


Figure 3. Test sample preparation procedure.

Table 1. Concrete mix proportion (1m³).

<i>Ingredient</i>	<i>$f'_c = 30 \text{ MPa}$</i>	<i>$f'_c = 50 \text{ MPa}$</i>	<i>$f'_c = 70 \text{ MPa}$</i>	<i>Unit</i>
D _{max}	19	19	19	mm
Cement	360	433	478	Kg
Fly ash	0	60	0	Kg
Silica fume	0	0	53	Kg
Water	183	162	161	Liters
Superplasticizer Sika Viscocrete 3000-20M	0	6.5	7.55	Liters
Sand	733	648	626	Kg
Gravel	1133	1108	1108	Kg

**Figure 4.** Slump test.**Figure 5.** Cut cylindrical concrete sample of 5x10cm.**Figure 6.** Samples of artificial crack.**Figure 7.** Introduce waterproofing layer.



Figure 8. Vacuum machine.

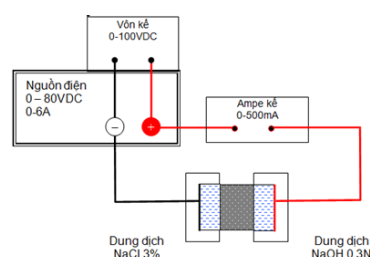


Figure 9. Electrical indication measurement.

4.2. Experimental approach or method (as TCVN 9337:2012- Heavy concrete -Method for electrical indication of concrete's ability to resist chloride ion penetration)

Measurement of electrical indication through a cylindrical concrete sample of 5x10cm was performed. The test was conducted in accordance with the principle of applying 60V DC to two sides of the test specimen, in which one side was exposed to a 3% sodium chloride solution connected to the cathode and the other was exposed to a sodium hydroxide solution connected to the positive electrode [9].

4.3. Formula to calculate the chloride ion diffusion coefficient

In this study, the chloride ion diffusion coefficient was determined by the electrical indication of concrete sample (Coulomb), based on the C-D relationship of some concrete references in the literature as following [10]:

- Normal concrete: $D = 0.0056(RCP) - 8.45$ ($10^{-8} \text{ cm}^2/\text{s}$)
- Silica fume concrete: $D = 0.0005(RCP) + 0.99$ ($10^{-8} \text{ cm}^2/\text{s}$)
- Fly ash concrete: $D = 0.0019(RCP) + 0.86$ ($10^{-8} \text{ cm}^2/\text{s}$)

In which RCP: the amount of Coulomb transmitted through concrete sample (Coulomb).

4.4. Experimental results

After conducting a test of electrical indication transmitted through cracked and un-cracked samples, the obtained results of chloride ion diffusion coefficient across the samples are shown as following:

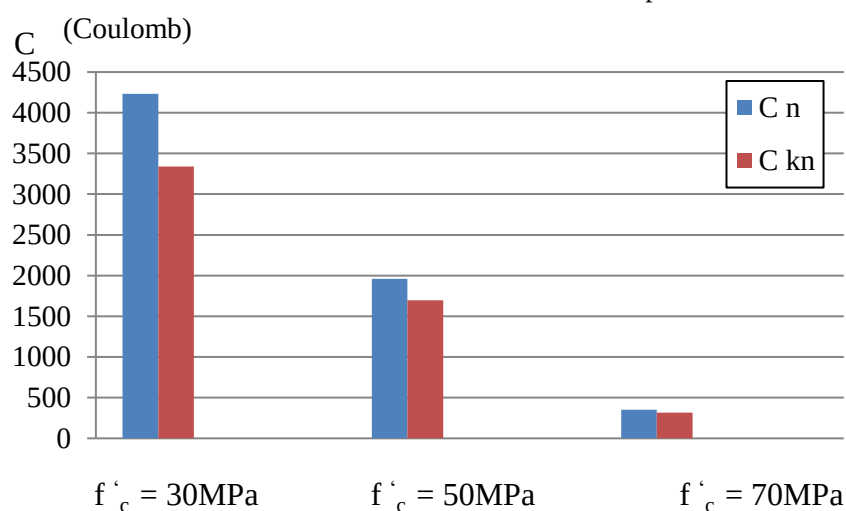


Figure 10. Electrical indication (Coulomb) passed through the concrete specimens (C_n : mean value of 18 samples, C_{kn} : mean value of 4 samples).

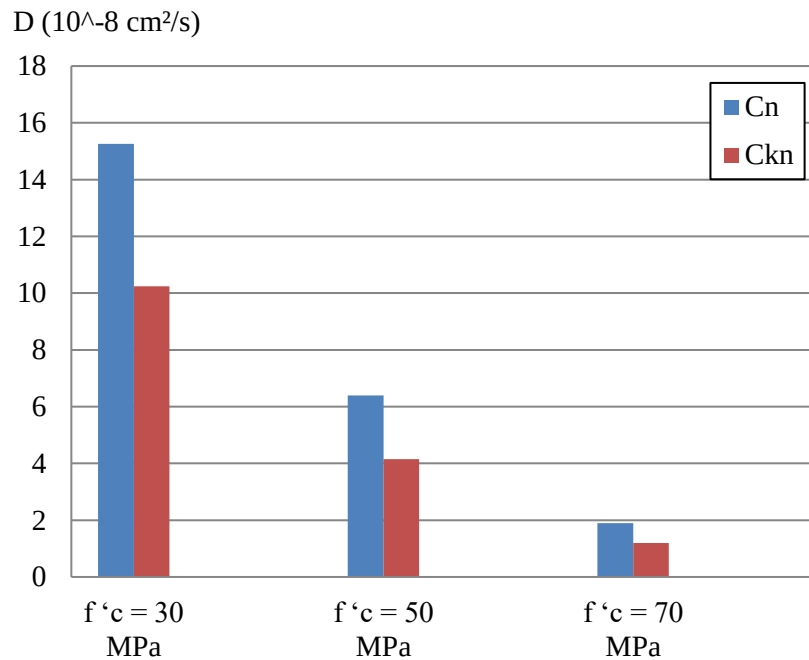


Figure 11. Diffusion coefficient of chloride ions (D) in different concretes.

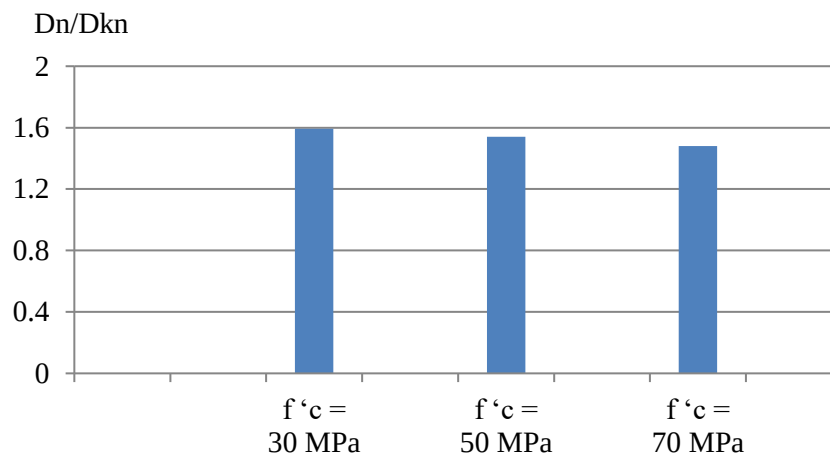


Figure 12. D_n/D_{kn} ratio of different concretes.

Based on the above results, some preliminary comments can be drawn as following:

- In case of only considering micro cracking in un-cracked concrete with different strengths:

The higher compressive strength it is, the smaller chloride ion diffusion coefficient becomes. The reason is that in higher strength concrete with lower W/C ratio, the concrete structure becomes more solid and denser, thus the smaller porosity makes the penetration of chloride ions into the concrete more difficult (as seen in Figure 11).

- In case of considering macro cracking in cracked concrete and un-cracked concrete with the same compressive strengths:

The presence of macroscopic cracks results in a substantial increase of chloride ion permeability (Figure 11). Once cracks appear, introducing a free way for chloride ion from the external environment easily to penetrate into the concrete.

D_n / D_{kn} ratio decreases as the strength of concrete increases as shown in Figure 12. This obtained result is in contrast to the result of applying proposed T B Viet's model [1] for three types of concrete: normal concrete (OC), high performance concrete (HPC), and high performance concrete using silica fume (HPCSF) with the compressive strengths of 46, 75 and 85.5 MPa, respectively (experiment presenting the relationship between the macro crack width and the average diffusion coefficient was conducted by Djerbi and co-authors, published in Cement and Concrete Research in 2008 [11]). It can be explained that the crack width in this study is quite large (2mm in width). Therefore, the penetration of chloride ions from the external environment to the surface of steel reinforcement is easier due to the large crack width and high porosity in lower strength concrete. Hence, chloride ion diffusion coefficient of cracked low-strength concrete is much greater than that of non-cracking. As a result, the smaller strength of concrete it is, the larger D_n & D_{kn} ratio becomes.

5. An illustration of service life calculation for cracked and uncracked reinforced concrete (RC) beams

5.1. Parameters of reinforced concrete beams

The I-shaped cross section prestressed RC beams were used to calculate the life expectancy of cracked and un-cracked concrete with the following parameters:

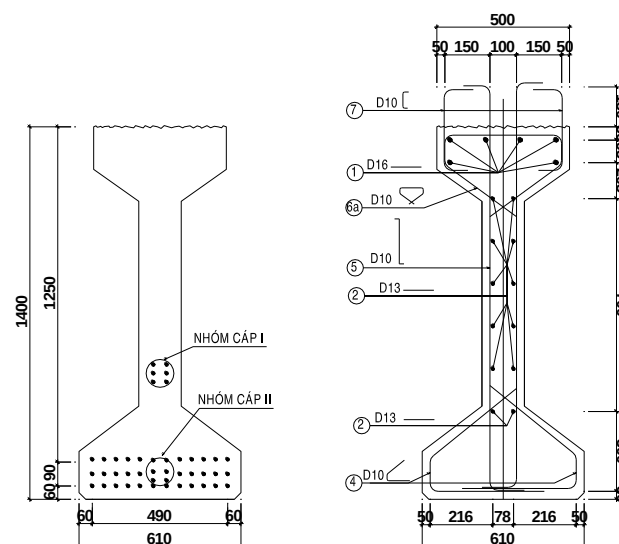


Figure 13. I-shaped cross section beam.

Table 2. I beam parameters.

Parameters	Value (mm)
Length x Height	33,000 x 1,400
Width of bottom flange	610
Width of top flange	500
Cover concrete	50
Compressive strength (MPa)	50 & 70

To evaluate the proposed model by T B Viet [1] as well as the above experimental results, the cracks appearing in these beams were assumed to be artificially cracked (crack width is not changed with crack depth).

For the purpose of investigating the effect of micro fracture or concrete structure characteristics, especially the shape and size of micro cracking on the serve life of cracked RC beams, two compressive strengths of concrete were applied ($f'_c = 50, 70\text{MPa}$).

And, to examine the effect of macro-crack expansion on the life expectancy of cracked RC beams, different crack parameters, such as crack width (W) and depth (L), were introduced as seen in Figure 14.

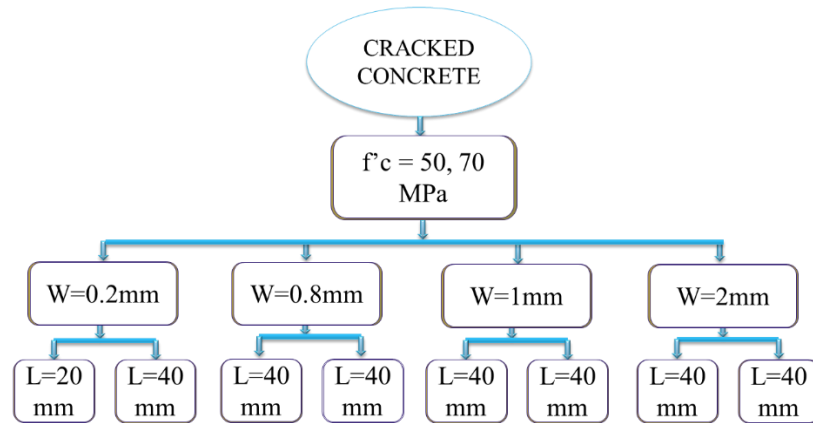


Figure 14. Calculated cases of cracked reinforced concrete beams with different strengths and crack characteristics.

Moreover, to validate the theoretical model with experimental results, the service life of RC beams should be calculated with diffusion coefficients according to the experimental and theoretical model results.

5.2. Results of calculation

After calculating the life expectancy of reinforced concrete beams, the results are shown as following:

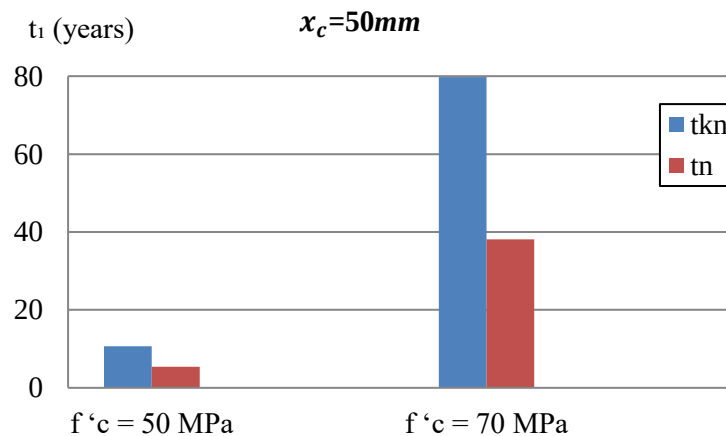


Figure 15. Service life of different types of RC cracked and un-cracked beams based on experimental results with crack characteristics of $W = 2\text{mm}$ in width, $L = 20\text{mm}$ in depth (t_{kn} and t_n : the un-cracked and cracked concrete service life) ($x_c = 50\text{mm}$: cover concrete depth).

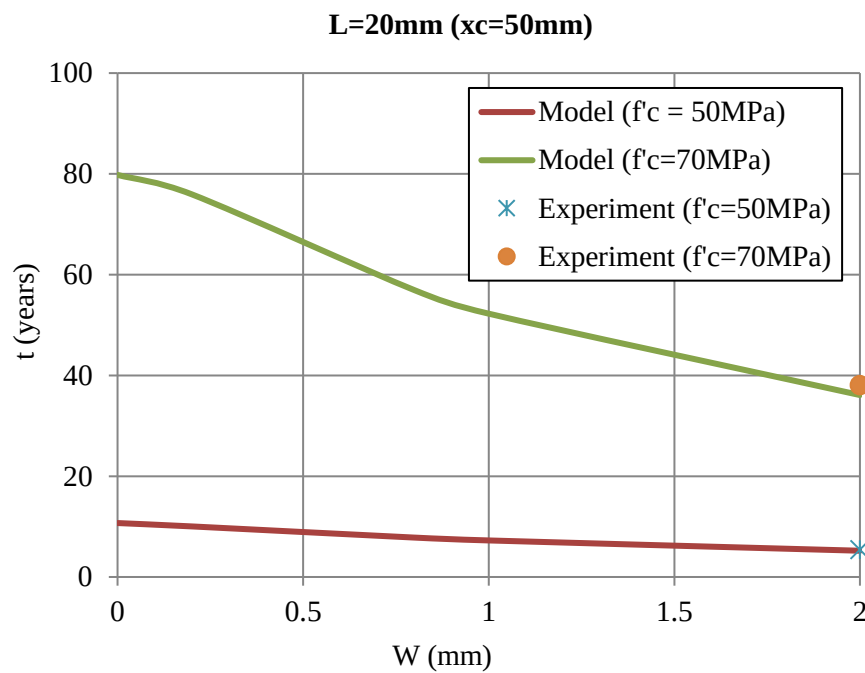


Figure 16. Comparison of the service life of cracked RC beams calculated according to the experimental results and model suggested by Viet ($L = 20\text{ mm}$, $x_c = 50\text{ mm}$).

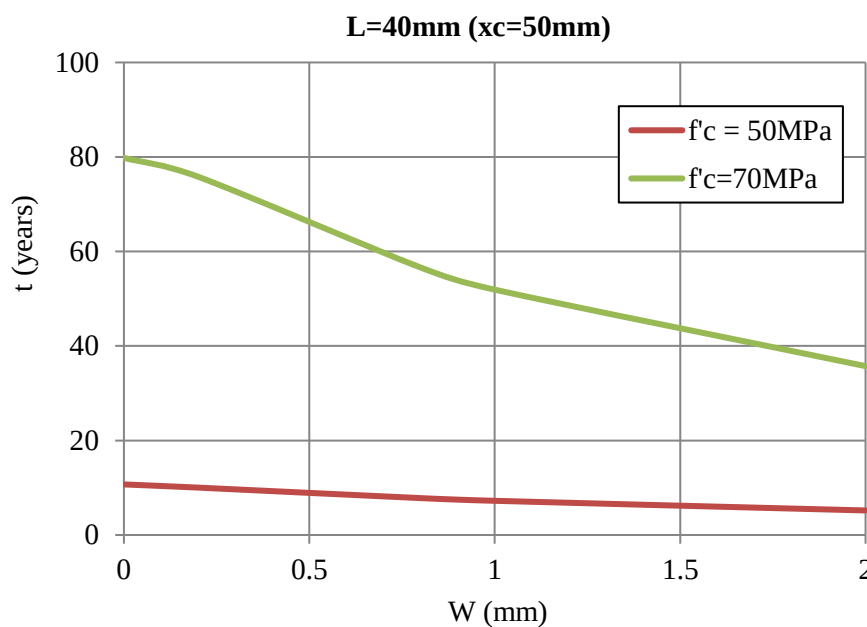


Figure 17. Relationship between the service life of cracked RC beams and crack width ($L = 40\text{ mm}$, $x_c = 50\text{ mm}$).

5.3. Discussions

The service life of RC beams depends on the strength of concrete. A higher strength concrete has a longer life expectancy as seen in Figure 15. This is due to the smaller chloride ion permeability in the higher strength concrete.

And, the service life of un-cracked RC beam is longer than that of cracked concrete (Figure 15). This is because the chloride ion permeability of cracked beams is much higher than that of un-cracked beams.

The difference in service life of RC beams, calculating based on the values of chloride ion diffusion coefficient obtained from the experiment and theoretical model is relatively small (less than 5%) (Figure 16). From this, it can be seen that the proposed model is relatively accurate by taking into account microcracks within the structure. The parameters of model can be estimated through the available information of microstructure or considered as free parameters experimentally determined.

The larger crack it is, the lower life expectancy becomes (Figure 16). The reason is that with the larger cracks, the higher possibility for chloride ion penetration into concrete occurs (larger diffusion coefficient), thus the shorter service life of the beam it is.

It is also found that with the same crack width, once the crack depth increases, the life expectancy of RC beams decreases. The reason is that the chloride ion diffusion coefficient depends not only on the crack width but also on the crack depth. When the crack depth is equal to the thickness of cover concrete, chloride ion penetrates freely or directly contact (through the crack) to the reinforcement surface. In the other hand, once a crack develops and not yet to reach the steel surface, the chloride ion penetration process requires much longer time to reach the steel due to remaining un-cracked concrete cover. However, it can be seen that the effect of crack depth is not significant compared to the crack width when calculating the service life of the beam as seen in Figures 16 & 17.

6. Conclusions and further research

The penetration of chloride ions into cracked reinforced concrete is directly affected by the characteristics of the macro crack (width and depth of crack). In addition, chloride ion intrusion depends on the characteristics of the microcracks (size and density) or structural characteristics of the concrete.

Based on the obtained results, it can be concluded that the model considering both the effect of macro and micro cracking to determine the chloride ion diffusion coefficient proposed by T B Viet (2016) shows a high accuracy and a useful approach for improving the prediction of effective chloride diffusivity in cracked concrete structures in case of parallel surface cracks.

In addition, further theoretical and empirical research should be continued to develop a computational model for practical cracks (taking into account the crack tortuosity and the reduction of the crack width in depth).

References

- [1] T B Viet, M D Loc and L M Cuong 2016 Influence of cracks on chloride diffusion in concrete structures *Journal of Transportation Science* **54** (in Vietnamese)
- [2] V Q Hoang, N T H Nhung and N N Thuy 2014 Prediction model of chloride ions dissipation into the cracks in reinforced concrete in the marine environment Ho Chi Minh City Open University *Journal of Science* **6 (39)** (in Vietnamese)
- [3] T N Nguyen and V Q Hoang 2015 A Simple Approach to Modeling Chloride Diffusion into Cracked Reinforced Concrete Structures *Journal of Civil Engineering Research* **5**
- [4] F A L Dullien 2012 Porous media: fluid transport and pore structure *Academic press Elsevier*
- [5] L Dormieux, D Kondo and Franz-Josef Ulm 2006 Microporomechanics New York *John Wiley & Sons*
- [6] K Maekawa, T Ishida and T Kishi 2008 Multi-scale modeling of structural concrete United States *CRC Press*
- [7] M G Richardson 2003 Fundamentals of durable reinforced concrete United States *CRC Press*
- [8] EU—B EuRam III 2000 DuraCrete - Final Technical Report Probabilistic performance based durability design of concrete structures The Netherlands *Document BE95-1347/R17(CUR)*
- [9] *TCVN 9337:2012- Heavy concrete - Method for electrical indication of concrete's ability to resist chloride ion penetration* (in Vietnamese)

- [10] H Kaesche 1959 Die Prüfung der Korrosionsgefährdung von Stahlarmierungen durch Betonzusatzmittel *Zement-Kalk-Gips* (in German)
- [11] A Djerbi, S Bonnet, A Khelidj and V Baroghel-Bouny 2008 Influence of traversing crack on chloride diffusion into concrete *Cement and Concrete Research* **38(6)** pp 877-883