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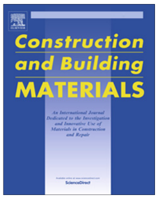

Prediction of chloride ingress into blended cement concrete: Evaluation of a combined short-term laboratory-numerical procedure

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HIGHLIGHTS

- Short-term tests and a numerical procedure are combined to predict long-term chloride profile.
- Partial replacement of cement by silica fume or natural zeolite decreases both MTC and CDC.
- Higher silica fume content decreases chloride concentration in diffusion zone.
- Higher silica fume content increases chloride concentration in convection zone.
- The interaction between the MTC and CDC impacts the chloride movement into concrete.

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ABSTRACT

Chloride-induced corrosion is commonly recognized to be a major cause of deterioration of coastal reinforced concrete structures (CRCS). Therefore, prediction of chloride penetration into concrete is a major concern in durability based design of CRCS. In this study, moisture transfer coefficient (MTC) and chloride diffusion coefficient (CDC) of some concrete specimens were determined by short-term laboratory tests and these parameters are used to numerically predict the chloride profile of the specimens subjected to long-term field tidal exposure. Thus, two series of concrete specimens with a constant water to cementitious materials ratio (w/cm) of 0.40 and different replacement levels of silica fume (SF) and natural zeolite (NZ) were prepared. The first group of the samples was exposed to the tidal condition of natural marine environment of the Qeshm Island, located in the south of Iran, for 50 months after curing in laboratory, while the second group of the samples was prepared for short-term laboratory tests to determine the MTC and CDC. Moreover, a finite element based convection–diffusion model was developed to predict the chloride penetration in the long-term field exposed specimens using short-term laboratory-determined MTC and CDC. The long-term field test results confirmed the feasibility of the proposed combined short-term laboratory-numerical procedure. In addition, the results showed that the chloride concentration decreased in the diffusion zone and increased in the convection zone with increase of SF replacement level of up to 10%. The similar trend was also observed for NZ mixtures with replacement level of up to 20%.

1. Introduction

The service life of a coastal reinforced concrete structure (CRCS) can be significantly reduced by premature corrosion of the embedded reinforcing steel. Thus, service life prediction has become one of the major tasks in the durability based design of CRCS. The most aggressive agent, responsible for deterioration of CRCS, is chloride ion which is originated from the surrounding environment such as sea water and deicing salt [1–6].

Chloride ions can ingress into saturated concrete due to diffusion, which is a complex process involving various physical and chemical interactions [7–9]. However, chloride penetration into concrete subjected to wetting and drying involves other mechanisms beside diffusion phenomena. These mechanisms include capillary suction or permeability depending on the exposure condition and the moisture distribution of the CRCS [10]. Swateki-

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titham reported that the movement of chloride ions into CRCS is caused by two main mechanisms: the diffusive transport caused by concentration differences of chloride ions, and advective movement due to the capillary suction of pore moisture [11]. In addition, Conciatori et al. suggested that the seasonal variations such as temperature and relative humidity (RH) can significantly influence chloride ion profiles (i.e., chloride ion concentration as a function of concrete depth) [12].

In order to study the durability and service life of CRCS, a quantitative assessment of the chloride ingress into concrete is preferable [13,14]. The complexity of the mathematical formulation of the chloride penetration mechanisms, resulting from nonlinearity and strong coupling with governing equations, usually makes it necessary to apply numerical methods [15]. Many chloride penetration models have been developed during the last several decades. Simple models derived from the Fick's second law of diffusion have been utilized to easily predict the chloride profile in practical situations. In most of the works, the service life or the length of the corrosion initiation stage is approximated with a transformation of Crank's solution to Fick's second law of diffusion for one-dimensional flow over a semi-infinite medium and the simplified assumptions [16,17]. However, these models have to be adjusted with experimental test results [18]. Other researchers have also tried to utilize the Crank's solution in the manners that an accurate prediction of the chloride profile is achieved [19–24]. Ishida et al. [25] established a model that can predict chloride movement in cracked concrete. Park et al. [26] also proposed an analytical model using equivalent diffusion and permeation for the evaluation of chloride penetration in cracked concrete. In another work, the experimental results showed that the chloride diffusion coefficient increased with the increase of crack width [27].

Castro et al. studied chloride profile in the concrete specimens exposed to a tropical marine climate and found that two zones were formed in the concrete subjected to marine environments [28]; one internal (diffusion zone) that is constantly moistened and one external (convection zone) that is always exposed to wetting and drying cycles (Fig. 1). Therefore, it is necessary to use other models to predict the chloride penetration into unsaturated concrete [29]. Meijers et al. [30], Marchand and Samson [31], and Lin et al. [32] utilized the methods that consider the simultaneous diffusion and advection mechanisms to predict the chloride ingress into partially saturated concrete. The commonly utilized numerical methods include the finite element method (FEM), the finite difference method (FDM), and the boundary element method (BEM).

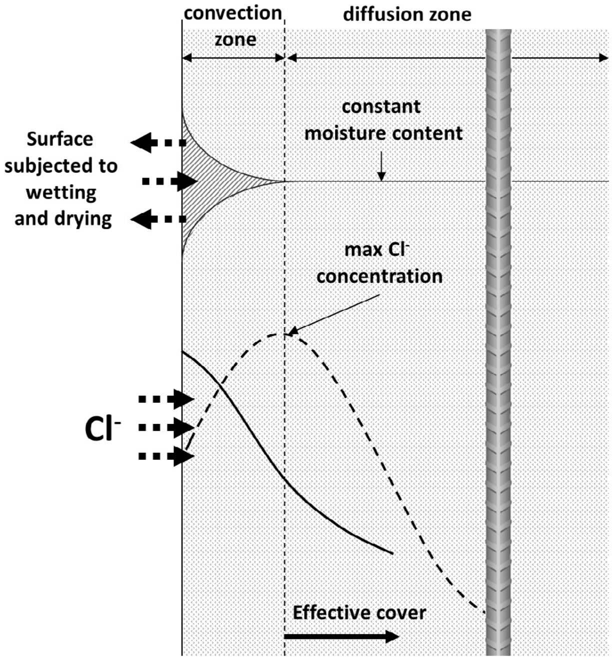

Fig. 1. Moisture and chloride profiles in the concrete cover of CRCS exposed to tidal condition [33]

An exact prediction could be achieved by a numerical model when moisture transfer coefficient (MTC) and chloride diffusion coefficient of the concrete specimens (CDC) are available as the main parameters to determinate the moisture distribution in the convection zone and chloride movement in the diffusion zone, respectively. Most of the currently published studies have focused on either numerical tasks [34] or experimental works [35–37], while, both experimental procedure and numerical modeling are necessary to successfully predict the chloride profile in concrete.

In this study, two series of uncracked specimens were prepared to evaluate the applicability of the combined laboratory-numerical procedure. The first series of specimens were exposed to the field environment for a long time of 50 months, while the second series were considered for the short-term laboratory tests to determine the MTC and CDC. Besides the laboratory and field experiments, a finite element model was also developed to predict the chloride penetration in the specimens using determined MTC and CDC. Thereafter, the predicted chloride profiles by short-term laboratory-determined parameters and FE model were compared to the long-term data obtained from specimens subjected to tide cycles of an actual harsh marine environment located in the south of Iran.

2. Theoretical background

2.1. Mathematical definition of the problem

In tide cycles, a portion of the moisture moves toward the outside of concrete surface due to drying. However, the saturation degree of the inner part of concrete closely remains constant due to the slow nature of desorption and relatively short time of each drying period. The dominant mechanisms of chloride ingress into the concrete structures exposed to tide phenomenon, are diffusion and convection [38,39]. The chloride profile also depends on temperature and moisture content of concrete; therefore coupled modeling of temperature, moisture, and chloride distribution leads to a more accurate estimation of the chloride ingress into concrete. The partial differential equations governed on heat, moisture, and chloride movements as well as simplified assumptions are summarized in Table 1 [40–50]. The laws and boundary conditions of the governing equations are also presented in the table [39,51–56].

When concrete surface is exposed to wetting, w_{env} is equal to 1.0, and when it is subjected to drying, w_{env} is equivalent to environment relative humidity (h_{env}) according to desorption isotherm. For each value of environmental relative humidity, desorption isotherm represents the moisture amount at a given temperature. The most commonly used equation for desorption isotherm is BET equation [58,59]. The relationship between h_{env} and w_{env} is nonlinear as follows:

$$w_{env} = \frac{(1-k)[1+(C-1)k]h_{env}}{(1-kh_{env})[1+(C-1)kh_{env}]} \quad (7)$$

$$C = e^{\frac{855}{T+273}} \quad (8)$$

$$n = \left(2.5 + \frac{15}{t_e}\right)(0.33 + 2.2w/cm); \quad t_e > 5\ days \& 0.3 < w/cm < 0.6 \quad (9)$$