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Service life modeling of a bridge in a tropical marine environment for durable design

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HIGHLIGHTS

- A prediction model for the corrosion initiation of reinforced concrete structures was developed.
- The effect of solar radiation on chloride penetration was considered.
- Solar radiation has a great capacity to increase the diffusivity of concrete.
- Chloride profiles from a bridge in a splash zone were studied.

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ABSTRACT

Concrete structures have shown premature signs of deterioration by corrosion due to the penetration of chloride ions. This paper performs service life modeling and validates the results with actual data of the total chloride concentration in a reinforced concrete structure. Chloride profiles are obtained from samples collected from a bridge in southeastern Brazil after 36 years of service. The life span of the concrete structure is assessed. The model offers a suitable option for predicting the life span of concrete structures as an engineering tool for the evaluation of risk areas and the construction of durable projects.

1. Introduction

Reinforcing steel corrosion due to the action of chloride ions is one of the main causes of premature deterioration of reinforced concrete structures, which directly affects their durability and life span. Reinforcing steel corrosion in aggressive environments begins when chloride ions from the outer surface enter the concrete pores, migrate to the reinforcement region and, after reaching a critical concentration, break down the passivation layer of the reinforcement. These chlorides may derive from seawater, salt fog or de-icing salts that are used during winter [1].

The corrosion mechanism is defined as a two-step process: the initiation period and the propagation period [2]. The first step is characterized by penetration of chloride ions until the concentration attains a critical concentration on the surface of the reinforcing steel and depassivation occurs. Subsequently, the second step—the propagation period—begins, where the electrochemical corrosion mechanism causes deterioration to the structure. With the continuation of this mechanism, corrosion products progressively accumulate around the reinforcing steel, which increases their volume compared to the non-corroded metal. This increase in volume generates tensile stresses on the concrete that cause cracking and slabbing of the concrete when the tensile strength of the material is exceeded. Over time, a loss of the concrete-to-steel bond occurs due to cracking of the cover and a decrease in the steel bar cross-section area. Cracking and loss of coating indicate concrete degradation. Thus, the reinforcement is exposed to direct weathering, which tends to accelerate corrosion.

Traditionally, most concrete structures are designed for a 50-year life span, and large structures, such as bridges, are designed to last 100 years. However, many studies have verified corrosion deterioration in concrete structures after a few years of operation [3,4]. In addition to the importance of structural safety, the service life of reinforced concrete structures serve an important role in sustainable development because the construction industry

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is responsible for high CO_2 emissions and high consumption of raw material and energy. From the perspective of durable design, the knowledge of deterioration mechanisms and the development of a tool based on the performance of a structure are essential to ensuring the safety and execution of durable structures and for identifying appropriate measures to maintain the life spans of structures and a rational approach for repairing damaged structures [4,5].

Considering the sustainable development in concrete technology, the use of deterministic models instead of prescriptive approaches is a promising innovation [6]. Current approaches are methods that consider time in an implicit manner by delimiting the concrete cover and some concrete properties, such as cement content and the water/cement ratio, to obtain the required durability in a particular environment. Especially in aggressive environments, this method is not sufficient for guaranteeing the service life [6]. More sophisticated durability models should be considered for the design to estimate the service life of the structure and reduce the consumption of materials and energy through the optimization of the concrete cover and proper choice of materials [7]. Thus, estimating the amount of deterioration that a concrete structure can sustain over its service life can optimize the design, maintenance and repairs of the structure.

Therefore, a numerical tool, which may realistically demonstrate corrosion processes and their consequences on concrete performance, is desirable for predicting the service life of concrete structures. In practice, the control of the penetration of chlorides, that is, the corrosion initiation period, is more interesting because it requires less effort to plan the repair and lowers the costs of rehabilitation strategies.

Currently several numerical models have been developed to attempt to simulate the mechanisms involved in reinforcement corrosion, especially with respect to the diffusion of chloride ions in concrete and the distribution of chloride concentration in concrete [5,8–18]. Different boundary conditions, different approaches to considering the chloride diffusion coefficient and changes in Fick's Second Law—the equation that represents the diffusion of chlorides—are the main peculiarities of the models observed in the literature. Some studies investigate the influence of boundary conditions—initial and surface concentration of chlorides—in the diffusion process [19–21]. In other models, the influence of cracks on concrete [22,23] and the effect of loads on chloride penetration [24] are considered. Three-dimensional models are also discussed in the literature [25,26].

Due to the number of variables used to realistically simulate the corrosion phenomenon and concrete complexity, additional research on the use of computer modeling is necessary [26]. The number of models, which is diverse, can create confusion for the user, especially due to the lack of validation of models with real structures based on their simulation of concrete behavior in the field [6,27,28]. Thus, the efficiency of new models remains controversial due to the lack of experience in their use [6].

Most research on the behavior of concrete due to the action of chloride ions was developed in the laboratory. Although corrosion in concrete structures has been well investigated, few models have been applied to real structures to predict the behavior and response of a structure to different environmental actions [1,3,4,29,30]. The analyses of these studies have been valuable for confirming the usefulness of mathematical models and detecting the parameters that affect the service life of structures.

The diffusion of chlorides is particularly affected by variations in temperature and concrete properties, which makes the issue of concrete behavior in different climates and environments interesting. Although different models exist in the literature, additional research is needed to demonstrate the efficiency of these models in the design and maintenance of concrete structures [28].

The main objective of this paper is the use of software developed by Dominicini [31] to predict the service life of a real concrete structure and to compare the model results with the concentrations of chlorides experimentally obtained in parts of the structure. The samples are taken from a pillar of the Dep. Darcy Castello de Mendonça Bridge ("Terceira Ponte"; Third Bridge) in Vitória, Brazil. In addition, the 50-year life expectancy of the structure pillar was calculated, and the main parameters that influence the diffusion are described, including solar radiation, the effect of which is rarely considered in service life models.

This paper is arranged as follows: Section 2 describes the considered chloride ion diffusion model and its main variables. Section 3 describes the numerical analysis performed for the reinforced concrete pillar; the results obtained from the simulations are shown. Section 4 depicts the service life prediction of the structure and its importance in the use of new durable design.

2. Chloride diffusion model

The proposed numerical model only considers the initiation period (Fig. 1), which is defined as the period from the beginning of the service life to the moment when the accumulation of chloride ions on the reinforcement attains a critical concentration that characterizes depassivation of the reinforcing steel and the beginning of the propagation period.

The model predicts the evolution of the chloride concentration over time and the moment when the critical concentration of chlorides is attained, which indicates the end of the service life. Although the end of the initiation period does not represent unacceptable damage to the structure and months or years remain prior to the end of the service life [6], this time is ideal for managers or engineers to program the necessary maintenance or repair the concrete structure to limit costs.

2.1. Transport of chloride ions

The transport mechanism of chloride ions in the concrete can be mathematically modeled using the diffusion equation according to Fick's law, as shown for two-dimensional models in Eq. (1). These ions are carried by diffusion through the pores saturated with water in the cement matrix due to differences in concentration between the surface and the solution in the concrete pores.

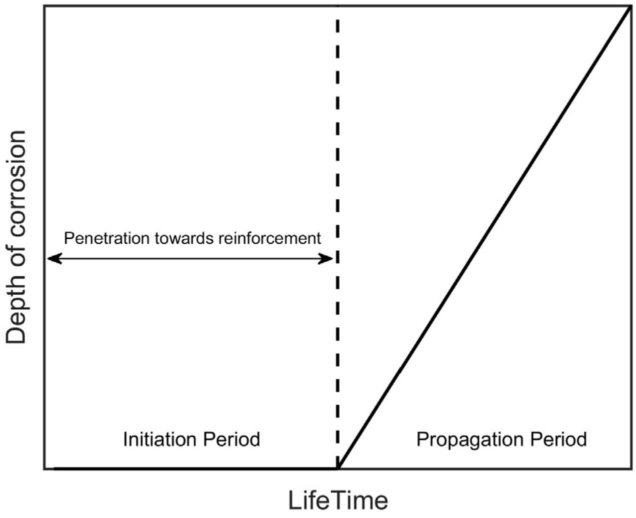

Fig. 1. Corrosion process of reinforcement [2].