Durability based service life prediction of bacterial concrete

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Abstract. Concrete durability is one of the essential factors affecting the service life of structures. The problem in durability of structures not only gives great impact on the functionality of the structures themselves but also on their environment. The maintenance and repair process resulting from the problems will consume a lot of energy and resources. The use of bacteria as an effort for repairing concrete cracks becomes popular recently. Crack formation is a common problem in many concrete structures. Durability problems may arise due to these cracks usually reducing concrete integrity and permeability. There are many degradation mechanisms affecting concrete performance, two of them are carbonation and chloride ingress. Several researches prove increased resistance towards those two mechanisms. This paper is aimed to simulate service life of bacterial concrete based on carbonation and chloride ingress mechanisms incorporating carbonation rate constants and chloride migration coefficients. It is concluded that the utilization of bacteria in concrete is prospective in increasing the durability of concrete structures.

1. Introduction
Concrete is one of the popular construction materials nowadays. This is due to its remarkable compressive strength property. On the other hand, concrete also famous for its brittleness with low tolerance for tensile strain. The high tensile stresses may be grown in the concrete structures due to external loads, imposed deformations, plastic shrinkage, plastic settlement and expansive reactions [1]. This leads to the crack formations in many concrete structures that then become the typical durability-related phenomenon. The proper and immediate measures should be taken in order to rectify these cracks. Without any treatment, cracks will expand further and later require an expensive repair.

Cracks in concrete are inevitable occurrences and one of the inherent weaknesses of concrete [2]. A large crack hinders the structural integrity meanwhile a smaller sized crack may result in durability problems. The connected smaller cracks will give rise to matrix permeability where substance like water and chemicals seep through these. This can cause premature matrix deterioration and corrosion of the embedded steel reinforcement bars and thus reduce the service life of concrete [2,3].

Several studies [4-6] show that concrete structures have a certain autogenous healing or self-healing of such micro-cracks (cracks with widths 0.1-0.2 mm). The self-healing mechanism of micro-cracks depends primarily on the concrete mixture composition. For example, the mechanism of lime-based mortar matrix in a centuries-old brick building is according to the following reactions:

\[ \text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 \]
\[ \text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \]
The produced minerals precipitate on the surface of cracks and result in the crack-sealing [7]. A concrete mixture composition having high binder content gives a significant crack-healing behavior. This only comes into view for micro-cracks [8]. There are two reasons why a high binder content mixture is not favorable. First, the amount of non-hydrated cement lying exposed at the crack surface is limited. Second, the use of high binder content is not sustainable as it can give rise to global CO2 emissions [9]. A regular treatment of cracks is costly and sometimes is not possible. The most promising way is the application of mineral producing bacteria resulting from metabolic activities of favorable bacteria.

2. Literature review

Durability of concrete is defined as the ability of concrete to withstand chemical and environmental degradation as its function, stability, and aesthetic remain preserved. Structural service life is known as a period of time when the structure still fulfills the required repair and maintenance scenarios [10]. In recent years, durability and service life prediction become very popular. It is due to many reinforced concrete structures built in the past few decades begin to show their inadequate durability performance [11]. Among the infrastructure owner, it is quiet demanding that design for service life can be applied especially for the structure having service life of 50 years, or maybe even 100 years [12]. The application of self-healing repair mechanism in concrete will be very advantageous as it is able to decrease maintenance and at the same time increase concrete durability.

A novel technique developed by means of a selective microbial embedding process, in which microbial metabolic activities encourage calcium carbonate (calcite) precipitation in the crack is called Microbiologically Enhanced Crack Remediation (MECR) [13]. In this technique certain types of bacteria are used therefore the concrete is called Bacterial concrete [14]. The spore forming bacteria added in the preparation of bacterial concrete is able to continuously precipitate calcite. This process is known as Microbiologically Induced Calcite Precipitation (MICP) [15]. The available literatures state that bacterial concrete is quiet promising in improving the strength and the durability of concrete and therefore its service life.

3. Methodology

The service life prediction of bacterial concrete is carried out by two degradation models, namely carbonation model and chloride diffusion model. The carbonation model follows the formulation proposed by Brown [16] where chloride diffusion model Khan [17]. The complete model can be seen as follows.

3.1. Carbonation model

The universal model of carbonation commonly express in the simplest formula for predicting the progress of carbonation widely used in practice. It is necessary to have a model that is simple but not simplistic, practically executable, and able to utilize readily available data with ease. The following general formulation can be used as reference (equation 1).

\[ x = b \cdot t^{1/2} \]  

(1)

Where, \( x \) = carbonation depth, \( b \) = coefficient of carbonation rate, and \( t \) = time of exposure. In 1991, Brown proposed carbonation model based on the field survey results from some 400 structures. The model describes the approximate course of carbonation with time \( t \) as inversely proportional to the concrete compressive strength (equation 2).

\[ x = \frac{Kc \cdot t^{1/2}}{fc} \]  

(2)

where, \( x \) = carbonation depth (mm), \( Kc \) = carbonation rate (mm/years\(^{1/2}\)), \( fc \) = compressive strength (MPa), \( t \) = exposition time (years).
3.2. 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 yields equation (3).

\[
C_{x,t} = C_s \left[ 1 - \frac{x}{2(3D \tau)^{0.5}} \right]^2
\]  

(3)

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 (\( C_{\text{crit}} \)), \( t \) is the time of initiation, and \( x \) is the concrete cover thickness (a). The equation (3) now read as follows.

\[
t_i = \frac{1}{12D} \left[ \frac{a}{1 - (C_{\text{crit}}/C_s)^{0.5}} \right]^2
\]  

(4)

In this research, the value of \( C_{\text{crit}} \) and \( C_s \) are taken 0.3 and 0.6 respectively.

4. Results and discussion

The prediction of reinforced concrete structures’ service life is performed to study the effect of using carbonation and chloride diffusion model on how long the initiation time of corrosion will occur. The results for each model will be discussed as follows.

4.1. Carbonation model

Essential data used as input parameters in carbonation models namely concrete compressive strength, carbonation rate constant, and time of exposition. Concrete compressive strength simulated as commonly used in Indonesian construction practice which is from 10 MPa until 50 MPa. Carbonation rate constant for untreated model (non-bacterial concrete) is taken 8.6 mm/(year)^{1/2} as investigated by Roy et al. for tropical environment [18]. For bacterial concrete, carbonation rate constant is taken from 25% until 30% less than those from untreated model [19]. Time of exposition is taken from 0 until 150 years.

Figure 1

Figure 1 depicted the relation between concrete strength versus carbonation depth. The simulation is carried out for 3 value of \( K \), which is 100%K, 75%K, and 70%K. As can be observed, the untreated model (100%K) will suffer deeper carbonation for concrete strength lower than 20 MPa. Incorporating bacteria in concrete will be able to reduce the carbonation depth around 1.5 mm.
Figure 2 illustrates the relation time of exposition strength versus carbonation depth. The simulation is carried out for 3 value of K, which is 100%K, 75%K, and 70%K. As can be observed, the untreated model (100%K) will undergo deeper carbonation as the time. Incorporating bacteria in concrete will be able to reduce the carbonation depth around 1,2 mm. For the same carbonation depth, e.g. 4 mm, the life time of structure can be expanding by 60 years by using bacterial concrete.

4.2. Empirical chloride diffusion model
Figure 3 shows the relation between concrete cover versus carbonation depth. The simulation is carried out for 3 value of D, which is 100%D, 75%D, and 70%D. As can be observed, the untreated model (100%D) will experience immediate corrosion initiation time. For the same concrete cover, e.g. 70 mm, the life time of structure can be extent by 40 years by using bacterial concrete.

5. Conclusion
The service life estimation of reinforced concrete structures exposed to carbonation and chloride induced corrosion has been done using two models of degradation. These models are Brown’s carbonation model and empirical chloride diffusion model. Several relevant parameters are included in the service life simulations in order to predict deterioration behavior under Indonesian climate for the untreated concrete and the bacterial concrete. Based on the results, the following conclusions achieved. First, Brown’s carbonation model and empirical chloride diffusion model simulate similar trends and values in predicting time of corrosion. Second, incorporating bacteria in concrete will be able to reduce the
carbonation depth around 1.2 mm until 1.5 mm. For the same carbonation depth, e.g. 4 mm, the life time of concrete structure can be expanding by 60 years by using bacterial concrete. Last but least, incorporating bacteria in concrete will be able to extend the corrosion initiation time. For the same concrete cover, e.g. 70 mm, the life time of concrete structure can be extent by 40 years by using bacterial concrete.

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