Cement and Concrete Composites 72 (2016) 133–145

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Chloride ingress into marine exposed concrete: A comparison of empirical- and physically- based models

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form
8 March 2016
Accepted 6 June 2016
Available online 8 June 2016

Keywords:
Concrete
Full-scale testing
Marine environment
Modelling
Durability
Performance

ABSTRACT

In establishing the reliability of performance-related design methods for concrete – which are relevant for resistance against chloride-induced corrosion - long-term experience of local materials and practices and detailed knowledge of the ambient and local micro-climate are critical. Furthermore, in the development of analytical models for performance-based design, calibration against test data representative of actual conditions in practice is required. To this end, the current study presents results from full-scale, concrete pier-stems under long-term exposure to a marine environment with work focussing on XS2 (below mid-tide level) in which the concrete is regarded as fully saturated and XS3 (tidal, splash and spray) in which the concrete is in an unsaturated condition. These exposures represent zones where concrete structures are most susceptible to ionic ingress and deterioration. Chloride profiles and chloride transport behaviour are studied using both an empirical model (erfc function) and a physical model (ClinConc). The time dependency of surface chloride concentration (C_s) and apparent diffusivity (D_a) were established for the empirical model whereas, in the ClinConc model (originally based on saturated concrete), two new environmental factors were introduced for the XS3 environmental exposure zone. Although the XS3 is considered as one environmental exposure zone according to BS EN 206-1:2013, the work has highlighted that even within this zone, significant changes in chloride ingress are evident. This study aims to update the parameters of both models for predicting the long term transport behaviour of concrete subjected to environmental exposure classes XS2 and XS3.

1. Introduction

The most predominant process associated with reinforced concrete deterioration is the ingress of water contaminated with chloride either from deicing salt used for snow and ice control on roads for winter maintenance purposes or from the marine environment where, for example, bridges span tidal estuaries. Because the use of deicing salt is likely to continue for the foreseeable future, and concrete structures will always be placed in, or near, the marine environment, little can be done to prevent structures from being exposed to chloride salts. The premature deterioration of concrete structures due to chloride ingress and subsequent corrosion of the steel reinforcement is a world-wide problem and imparts a significant drain on maintenance resources, not only in terms of the remedial work required, but also in the costs associated with periodic inspections and testing together with indirect costs such as traffic delays and lost productivity. According to the survey by Nwaubani and Katsanos [1], the maintenance expenditure of many developed countries including the US, Canada, Japan, Australia and the UK resulting from the premature deterioration of concrete bridges was estimated to be in the range 0.01–0.1% of gross domestic product (GDP); in addition, the indirect costs due to traffic delays and lost productivity resulting from bridge maintenance and superstructure replacement programmes are more than ten times the direct cost of corrosion.

The deterioration of concrete structures exposed to chloride-rich environments is inevitable, hence the long-term performance of concrete assumes an important role in ensuring durable concrete structures. The concrete composition and the constituent materials need to be closely defined to enable the required level of performance to be maintained, hence the growing interest, and

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http://dx.doi.org/10.1016/j.cemconcomp.2016.06.002
0958-9465/

indeed need, for performance-based specifications. Performance-related methods – which are more relevant to corrosion resistance - consider, in a quantitative way, each relevant deterioration mechanism, the working life of the element or structure and the criteria that define the end of this working life (e.g. time to corrosion initiation). The level of knowledge of the ambient and local micro-climate is thus critical in establishing the reliability of performance-related design methods. Although BS EN 206 [2] still defines prescriptive design methods for durability, Section 5.3.3 of this code allows for performance-related methods and defines concrete on the basis of an *equivalent durability procedure* (EDP); further detail on the EDP is presented in PD CEN/TR 16563 [3]. However, in order to fully implement a performance-based approach requires,

(i) long-term experience of local materials and practices, and on detailed knowledge of the local environment;
(ii) test methods based on approved and proven tests that are representative of actual conditions and have approved performance criteria; and,
(iii) analytical models that have been calibrated against test-data representative of actual conditions in practice.

Regarding (iii) above, a number of predictive models have been developed and have become increasingly more refined owing to our improved understanding the chloride transport mechanisms in concrete. These models range from simple, empirical models based on Fick's 2nd law to determine the propagation of chloride within concrete [4–6] to more complex, physically-based models using the flux-balance system of equations. Regarding the latter, the ClinConc model [7,8] focusses on the mechanisms occurring within the concrete, namely diffusion and chemical interactions; the STADIUM® model [9], which is a multi-ionic transport model and, in addition to diffusion and chemical interactions, considers electrical coupling of ions in the pore solution. The more sophisticated service-life prediction models become, most, if not all, cannot accurately predict the performance of a concrete in different environments without previously carrying out extensive calibration measurements [10] to evaluate, surface chloride concentrations, capillary porosity, chloride binding etc.

It is evident that an additional refinement is required to both the physically-based model and empirical model to cover local conditions as these, ultimately, influence the long-term movement of chloride into concrete. This refinement enhances both models for predicting chloride transport in the *target* structure. To this end, this paper uses data obtained from an extensive chloride-profiling programme undertaken over an 8-year period, together with a more limited study at 20-years, to evaluate both empirically-based and physically-based models. The testing was undertaken on full-scale, concrete bridge pier-stems exposed to a marine environment represented by the following environmental classifications defined in BS EN 206 [2] and BS 8500-1 [11],

(i) XS1 – exposed to airborne salt but not in direct contact with seawater;
(ii) XS2 - permanently submerged which also includes all concrete below mid-tide level i.e. at a level were the concrete remains saturated and has little/no time to dry out; and,
(iii) XS3 - tidal, splash and spray zones.

This paper focusses on XS2 and XS3 exposure classes.

2. Empirical and physical models for chloride ingress in concrete

2.1. Empirical (Fickian) model based on the erfc function

Assuming that diffusion is the dominant transport mechanism, the chloride profile in concrete can be expressed through Fick's Law for one-dimensional diffusion as,

$$\frac{\partial C_t}{\partial t} = D_a \frac{\partial^2 C_t}{\partial x^2} \tag{1}$$

where, C_t is the total chloride content (free and bound chloride) at the exposure time, t (sec) at depth of x (m) from the surface, D_a is the apparent diffusion coefficient (m^2/s). Provided that both the diffusion coefficient and surface chloride concentration are constant in the duration of exposure, the solution to (1) gives the basic empirical model which can be expressed in terms of the error function complement (erfc) as [12],

$$C_t(x,t) = (C_s - C_i)\,\mathrm{erfc}\left(\frac{x}{2\sqrt{D_a t}}\right) \tag{2}$$

In this equation, C_s is the equilibrium chloride content on the concrete surface and C_i is the initial chloride content of the concrete before the exposure to the chloride environment. Hereinafter this will be referred to as the erfc model. The calculation is simple and convenient and, in addition, the values of parameters C_s and D_a can be easily estimated from experimental or field data using regression analysis. However, this model has limitations when applied to concrete [13–15] and a number of modifications have been proposed to account for the time-dependency of these parameters through *aging factors*, some of which are presented in Table 1 [16–24]. As the factors applied on C_s and D_a, are determined empirically they can vary within wide limits [25–28]. If the values derived from a particular test are then used to predict the service life without consideration of environmental conditions, the predicted chloride ingress is likely to be incorrect. However, due to its simplicity and wide use, this formalism has been used in the current study to obtain the basic parameters which provide information on the long-term behaviour of chloride transport in concrete exposed to a marine environment.

2.2. The ClinConc model

This is a physical model which uses a flux equation based on the principle of Fick's law [7,8]. A numerical solution is obtained using the mass balance equation combined with a non-linear chloride binding isotherm, with both free- and bound-chlorides considered in chloride transport. This can be summarised as,

$$\frac{\partial q_{cl}}{\partial x} = -\frac{\partial}{\partial x}\left(D_o \frac{\partial C_f}{\partial x}\right) \tag{3}$$

$$\frac{\partial C_t}{\partial t} = \frac{\partial C_f}{\partial t} + \frac{\partial C_b}{\partial t} \tag{4}$$

where, C_t, C_f and C_b are, respectively, the total, free and bound chloride contents, q_{cl} is the net flux of free chloride per unit area and D_0 is the intrinsic diffusion coefficient. The model input parameters include concrete mix proportions, binder components, curing temperature, environmental temperature and the chloride concentration in the solution to which the concrete is exposed. The