Evaluation of Current Condition State of Reinforced Concrete Structures Exposed to Severe Environmental Condition

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Abstract

Deterioration of reinforced concrete structures arise due to corrosion of steel present in concrete which leads to structural failure. A number of techniques and methods are being followed and studied by various researchers to predict the service life of the reinforced concrete (RC) structures. Chlorides initiate the corrosion of embedded reinforcements, which not only produces signs of deterioration on the concrete surface, such as rusting, cracking and spalling, but also reduces the load-carrying capacity. This paper discusses service life prediction methods of RC structures exposed to severe environmental conditions.

Several methods were used to predict the service life and current condition state of the existing structures. Based on the mathematical modeling, the corrosion process could be formulated by three stages. They are namely, the initiation time (t_c), the de-passivation time (t_p), and the corrosion propagation time (t_{corr}). The total service life of RC structures can be expressed as summation of these time periods. In addition, crack observation method based on visual observation on the samples and existing structures and Accelerated Corrosion Testing Method (ASTM) was carried out at the laboratory. To identify the diffusion coefficient of the samples, the Rapid Chloride Penetration Test (RCPT) was carried out at the laboratory. Current condition assessment of the existing concrete structures was evaluated by using nondestructive techniques. This paper briefly discusses the current status of RC structures deteriorated by chloride attack in the Galle area, experimental investigation results and numerical analysis of corrosion cracking.

Keywords: Chloride attack, Accelerated Corrosion Testing Method, Rapid Chloride Penetration Test

1.0 INTRODUCTION

In the development of the infrastructure in any country, reinforced concrete (RC) is one of the most widely used construction materials. Many buildings, bridges, and high-way structures are constructed with RC. Most infrastructures use concrete extensively, such as dams, airports, coastal embankments, thermal power or nuclear energy plant, road and railway bridges, harbors and wharfs. Nevertheless, if these structures are exposed long-term to a severe environment of chloride ions or carbon dioxide, it will reduce their service lives. The safety of RC structures during the service period needs to be taken into consideration. Moreover, the durability of RC structures has to be investigated. A worthwhile subject for study would be to set up firmly a complete evaluation method for reasonably calculating the service life of RC structures and for furnishing judgment for repair, strengthening, or demolition.

Figure 2: Deterioration Process of RC structures due to corrosion.

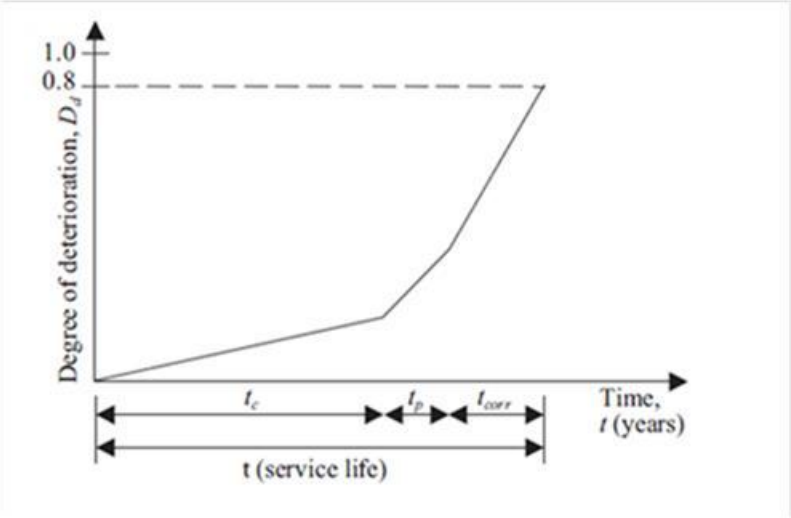


Figure 02: Deterioration Process of R/C structures due to corrosion.

t = Mean service life $\quad$ t =Depassivation time

t_c = Initiation time $\quad$ t_{corr} =Propagation Time

The total service life of RC structures can be expressed in terms of

$$t = t_c + t_p + t_{corr} \qquad \textit{Eq 1}$$

According to the theory of elasticity, Bazant established two classical formulas for calculating depassivation time (t_p) and corrosion (or propagation) time (t_{corr}). The depassivation time is defined as depassivation normally provided to the steel by the alkaline hydrated cement matrix locally leading to pitting corrosion. The corrosion time extends from the time when corrosion products form to the stage where they generate sufficient stress to disrupt the concrete cover by cracking or spalling, or when local attack on the reinforcement becomes sufficiently severe to impair its load-carrying capacity.

2.0 METHODOLOGY

2.1 Experimental Program

For the experiment 40 numbers of specimens were prepared. The experimental parameters were concrete cover, compressive strength of concrete, and diameter of r/f steel. Table 1 shows the experimental parameters.

The size of the specimen was 400 x 100 x 150 mm as shown in Figure 3. Non- corroded reinforcement steel was used. Stirrups should be prepared by 6 mm diameter mild steel bar.

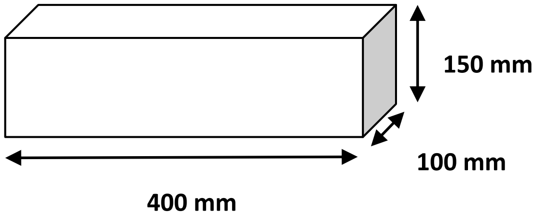


Figure 3: Dimensions of Specimens

Table 1: Test Parameters

Specimen location	***Method***	***Concrete Grade (N/mm^2)***	***Concrete Cover (mm)***	***Reinforcement bar Diameter (mm)***	***Number of Samples***
Laboratory Test (ACTM)	*Crack Observation*	*20 and 40*	*10 and 20*	*12 and 16*	*8*
Along the coastal Belt	*Numerical Method*	*20 and 40*	*10 and 20*	*12 and 16*	*24*
	Crack Observer Method	*20 and 40*	*10 and 20*	*12 and 16*	*8*

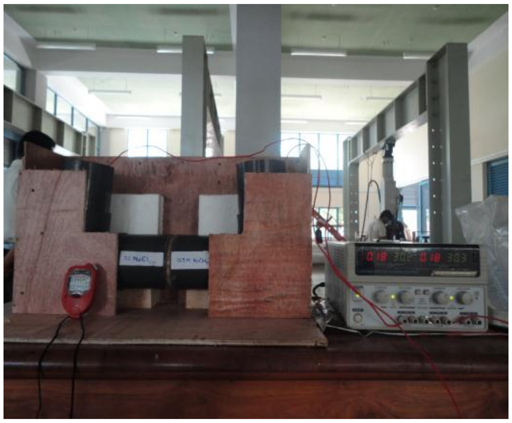
2.2 Data Observations

In the numerical calculation method, four numbers of parameters were monitored using laboratory experiments. These parameters are, concentration of chloride ion (Cl^-) on concrete surface (C_0), tensile strength of concrete (f_t'), rate of rust production per unit area of the plane (J_r) and diffusion coefficient of concrete (D_c). Time intervals of the data observation process are shown in Table 2.

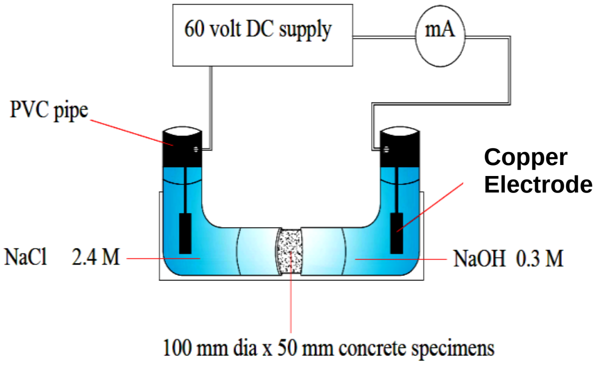
Table 2: Data Observation Process: Part - 1

Experiment Method	***Parameter***	***Methodology***	***Time Duration***
Numerical Calculation Method	*Diffusion Coefficient* (D_c)	*By Rapid Chloride Permeability Test (RCPT)*	*6 hour (after 28 and 90 days)*
	Tensile Strength of Concrete (f^1_t)	*Splitting tensile strength test*	*after 28 days*
	Concentration of Chloride ions on concrete Surface (C_0)	*Sea water titrating by* $AgNO_3$ *(by measuring precipitated weight)*	*Randomly (less than 10 times)*
	Rate of rust production per unit area of the plane (j_r)	• *volume reduction of r/f bar by measuring bar diameter* • *by measuring weight of rust product*	*once in 50 days*
Crack Observation Method (Allowable crack width to 0.2 mm.)	*Crack Width*(w_c)	*using Crack Gauge*	*once in 3 days*

Diffusion coefficient of concrete can be found by Rapid Chloride Permeability Test (RCPT). Test step for the Rapid Chloride Permeability Test (RCPT) prepared at the laboratory is shown in Figure 4.



(a) Experiment Setup at the Laboratory



(b) RCPT Setup

Figure 4: Rapid Chloride Permeability Test Set-up

The concrete specimens for RCPT with completion of moist curing of 28 and 90 days should be used for RCPT according to, ASTM C 1202 standard. The positive tank of the cell was filled with 0.30 M NaOH solution while the negative reservoir was filled with 3.0% NaCl solution as shown in Figure 4. Two identical copper substrate insoluble anodes (TSIA) were used as anode and cathode. A direct current (DC) of 60 ± 0.10 V was applied across the specimen faces, and the current across the specimens was recorded at every 30 min intervals, covering a total period of 6 hours. By knowing the current and time history, the total charge passed (CP) through the specimen was computed by Simpson's rule as given in the ASTM 1202 standard.

$$\mathbf{CP = 900\,[\,I_0 + 2I_{30} + 2I_{60} + 2I_t + \ldots\ldots + 2I_{330} + I_{360}\,]} \qquad \textbf{\textit{Eq 02}}$$

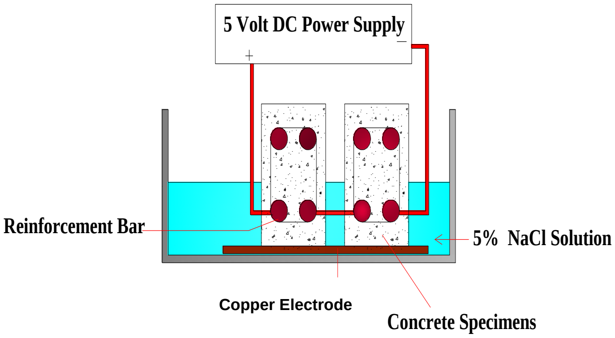
where CP is total charge passed in coulombs, I_0 is initial current in ampere and I_t is ampere at time t min.

The chloride diffusivity (***D***) was calculated as per the following expression

$$D = \beta \frac{kTLV\,(dc/dt)}{ZeECA} \quad (cm^2/s) \qquad \textbf{\textit{Eq 03}}$$

Simultaneously, the crack observer method was carried out to find service life of these specimens by using the Accelerated Corrosion Test Method (ACTM). Test set-up for the ACTM is shown in Figure 5.

(a) Specimens under Acceleration Corrosion Testing at the Laboratory



(b) Schematic diagram for ACTM

Figure 5: ACTM Test setup

3.0 Results and Discussions

Crack width was measured once in every three days using a crack gauge. The measured crack width vs. days was tabulated. Using this figure (Figure 6) the various times required to reach allowable crack width of 0.2 mm was determined. That particular time period was defined as the service life of the specimen in days.

Simultaneously, observation was carried out until initial crack appeared in the specimens that were placed at actual environment (coastal belt) condition. It was equal to the actual service life of those specimens. It was compared calculated service life from the numerical calculation method and the crack with observed in the field inspection method. Using these methods, it would be predicted approximately service life of any RC structure.

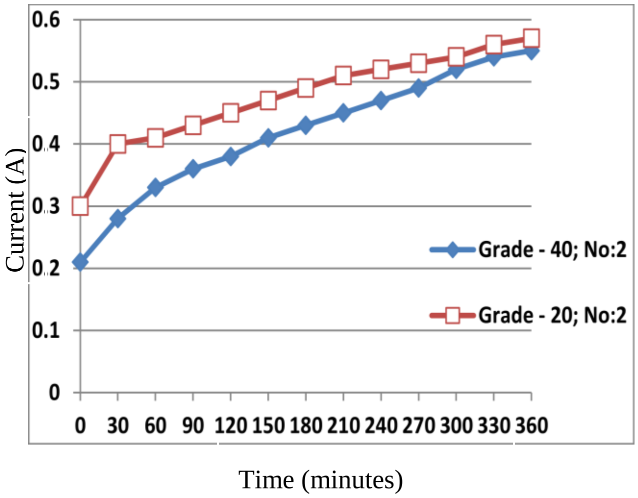


Figure 6: Rapid Chloride Permeability Test Data

The Rapid Chloride Permeability Test was carried out to calculate Diffusion coefficient. The current across the specimens was recorded at every 30 minutes intervals, throughout 6 hours. Diffusion coefficient can be calculated using Equation 4.

Initiation time was predicted using Fick's Second law

$$C(x,t) = C_o \operatorname{erfc} \frac{x}{\sqrt{4D_c t_c}}$$ ***Eq. 04***

Depassivation Time was predicted using average value of Bazant Proposed method (Eq. 05).

$$t_p = \frac{1}{12D_c}\left(\frac{L}{1-\sqrt{\frac{C^*}{C_o}}}\right)^2$$ ***Eq 05***

$$t_p = \frac{1}{4D_c}\left(\frac{L}{1-\sqrt{\frac{C^*}{C_o}}}\right)^2$$ ***Eq 06***

Propagation Time was calculated using Modified Bazant method (Eq. 07) [6].

$$t_{corr} = \rho_{cor}\frac{D}{s}\frac{\Delta D^*}{j_r},\ \Delta D^* = f_t'\left[2\left(\frac{L}{D}+1\right)\right]\delta_{pp}$$ **Eq 07**

Table 3: Calculated Service life using numerical method

Specimen No.	**D_c mm^2/yr**	**J_r $(g/m^2.s)$**	**Initiation time (yr)**	**Depassivation time (yr)**	**Propagation time (yr)**	**Service life (yr)**
B1	*19.29*	7.515×10^{-8}	*2.52*	*8.23*	*3.6*	*14.35*
B2		1.859×10^{-7}	*2.52*	*8.23*	*3.34*	*14.09*
B3		2.148×10^{-7}	*9.80*	*32.92*	*4.27*	*49.99*
B4		1.009×10^{-6}	*9.80*	*32.92*	*3.86*	*46.58*
B5	*10.71*	6.227×10^{-8}	*4.53*	*14.82*	*3.13*	*22.48*
B6		1.729×10^{-7}	*4.53*	*14.82*	*2.92*	*22.27*
B7		1.872×10^{-7}	*18.17*	*59.29*	*3.98*	*81.44*
B8		8.558×10^{-7}	*18.17*	*59.29*	*3.71*	*81.17*

Table 4: Accelerated Corrosion Test Parameters

Specimen no	***B 9***	***B 10***	***B 11***	***B 12***	***B 13***	***B 14***	***B 15***	***B 16***
Grade	*20*	*20*	*20*	*20*	*40*	*40*	*40*	*40*
Cover(mm)	*10*	*10*	*20*	*20*	*10*	*10*	*20*	*20*
Diameter(mm)	*12*	*16*	*12*	*16*	*12*	*16*	*12*	*16*

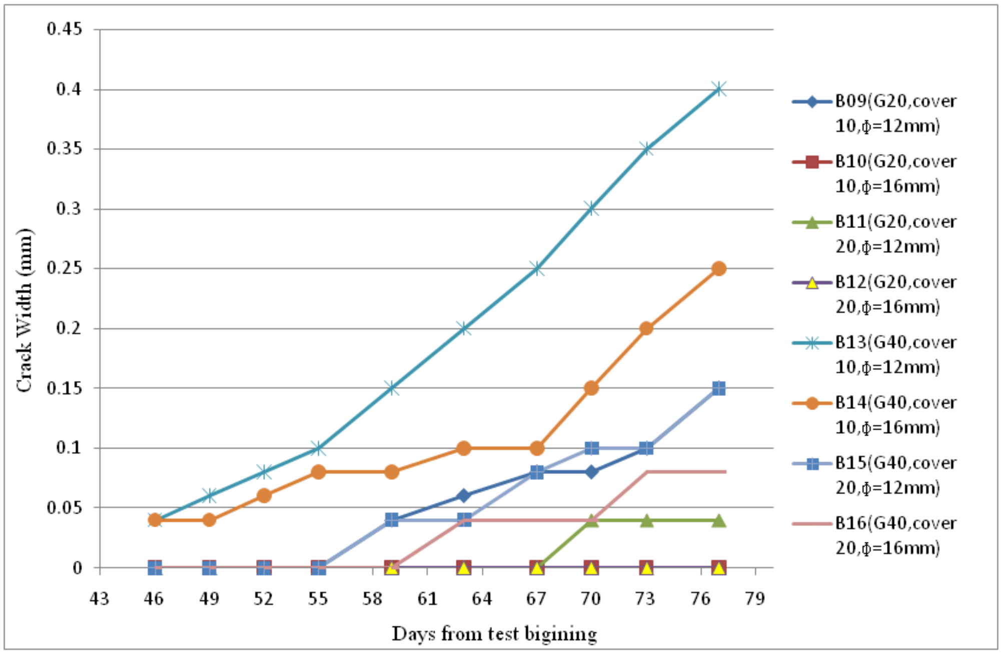


Figure 7: Accelerated Corrosion Test Results

4.0 RESULTS AND DISCUSSION

Finally service lives of RC structures exposed to chloride environment were predicted by using two different methods and effort was obtain relationship between these two methods. Service life of RC structures were calculated from numerical calculation method can be reasonably considered as the actual service life of the specimens as shown in Table 3. Service lives of the RC structures under accelerated condition were obtained from the ACTM and shown in Figure 7.

In this study, under numerical method calculated values for depassivation time was showed higher values than the initiation time and propagation time as shown in Table 3. For specimens B1 (G20, C10, D12) and B2 (G20, C10, D 16) propagation time is relatively higher than the initiation time. For other six specimens initiation time dose shows higher values than the propagation time according to Table 3.

5.0 CONCLUSIONS

This study provided an effective approach to accurately simulate the corrosion initiation process under dynamic environmental conditions. Based on the findings, a few key points are highlighted below:

The acceleration corrosion test method results show that there is no significant effect on service life of the specimens by changing the r/f bar diameter. The results suggest that the clear cover of the concrete and concrete grade may directly affect to the service life. Therefore it shows that most critical factor caused corrosion cracking is clear cover of the concrete specimen.

However, while conducting condition assessment of existing RC structures both carbonation and chloride attack was observed. Simultaneously nondestructive test data show that most critical deterioration conditions of the structures are at the costal belt. Distance from the sea and exposed conditions were significant factors while conducting the test rather concrete cover, grade and the bar diameter.

Apart from the material properties of the concrete, it has been demonstrated that the annual variation of the environmental conditions, such as temperature, humidity, and surface chloride concentration, have a very significant impact on the corrosion initiation process in RC bridges.

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