Construction and Building Materials 47 (2013) 66–79

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Influence of cracking on chloride diffusivity and moisture influential depth in concrete subjected to simulated environmental conditions

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HIGHLIGHTS

- EMPA is used to accurately obtain the chloride concentration.
- Detailed lab investigation is elaborated on chloride profiles in cracked zone.
- A simple approach to calculate coefficient of cracked concrete.
- Different concrete mixes and crack patterns are tested for modeling.
- Moisture influential depth in cracked concrete is investigated.

ARTICLE INFO

Article history:
Received 3 December 2012
Received in revised form 18 April 2013
Accepted 19 April 2013

Keywords:
Chloride ions
Crack
Cracked concrete
Moisture influential depth
Artificial environments

ABSTRACT

Although Fick's second law is always applied to predict chloride profiles in concrete due to its simple mathematical expression, it takes no consideration of cracking affects. However, concrete structures are not always crack-free, therefore clarifying the internal environment and relevant chloride diffusivity in cracked concrete is essential to predict chloride ingress since cracking always has a negative impact on concrete durability. In present work, series of experimental investigations on two coefficients (i.e., chloride diffusion coefficients and moisture influential depth) affecting chloride profiles at cracked concrete were carried out. For the investigation of chloride diffusivity, Electron Probe Micro Analysis (EPMA) was used to extract the accurate chloride concentration via area scanning, line scanning, and point scanning. In addition, specimens with two different types of mix (i.e., ordinary concrete and blast furnace slag concrete) and with two different exposed times (i.e., 30 days and 60 days) were tested for different surface crack patterns. Crack width investigated in present work ranges from 0.05 mm to 0.20 mm. Furthermore, the effective chloride diffusion coefficient for cracked concrete was calculated under the law of flux conservation by taking consideration of both crack patterns and concrete mixtures. On the other hand, for the investigation of moisture influential depth, a series of laboratory experiments with different cracking specimens were conducted to clarify the influence of external artificial weather on the relative humidity distribution in concrete crack, including periodic changing of external relative humidity and temperature, fog and rainfall simulation environments, the drying phase after precipitation.

1. Introduction

Chloride-induced corrosion of steel reinforcement is a major cause affecting the service life of reinforced concrete structure exposed to marine environments. Thus, reliable prediction of chloride ingress in concrete is one of the key elements in durability design of concrete structures. Many deterministic and probabilistic studies adopt a simplified solution to Fick's second law where the chloride concentration at a given time and position, $C(x,t)$ is estimated by an error function complement solution, and this empirical solution is later modified to account for a near surface convection zone of depth ΔX (e.g., for cyclic drying and wetting condition) and an initial chloride content [1,2]:

$$C(x,t) = C_0 + (C_{S,\Delta X} - C_0)\mathrm{erfc}\left(\frac{x - \Delta X}{2\sqrt{D_{\mathrm{app},C}t}}\right) \tag{1}$$

where C_0 is initial chloride ions content; $C_{S,\Delta X}$ is chloride ions concentration at ΔX, X is the distance from the surface exposed to chloride; erfc is the complement to the error function, $D_{\mathrm{app},C}$ is apparent diffusion coefficient. As a matter of fact, chloride ingress implies a complex interaction between physical and chemical processes, such a simplified solution is valid merely based on several assumptions, such as diffusion coefficient is constant in time and space, materials is saturated, and chloride concentration at surface remains con-

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http://dx.doi.org/10.1016/j.conbuildmat.2013.04.024

stant. In spite of the oversimplified assumptions, Fick's second law is widely used by engineers in practical applications because of its relatively simple mathematical expression [2,3].

The formula above is derived for chloride ingress in crack-free concrete; however, cracking cannot be avoided for a real reinforced concrete structure due to many reasons. Further, crack has a positive influence on chloride ingress by providing a short path to rebel steel. Generally, it is recognized that the crack accelerates the ingress of chloride ions. There are many researchers conducting this issue recently. Ye et al. proposed a model describing the chloride ingress into cracked concrete subjected to wetting–drying cycles and found that crack width is a key parameter in determining chloride profiles in cracked zone [1]; Boulfiza et al. established a simplified smeared approach to estimate the influence of cracks on chloride ingress using Fick's law [4]; Djerbi et al. found that chloride diffusivity in cracks was independent of material properties by migration test of traversing cracks for OC, HPC and HPCSF concrete [5]; Marsavina et al. used artificial cracks with different patterns and found a higher penetration of chloride at the tip of crack in comparison with the sound parts [6]. Park et al. proposed a model to calculate the equivalent chloride diffusivity of cracked concrete and found that the diffusion coefficient increases with the increase in crack width [7,8]. In addition, Kwon et al. obtained the diffusion coefficients of sound and cracked concrete exposed to chloride attack for 8–11 years from field investigation using a simple mathematical form [9]. Thus, it is essential to rewritten Fick's second law using a modified diffusion coefficient taking account for cracks to evaluate the chloride profiles in cracked concrete.

Besides chloride diffusion coefficient, another important task is to determine the depth of convection zone ΔX in cracked concrete, which is different from sound concrete as well. The depth of convection zone acts as an important coefficient for predicting chloride profiles as shown in Eq. (1), especially when subjected to cyclic drying–wetting condition. Since the chloride ingress process is closely related to the moisture state in concrete, and more importantly, the depth of convection zone is believed to have a close relationship with moisture influential depth, and sometimes, they can be approximately regarded as equal for the safety in engineering application in predicting chloride profiles, since moisture influential depth is lightly lager than chloride convection zone. Therefore, for durability design, it is scientifically significant to predict the moisture state in crack and the moisture influential depth. For both sound and cracked concrete, many researchers have attempted to develop various theories and conduct abundant experiments to clarify the inner moisture state and moisture influential depth. Andrade et al. measured the internal relative humidity (RH) and temperature inside of concrete exposed to periodical changes of temperature and RH through artificial rainfall [10]. Nyman et al. established a model to calculate the equilibrium and transfer of moisture using sorption hysteresis model [11]. Espinosa and Franke tried to elucidate the behavior of moisture in concrete by adopting physical adsorption theory and condensation theory together through experimental research [12]. Ryu et al. measured the relative moisture content and the RH within concrete crack to elucidate the influence of cyclic daily changes of environmental conditions and rainfall on the internal RH and relative moisture content distribution in crack [13].

Although drying–wetting cyclic condition is always identified as the most unfavorable environmental condition for reinforced concrete structures, the immersion zone is also very important since it is always the first step to predict the service life of a marine concrete structure in unsaturated state [1]. Thus, in present work, series of experimental investigations using Electron Probe Micro Analysis (EPMA) were conducted to describe chloride ingress into cracked concretes, of different mix proportions, at different exposed ages and with different surface crack widths under immersion. In addition, a simplified equation for calculating chloride diffusion coefficient was proposed based on the law of flux conservation. Besides, the influential depth of moisture was experimentally investigated by specimens with different crack widths. In order to clarify the influence of external artificial weather on the ambient relative humidity and temperature in cracked concrete and further predict the influential depth of moisture, totally five different exposed artificial environmental conditions were conducted: (1) periodic change in RH at constant temperature, (2) periodic change in temperature, (3) fog environment, (4) rainfall environment, and (5) drying process after precipitation. For the periodic change in external RH, the hysteresis due to inkbottle effect makes the moisture transfer phenomenon in crack complicated, and the actual environmental conditions where concrete structures are located include both changes in ambient relative humidity and temperature simultaneously, causing repeated drying–wetting stages (water vapor desorption and adsorption). In addition, the interaction between moisture and temperature also appear to be complicated. Based on the experimental research in present work and theoretical analysis, the influential depth of moisture is proposed for different surface crack widths. The objective of present work is to highlight the influence of cracking on chloride profiles and to improve present modified Fick' s second law by taking account of cracks.

2. Experimental procedure

2.1. Materials

Two types of concrete mixes were used in the investigation of chloride diffusion diffusivity in cracked concrete, ordinary concrete, and concrete mixed with grounded blast furnace slag with the fineness of 450 m^2/kg. While for the investigation of influential depth of moisture in cracked concrete, only the ordinary concrete was used. The mix proportions of concrete are listed in Table 1. Cement used in this research is ordinary Portland cement, ASTM Type I 32.5. The coarse aggregate is crushed gravel with continuous grading which ranges from 5 mm to 20 mm. The fine aggregate is natural sand with fineness modulus of 2.64.

2.2. Details of specimen

For both these two experimental investigations, configurations of specimens are the same. As shown in Fig. 1, the specimen has a rectangular cross section of 150 mm × 75 mm, and total length is 400 mm. All specimens were demolded at 1 day and cured with RH of 100% and temperature of 20 ± 3 °C for 28 days.

With the help of two stainless screws, specimens were all prefabricated with cracks with natural shape in designed width and depth, as well as in aimed direction. The prefabrication was conducted in three steps. At first, a natural shape crack was generated by loading at the middle span of the specimen as indicated in Fig. 1. As a crack tip was reserved at XY plane, the manipulated specimen would generate a crack whose trend was conformably along the anticipated direction under the application of external loading. In order to control the crack width along the crack path at XZ plane until it reached the expected value for further investigation, the method firstly introduced by Ye et al. [1] was applied here. As shown in Fig. 1, two screws were separately located in the specimen when depositing concrete. After loading, the crack width was measured and recorded at XZ plane for each specimen by microscope and the crack depths at the side surfaces were measured and recorded by micrometer. At last, by adjusting the loading value with the screws at XY plane, the expected crack width can be obtained. In addition, all surfaces except the XY plane were coated with epoxy in order to control the penetration of chloride ions into concrete.

The ranges of crack widths for these two experimental investigations are different. For the investigation of chloride diffusion coefficients, specimens with surface crack width of 0.05 mm, 0.10 mm, 0.15 mm, and 0.20 mm were prepared both for

Table 1
Mixing ingredients of concrete (kg/m^3).

w/c	Cement	Fine aggregate	Coarse aggregate	Water	Blast furnace slag
0.53	370	750	1112	188	0
0.53	185	750	1112	188	185