Cement and Concrete Composites 79 (2017) 21–33

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Depassivation time estimation in reinforced concrete structures exposed to chloride ingress: A probabilistic approach

G. de Vera*, C. Antón, M.P. López, M.A. Climent

Departament d'Enginyeria Civil, Universitat d'Alacant, Ap. 99, 03080 Alacant, Spain

ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
10 November 2016
Accepted 29 December 2016
Available online 20 January 2017

Keywords:
Corrosion
Reinforced concrete
Probability
Chloride

ABSTRACT

Estimation of depassivation time is a key issue in corrosion prevention. A method to get a probabilistic model from a deterministic one is presented and applied to three simple models: square root of time (SRT), error function (EF) and constant flux (CF) models. Probability distributions of the involved random variables are needed as input parameters. Experimental data have been obtained from a concrete structure exposed to the atmospheric marine environment. These data are analysed to obtain the probability distributions of chloride transport parameters: penetration velocity k (SRT model), diffusion coefficient D (EF and CF models), surface chloride concentration C_S (EF model), and chloride ingress flux J (CF model). These distributions are used to calculate the depassivation time probability distributions according to the three models and the orientation of the samples respect to the sea. This allows to estimate depassivation time for a given depassivation probability.

1. Introduction

Port and maritime constructions are infrastructures of high economic and social value. For this reason tools for calculating their service life are of especial interest. In the case of reinforced concrete structures exposed to the marine environment a prime cause of distress is steel corrosion due to chloride ingress [1]. The damage of the structure due to corrosion is produced after the depassivation of steel, which is produced when a high-enough chloride content is reached in the concrete around the steel rebar [2].

Although structural damages only appear after there has been a certain development of the corrosion process, at times the occurrence of steel depassivation has been considered as the event marking the end of service life [2,3]. This can be considered as a conservative approach, that can be of interest for instance at the design or maintenance phases of the construction of important infrastructures.

The calculations of the end of service life can be carried out through deterministic or probabilistic methods [4]. Deterministic methodologies, which rely on the calculation of the time at which a certain variable reaches a critical value, have been widely used and are even still included in some structural concrete codes [5]. During the last years probabilistic methods for the calculation of service life have gained importance [6–10], since they take into account the uncertainties of the model parameters, thus allowing to introduce the concept of failure probability. The aim of the probabilistic methods is to obtain the probability of an undesirable event (limit state) occurring. In the case of calculations related with the onset of reinforcement corrosion in maritime structures, the conservative limit state would be surpassed when the probability of reaching a critical value for the chloride content at steel depth would be higher than a set value.

Several concrete codes include service life calculation tools [11,12], which contain their own set of assumptions, for instance regarding the chloride transport model and probability density functions adopted for each one of the considered random variables. They can be fully exploited at the design phase, after setting the duration of the service life and the maximum allowable probability of failure, for calculating appropriate values for some of the design parameters, for instance the minimum reinforcement concrete cover.

Another situation of interest is represented by the surveys of existing structures affected by reinforcement corrosion due to chlorides, for assessing their residual service life [13,14]. In such cases it is frequent to perform more or less extensive campaigns for obtaining experimental raw data, typically chloride content profiles, and calculated transport parameters representing the performance of the structure. In these cases the abovementioned tools,

* Corresponding author.
E-mail address: Guillem.Vera@ua.es (G. de Vera).

http://dx.doi.org/10.1016/j.cemconcomp.2016.12.012
0958-9465/

included in the concrete codes, may represent some rigidity since they use fixed transport models and fixed probability functions for the random variables. The modeler might wish to use some of the available transport models, empirical or physical with different sophistication levels. Furthermore, the experimental sets of data, corresponding to the relevant variables in the models, may fit better to a particular probability function, different from that prescribed in the codes.

The aim of the present work is to present a methodology that allows getting a probabilistic chloride transport model from a deterministic one, thus making possible to calculate the failure probability in relation with the steel depassivation limit state. This is achieved assigning the proper probability distributions to the variables in the deterministic model and computing the corresponding probability distribution of the calculated depassivation time. A method is also proposed for estimating the best choice for the probability density function applicable to any of the random variables. This is accomplished by calculating the minimum value of a newly proposed parameter, α, which represents the difference between the experimental values of the random variables and the values calculated trough any of the available theoretical probability density functions. The difference is integrated over the full domain of the random variable. The proposed procedures provide flexibility to the modeler in choosing the desired empirical transport model, and allow estimating the most adequate probability function for the relevant random variables.

The full methodology has been applied to data obtained from a harbour concrete structure exposed during 30 years to a Mediterranean marine atmosphere. The data were obtained during three field campaigns performed in 1997, 2004 and 2014.

2. Experimental

Concrete cores extracted from the Alacant harbour were studied [15]. Alacant is a Mediterranean city located in the south-east of Spain (38°19′N, 0°29′W). All samples had atmospherical marine exposure conditions and were taken from the Dock 17. This structure was built in 1984 and samples were taken at several locations in 1997 (8 cores), 2004 (6 cores), and 2014 (3 cores). According to the documentation, the structure was fabricated with bulk concrete H-175 [16] and cement used was ordinary Portland cement P-350 [17]. The following tests were performed following standard methods on concrete cores extracted from the studied structure: compressive strength, cement content quantification [18], bulk density, and porosity. Results are shown in Table 1.

Powder samples were obtained from the concrete cores using a profile grinder [19]. This technique allows obtaining powder samples in 2 mm intervals. Powder samples were analysed to determine its total chloride contents. The method used was potentiometric titration [20,21]. Thus, detailed chloride profiles were obtained. Background chloride concentration (present in concrete before exposure due to raw materials) was determined analysing the innermost part of 11 cores, and the mean value was used. It is shown in Table 1. Bulk density was also determined [22] in order to refer chloride concentrations as $kg\ Cl^-/m^3$ of concrete instead of mass percentages when necessary. The mean value obtained was used in all calculations involving density.

Table 1
Properties of the studied concrete.

Property	Value
Compressive strength (MPa)	25.6
Cement content (kg/m^3)	220
Bulk density (kg/m^3)	2150
Porosity (%)	15.8
Background Cl^- concentration (%)	0.0175

Mean values of at least three samples.

All calculations were performed using MATLAB R2013b software [23]. In particular, integrations were carried out with commands integral and integral3, which use adaptive methods [24] in order to enhance precision.

3. Probability distributions

Several authors have used statistics to evaluate experimental data regarding chloride ingress and steel depassivation. Normal [25], lognormal [25,26], beta [12] or gamma distributions [11] have been suggested in the literature for different parameters. Also, some parameters can be studied under the extreme value theory and generalised extreme value distributions (GEV) including Gumbel, Fréchet and Weibull distributions might be applied [27].

Experimental probability distributions have also been used [28]. The experimental probability density function can be estimated from a given set of values x_i $(i = 1 \ldots N)$ of the random variable X as follows. The domain of the variable is divided in m equally spaced bins of size $\Delta x = (x_{max} - x_{min})/m$, where x_{min} and x_{max} are respectively the minimum and maximum values of the set. Then, the number of values of the set that lay in each bin is counted and the value φ_i of the probability density function in bin i, which is assumed to be constant in the bin, is calculated as:

$$\varphi_i = \frac{n_i}{N \Delta x} \tag{1}$$

where n_i is the number of values that lay in bin i. The smaller the size of bins Δx is, the higher the precision in the probability density function is. Nevertheless, the size of the bin must be large enough to contain a significant number of values n_i. Thus, a precise experimental probability density function can be obtained only if the size of the set of values N is large.

When the precision of the experimental probability distributions is not good enough, the use of theoretical probability distributions is preferable. They can be estimated from the available experimental data. Five kinds of these theoretical probability distributions were used in this paper in order to model the random variables: normal, lognormal, beta, gamma, and Fréchet distributions. All of them depend on two parameters that can be estimated from a given set of values of the random variable. The mean value of the set and the variance of the set are defined respectively as:

$$e = \frac{1}{n}\sum_{i=1}^{n} x_i \quad ; \quad v = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - e)^2 \tag{2}$$

where the set of values of the random variable X is x_i $(i = 1 \ldots n)$. Given a theoretical probability distribution of the random variable X, the mean value (or expectation) of the distribution $E(X)$ and the variance of the distribution $Var(X)$ can be estimated as:

$$E(X) \approx e \quad ; \quad Var(X) \approx v \tag{3}$$

The value of the two parameters on which the distribution depends can be solved from equation (3) when appropriate expression for $E(X)$ and $Var(X)$ in terms of the two parameters are substituted here. Normal, lognormal, beta, and gamma probability distributions are summarized in Tables 2 and 3. Information shown in these tables is: the random variable domain, the two parameters on which the distribution depends, the probability density function $\varphi(x)$, the cumulative distribution function $\Phi(x)$, the mean value of the distribution $E(X)$, the variance of the distribution $Var(X)$, and