Service Life Design for Infrastructure under Indonesian Environmental Exposure

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Abstract: Reinforced concrete material is the most common material used in construction. This is due to its high durability which makes concrete classified as one of the world building materials having the longest service life. On the other hand, many research studies claimed that the application of concrete also has many durability problems. This is even worse for extreme environments such as sea due to its high chloride ion concentration. Environmental parameters such as temperature, humidity, and carbon dioxide concentration also have direct effects on the deterioration of concrete structures. Nowadays, the Indonesian Government builds much infrastructure which uses reinforced concrete as its main construction material. Concrete is chosen since its constituents are abundant in Indonesia. Deterioration mechanisms of concrete structures can be divided into the mechanism of concrete material deterioration and the mechanism of reinforcing bar corrosion. The corrosion of reinforcing bar is the most dangerous mechanism and the most difficult one to control. Chloride ions commonly coming from seawater become the main factor resulting in severe corrosion. This paper was aimed to give suggestions for several durability-related parameters such as cement type, water-cement ratio, concrete cover, etc. under Indonesian tropical climate.

1 INTRODUCTION

Indonesia, the world's largest archipelagic state, has a gigantic maritime domain of about six million square kilometers. It consists of more than 17,000 islands with five largest islands being Sumatera, Java, Kalimantan, Sulawesi, and Papua. Being located in proximity to the equator line, Indonesia is influenced mainly by the tropical rainforest climate. This climate is typically denoted by its high temperature, heavy rainfall, and high humidity. Its temperature is quite stable over the year, ranging between 23 °C to 28 °C spread from coastal plains to higher mountainous areas. It shows only a small fluctuation from season to season. Indonesia only has two main seasons, namely wet or rainy season and dry season. Most areas have their rainy season from September until March, which reaches its peak in January and February. Lowland areas have rainfall ranging between 1800 to 3200 mm per year. These values increase with the elevation of the area up to an average of 6000 mm in some mountainous regions. In a dry season, the rainfall decreases to 1800 mm annually. This dry season occurs from April to August with its driest peak occurring in July. The relative humidity varies between 70% and 90% (Logt, 2016).

Nowadays, the Indonesian Government has more focus on infrastructure development. It is achieved by improving ports and maximizing inter-island connectivity, and, in the end, it is hoped that Indonesia becomes a "Global Maritime Axis". The priority of this infrastructure development plan is in the infrastructure of the maritime sector. It is considered to be a project of nationally strategic importance given that Indonesia is the largest archipelago in the world (Carruthers, 2016).

There are many seaports having been built recently. Concrete is chosen to be their main construction material since its constituents are abundant in Indonesia. It is no wonder that reinforced concrete becomes very popular. Its high durability capacity makes concrete classified as one of the world building materials having the longest service life. On the other hand, many research studies claimed that the application of concrete also has many durability problems. This is even worse for extreme environments such as sea due to its high chloride ion

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concentration. Environmental parameters such as temperature, humidity, and carbon dioxide concentration also have direct effects on the deterioration of concrete structures. Deterioration mechanisms of concrete structures can be divided into the mechanism of concrete material deterioration and the mechanism of reinforcing bar corrosion. The corrosion of reinforcing bar is the most dangerous mechanism and the most difficult one to control. Chloride ions commonly coming from seawater become the main factor resulting in severe corrosion.

2 LITERATURE REVIEW

Seawater is one of the external sources of chloride ions which are corrosive to concrete reinforcing steel other than internal sources coming from concrete mixtures (Nguyen, et al., 2016). Corrosion due to chloride ions is one of the main basis of deterioration of reinforced concrete structures in chloride-exposed environments. This results in reduced service and security structures while increasing repair and maintenance costs (Bastidas-Arteaga & Schoefs, 2015).

Tutti's model (Figure 1) is widely accepted as a conceptual model in the modelling of structural deterioration. The model clearly shows the time of corrosion initiation to the time of corrosion propagation. In the initiation phase, chloride ions diffuse from concrete to reinforcing steel. When this phase ends, the initial corrosion of steel reinforcement begins when the chloride ion concentration reaches the threshold value. The propagation phase is defined as the time when the corrosion begins to the critical point of the loss of the function of the reinforcing steel. In this case, the service life of the structure is the sum of the initiation phase and the propagation phase (Wu, et al., 2015).

Service life of structures means that the structure will fulfil the performance requirements under defined repair and maintenance within a specified time period (Verma, et al., 2014). The estimation of service life of reinforced concrete structures in the marine environment is usually done by using a simple basic model of chloride diffusion. This model is popularly known as Fick's second law of diffusion. It is stated as follows.

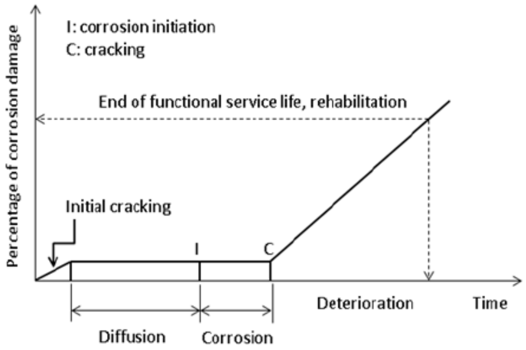


Figure 1: Reinforced concrete structure deterioration Process due to corrosion.

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \qquad (1)$$

3 METHODS

An estimation of the service life of reinforced concrete structures exposed to chloride ions is carried out by means of chloride diffusion models. There are three models used here namely empirical diffusion model, long-term chloride concentration model, and modified diffusion model.

3.1 Empirical Chloride Diffusion Model

This empirical chloride diffusion model is derived from Fick's second law of diffusion. The chloride profile in concrete is obtained by assuming that the governing transport mechanism is one-dimensional diffusion. The mathematical solution of this problem, equation (1), yields equation (2) as follows:

$$C_{x,t} = C_s\left(1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right), \qquad (2)$$

where $C_{x,t}$ is the concentration of chloride at depth x within time t, C_s is the concentration of chloride at the concrete surface, x is the depth from surface, t is time, and D is the coefficient of apparent chloride diffusion. Simplifying using parabolic function, equation (2) reads as equation (3) (Khan, et al., 2017).

$$C_{x,t} = C_s\left[1 - \frac{x}{2(3Dt)^{0.5}}\right]^2. \qquad (3)$$

The coefficient of apparent chloride diffusion, D, is defined by (Fib, 2006) as follows:

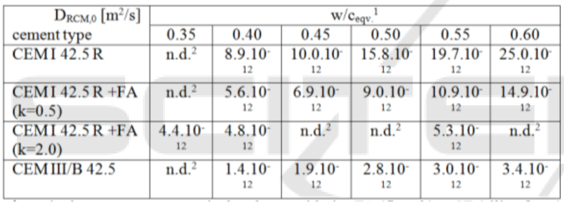
$$D_{app,c} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t)\,, \tag{4}$$

where ke is the environmental transfer variable, $D_{RCM,0}$ is the chloride migration coefficient (table 1), kt is the transfer parameter (set to 1), and A(t) is the sub-function considering the ageing.

$$k_e = \exp\left[b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right], \tag{5}$$

where be is the regression variable, Tref is the reference temperature (193 K = 20 °C), and Treal is the temperature of the ambient air or structural element.

Table 1: $D_{RCM,0}$ parameter quantification for different concrete mixtures.



$D_{RCM,0}$ [m²/s] cement type	w/c$_{eqv.}$^{1}					
	0.35	0.40	0.45	0.50	0.55	0.60
CEM I 42.5 R	n.d.^{2}	$8.9.10^{-12}$	$10.0.10^{-12}$	$15.8.10^{-12}$	$19.7.10^{-12}$	$25.0.10^{-12}$
CEM I 42.5 R +FA (k=0.5)	n.d.^{2}	$5.6.10^{-12}$	$6.9.10^{-12}$	$9.0.10^{-12}$	$10.9.10^{-12}$	$14.9.10^{-12}$
CEM I 42.5 R +FA (k=2.0)	$4.4.10^{-12}$	$4.8.10^{-12}$	n.d.^{2}	n.d.^{2}	$5.3.10^{-12}$	n.d.^{2}
CEM III/B 42.5	n.d.^{2}	$1.4.10^{-12}$	$1.9.10^{-12}$	$2.8.10^{-12}$	$3.0.10^{-12}$	$3.4.10^{-12}$

[1] equivalent water-cement ratio, hereby considering FA (fly ash) or SF (silica fume) with the respective k-value (efficiency factor). The considered contents were as follows: 22 wt.-%/cement; SF: 5 wt.-%/cement.
[2] n.d.–chloride migration coefficient RACC,0-1 has not been determined for these concrete mixes.

$$A(t) = \left(\frac{t_0}{t}\right)^a, \tag{6}$$

where t_0 is the reference point of time (chosen to be 0.0767 year = 28 day), and t is the time in year.

Table 2: Ageing exponent,a_e, parameter quantification.

Concrete	Ageing exponent a_e [-]^5
Portland cement concrete CEM I; 0.40≤w/c≤0.60	Beta (m^1 = 0.30; s^2 = 0.12; a^3 = 0.0; b^4 = 1.0)
Portland fly ash cement concrete f≥0.20z; k=0.50; 0.40≤w/c$_{eqv}$≤0.60	Beta (m^1 = 0.60; s^2 = 0.15; a^3 = 0.0; b^4 = 1.0)
Blast furnace slag cement concrete CEM III/B; 0.40≤w/c≤0.60	Beta (m^1 = 0.45; s^2 = 0.20; a^3 = 0.0; b^4 = 1.0)

[1] m = mean value, [2] s = standard deviation, [3] a = lower bound, [4] b = upper bound, [5] quantification can be applied for the exposure classes: splash zone, tidal zone, and submerged zone.

This chloride diffusion model can be utilized to predict the chloride-induced corrosion initiation time. It is assumed that $C_{x,t}$ is the critical chloride concentration (C_{crit}), t is the time of initiation, and x is the concrete cover thickness (a). The equation (3) now reads as follows.

$$t_1 = \frac{1}{12D}\left[\frac{a}{1-\left(C_{crit}/C_s\right)^{0.5}}\right]^2 \tag{7}$$

In this research, the values of C_{crit} and C_s are taken 0.3 and 0.6, respectively.

3.2 Chloride Diffusion Model Incorporating Time Effect

A model reported by (Lei, et al., 2018) incorporating the effect of time in the chloride diffusion model is as follows:

$$C_{x,t} = C_s\left(1 - erf\left(\frac{x}{2\sqrt{\frac{D}{1-m}t^{1-m}}}\right)\right), \tag{8}$$

where m is a constant of time decay factor.

A constant of time decay factor, m, depends on ratio of concrete mix and ambient surroundings. This paper assumes that m equals to 0.69, which is taken based on (Lei, et al., 2014).

$$C_{x,t} = C_s\left[1 - \frac{x}{2\left(\frac{3D}{1-m}t^{1-m}\right)^{0.5}}\right]^2. \tag{9}$$

Analogous to equation (7), equation (10) can be derived in the same manner, which results in the following equation:

$$t_2^{1-m} = \frac{1-m}{12D}\left[\frac{a}{1-\left(C_{crit}/C_s\right)^{0.5}}\right]^2. \tag{10}$$

3.3 Chloride Diffusion Model Incorporating Linear Stress Distribution

This model of chloride diffusion is gained by considering the linear stress distribution on a sectional structure. It is considered that the cross-sectional stress is under pure axial compressive load (Lei, et al., 2018). The resulting formula can be seen as follows:

$$C_{x,t} = C_s\left(1-erf\left(\frac{x}{2\sqrt{\left(D+A_0\sigma_s+A_1\sigma_s^2\right)t}}\right)\right) \quad (11)$$

,

where A_0 and A_1 are the considered cross-sectional areas, and σ_s is the cross-sectional stress. In this paper, $A_0 = 0.56$, $A_1 = 0.38$, and $\sigma_s = 0.32$ MPa.

$$C_{x,t} = C_s\left[1-\frac{x}{2\left(3\left(D+A_0\sigma_s+A_1\sigma_s^2\right)t\right)^{0.5}}\right]^2 \quad (12)$$

.

Equivalent to equation (7), equation (13) can be derived in the same manner, which yields the following equation:

$$t_3 = \frac{1}{12\left(D+A_0\sigma_s+A_1\sigma_s^2\right)}\left[\frac{a}{1-\left(C_{crit}/C_s\right)^{0.5}}\right]^2 . \quad (13)$$

Those three formulas of corrosion initiation time, equations (3), (9), and (12), are then compared to each other taking into account parameters such as cement type, water-cement ratio, and concrete cover suitable for Indonesian construction practices.

4 RESULTS AND DISCUSSION

The prediction of reinforced concrete structures' service life is performed to study the effect of the use of each diffusion model on how long the initiation time will last. These simulations are carried out for several parameters such as water-cement ratio, cement type, and temperature. Every simulation uses the three model of chloride diffusion, which are equations (3), (9), and (12). The results of the simulations are then plotted in "concrete cover" vs "initiation time of corrosion" graphs (Figure 2 until Figure 5).

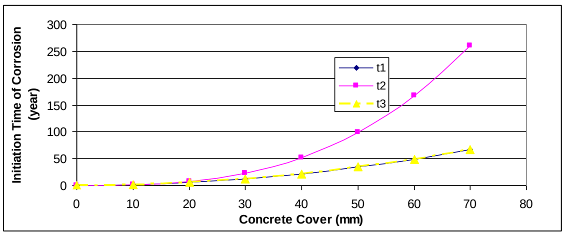


Figure 2: Concrete cover vs. initiation time of corrosion—three models.

Figure 2 depicts the relation between concrete cover and the initiation time of corrosion incorporating three models of chloride diffusion. The models are empirical diffusion model, long-term chloride concentration model, and modified diffusion model, which are indicated as t1, t2, and t3, respectively. As can be observed, the initiation time of corrosion is longer for thicker concrete cover.

For common interior structural elements, the concrete cover is usually 40 mm thick. This value corresponds to initiation time of corrosion in around 20 year for models t1 and t3 and 50 years for model t2. In general, chloride diffusion models t1 and t3 coincide with each other, while model t2 tends to deviate from the other models. For concrete cover ranging from 0 mm to 25 mm, all three models result in almost similar initiation time. When concrete cover reaches 30 mm, model t2 yields initiation time values which are higher than those of the two other models. Overall, model t2 predicts higher values of initiation time.

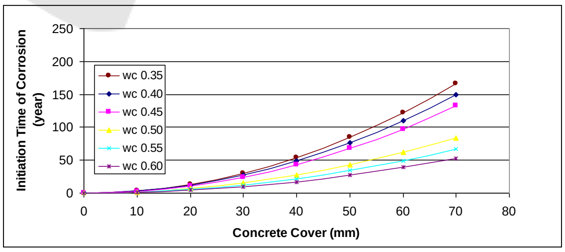


Figure 3: Concrete cover vs. initiation time of corrosion—w/c ratio.

It is obtained that t2 deviates a lot from other two models and yields illogical values of initiation time of corrosion for higher concrete cover. It is, thus, reasonable to choose t1 and t3 for the rest of the simulations. Having known that the results from t1 and t2 are coinciding, it is easier to use t1 model as the governing model. The relation between concrete cover and initiation time of corrosion which incorporates various water-cement ratio parameters can be seen in Figure 3. In general, all plotted graphs are giving the same curve trends. The simulations take five water-cement ratios (w/c): 0.40; 0.45; 0.50; 0.55; and 0.60. There are two groups of water-cement ratios that are close to each other. These two groups are w/c ratios from 0.40 to 0.45 and w/c ratios from 0.50 to 0.60. Taken as a whole, the w/c ratio 0.40 predicts the highest time of initiation, while the w/c ratio 0.60 yields the lowest initiation time of corrosion.

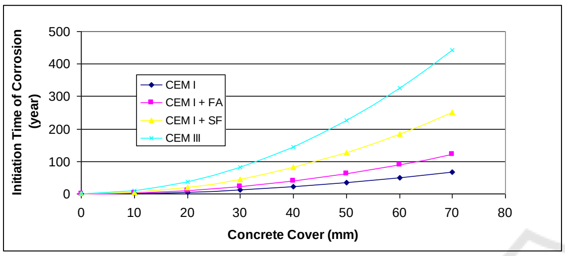


Figure 4: Concrete cover vs. initiation time of corrosion—cement type.

Figure 4 simulates the relation between concrete cover and initiation time of corrosion taking into account different cement types. These cement types include CEM I, CEM I + FA, CEM I + SF, and CEM III/B. From the simulations, it can be noted that the highest prediction values of corrosion initiation time are given by CEM III/B. On the other hand, CEM I gives the lowest values.

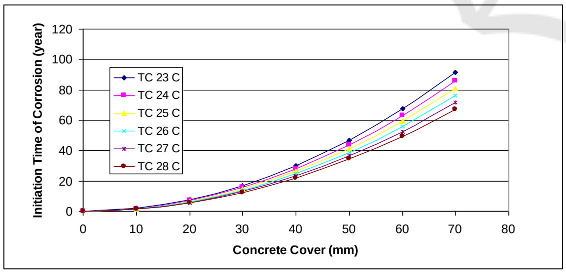


Figure 5: Concrete cover vs. initiation time of corrosion—temperature

In order to give insight into Indonesian tropical climate's parameter, figure 5 illustrates the relation between concrete cover and initiation time of corrosion taking into consideration temperature effect. The temperatures are simulated from 23 °C to 28 °C. For concrete cover ranging from 0 to 25 mm, all six graphs give almost similar initiation time. When concrete cover reaches 30 mm, each model gives values of initiation time which are slightly different.

5 CONCLUSIONS

A service life estimation of reinforced concrete structures exposed to chloride-induced corrosion has been performed using three models of chloride diffusion. These models are empirical diffusion model, long-term chloride concentration model, and modified diffusion model. Several relevant parameters are included in the service life simulations in order to predict deterioration behavior under Indonesian climate. Some important parameters in reviewing initiation time of corrosion such as concrete cover, water-cement ratio, and cement type are calculated. Based on the results, the following conclusions are achieved:

1. Empirical diffusion model and modified diffusion model simulate similar trends and values in predicting initiation time of corrosion.
2. Concrete cover parameter should be chosen carefully so that it is not too thick (considering the influence of the weight and performance of the structure and the economical aspects of the construction) or even too thin that it will accelerate corrosion. The ideal concrete cover for the Indonesian marine environment based on the simulations is 70 mm. Figure 5 shows that all of the values of initiation time of corrosion are over 60 years. They are higher than the design service life of Indonesian common buildings, which is only 50 years.
3. It is important to regulate and keep the water-cement ratio parameter low in order to hamper the speed of the migration process of chloride ions. This not only helps postpone the corrosion process but also affects the control of volumetric deformation of concrete material, for example, the phenomenon of creep and shrinkage. The ideal value for water-cement ratio is 0.35. Figure 3 shows that the w/c ratio of 0.35 in conjunction with 70-cm cover is enough to give the concrete structures life of more than 150 years.
4. It is also important to observe the predefined values in the formulation, especially its compatibility aspects with Indonesian construction practices and the Indonesian climate condition in most cases.

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