Construction and Building Materials 125 (2016) 714–723

Contents lists available at ScienceDirect

Construction and Building Materials

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

Chloride penetration into concrete damaged by uniaxial tensile fatigue loading

Chuanqing Fu [a], Hailong Ye [c], Xianyu Jin [b], Dongming Yan [b,*], Nanguo Jin [b], Zhaoxiong Peng [a]

[a] College of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou 310034, PR China
[b] College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310027, PR China
[c] Department of Civil and Environmental Engineering, The Pennsylvania State University, 3127 Research Drive, State College, PA 16801, United States

HIGHLIGHTS

- Quantitative analysis of uniaxial tensile fatigue damage on chloride penetration.
- Binder type, exposure duration, condition, and degree of damage were considered.
- A simple expression was proposed to predict fatigue damage on chloride diffusivity.

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 21 August 2016
Accepted 24 August 2016
Available online 28 August 2016

Keywords:
Chloride-induced corrosion
Concrete
Fatigue
Damaged concrete
Residual strains

ABSTRACT

In this work, the chloride penetration into concrete damaged by uniaxial tensile fatigue loading was characterized. Various fatigue-damaged concrete were exposed to two environmental conditions (i.e. immersion and drying-wetting cycles) for different durations. A quantitative correlation has been established to predict the effects of residual strains on the apparent chloride diffusivity of fatigue-damaged concrete. The experimental results show that the tensile fatigue damage can accelerate the chloride penetration in concrete by 1.5–3.0 times, when the magnitude of maximum tensile fatigue load is between 25% and 45% of the ultimate tensile load of the specimen. When the maximum fatigue load is greater than 30% of the ultimate tensile loads, the chloride penetration is substantially accelerated. In summary, the chloride ingress into concrete is dependent on the exposure condition, duration, type of binder, and degree of fatigue damage.

1. Introduction

Chloride-induced corrosion of reinforcement is one of the major causes degrading the service-life performance of reinforced concrete (RC) structures exposed to marine environments [1,2]. In particular, chloride ions can destroy the passive film of steel and trigger corrosion, which finally leads to the peeling off of concrete covers and reduction of structural capacities [3,4]. Due to the significance of this issue, tremendous amount of investigations have been conducted over decades to characterize the chloride penetration in concrete. In the meantime, many empirical or theoretical models have been established to predict the chloride profiles in concrete [5–10]. Among all these predictive models, Eq. (1) is the most widely adopted mathematical expression to predict chloride profile in concrete, due to its simple mathematical forms [11]:

$$C = C_0 + (C_{s,\Delta x} - C_0) \cdot \left[1 - \mathrm{erf}\left(\frac{x - \Delta x}{2\sqrt{D_{app,c}t}}\right)\right] \tag{1}$$

where C is the chloride content, C_0 is the initial chloride content, $C_{s,\Delta x}$ is chloride content at depth Δx; In saturated condition, $\Delta x = 0$, then $C_{s,\Delta x}$ is the chloride content at concrete surface; For unsaturated condition (e.g. drying-wetting cycle), Δx is the depth of convection zone. t is the time, erf $(\cdot)$ is error function, and $D_{app,c}$ is the apparent chloride diffusivity. The Eq. (1) was derived primarily based on the Fick's second law and was first proposed by Collepardi et al. [11] to predict chloride profile in concrete. It should be noted that the direct application of Eq. (1) for chloride profile prediction is problematic since it bases on several oversimplified assumptions (e.g. homogenous media and constant diffusivity), which is basically invalid in realistic concrete. As an effort to improve the accuracy of Eq. (1) while keeping its simple mathematical form, many investigators attempted to modify the apparent chloride diffusivity to account the influence of other factors [12–16]. According to previous studies, the apparent chloride

---

* Corresponding author.
E-mail addresses: chuanqingfu@126.com (C. Fu), yehailong1@gmail.com (H. Ye), dmyan@zju.edu.cn (D. Yan).

http://dx.doi.org/10.1016/j.conbuildmat.2016.08.096

diffusivity is influenced by water-to-binder ratio [17], mix proportion [17], chloride binding capability [16], ambient temperature and relative humidity [9], concrete age [14], degree of carbonation [15,18], presence of cracks [19–22], and external loads [12,13,15,23–27].

Depending on the magnitude and nature of loads, the loaded concrete can undergo either microstructural alteration [28], permanent damage (micro-cracks) [25,29,30], or macro-cracks formation [19,22,31], all of which can affect the chloride diffusivity and penetration process. Based on the nature of external loads, the concrete members in RC structures can be in the form of uniaxial sustained compression and tension, pure shear, flexural, cyclic loading (including fatigue), and multi-axial stress conditions. The different nature of stress would result in a different microstructural alternation in concrete and hence affects the chloride penetration differently [32]. Based a survey of literature, most of existing investigation regarding the influence of loading on chloride diffusion are limited to the cases that concrete is subjected to static uniaxial compression [23,24] and tension [23], flexural loads [13,15,25,33], and cyclic compression loads [26,27]. According to the outcomes of previous studies, cyclic compression loading was shown to cause severe damage and significantly enhance the chloride ingress and rebar corrosion in concrete, in comparison to static loads [26,32,34,35]. However, to the best of authors' knowledge, no one has ever systematically investigated the effects of tensile fatigue loading on the chloride penetration in concrete. Nevertheless, fatigue tensile loading may be closely related to the initiation, propagation, and coalescence of micro-cracks in concrete, particularly associated with the interfacial region between aggregate and paste, which can considerably impact the transport properties of concrete.

To fill the aforementioned knowledge gap, this study investigated the chloride penetration in fatigue-damaged concrete with various levels of loading. To fully characterize the influence of exposure age and environment on chloride penetration, the tests were performed at two conditions (i.e. immersion and drying-wetting cycle) and three exposure durations (i.e. 30, 45, 60 days). In addition, the effect of supplementary cementitious materials (i.e. blast-furnace slag and Class F fly ash) on the chloride penetration in fatigue-damaged concrete was illustrated. Finally, a quantitative expression to predict the effects of residual strain after tensile fatigue loading on the apparent chloride diffusivity was established.

Table 2
Mineral composition (% by mass) and fineness of ordinary portland cement.

Mineral composition	C_3S	C_2S	C_3A	C_4AF	$CaSO_4{\cdot}2H_2O$	Fineness (m^2/kg)
Content	55.5	19.1	6.5	10.1	5	350

2. Experimental procedures

2.1. Materials

As shown in Table 1, three types of concrete, including pure ordinary portland cement concrete (PC), ordinary concrete blended with ground granulated blast-furnace slag (SL), and ordinary concrete blended with Class F fly ash (FA), were investigated. All three mixtures were designed to have the same water-to-binder (cement + supplementary cementitious materials) ratio and paste-to-aggregate ratio. In particular, ASTM Type I cement was used, with the mineral composition and fineness listed in Table 2. ASTM C989 Grade 100 slag with fineness of 450m^2/kg and ASTM C618 Class F fly ash with a density of 2210 kg/m^3 were used. The fine aggregate was natural river sand with fineness modulus of 2.64. The coarse aggregate was crushed gravel with the maximum size of 20 mm and continuous grading ranges from 5 mm to 20 mm. The water was from tape water. In addition, to prepared reinforced concrete specimens, a series of Φ 12 HRB 335 bars (the characteristic value of yield strength is 335 N/mm^2, according to Chinese Standard GB 50010-2002) were used as the longitudinal steels.

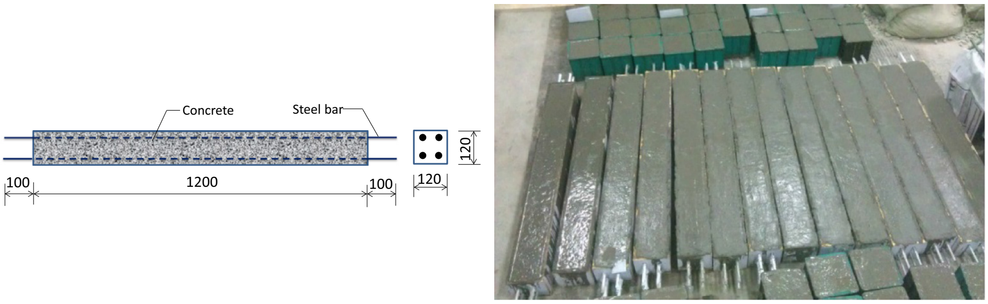
2.2. Sample preparation

The configuration of the specimen subjected to tensile fatigue loads was a prism with a dimension of 120 mm × 120 mm × 1200 mm, as shown in Fig. 1. For each specimen, four HRB 335 steel bars with a diameter of 12 mm and a length of 1400 mm were placed inside the concrete, leaving the concrete cover as a thickness of 20 mm for each side. At the two extremities of each specimen, the steel bars with a length of 100 mm stick out, as shown in Fig. 1(a).

Totally 12 specimens were prepared, including 11 reinforced specimens (i.e. two SL mixture, two FA mixture, and seven PC mixture) and 1 un-reinforced PC mixture. In the meantime, 18 cubic

Table 1
Mix proportion (kg/m^3) and mechanical properties of concrete.

Mixture ID	Cement	Slag	Fly ash	Fine aggregate	Coarse aggregate	Water	28-day compressive strength (MPa)	28-day tensile strength (MPa)
PC	372	0	0	698	1116	175	41.6	2.65
SL	223	149	0	698	1116	175	36.7	2.31
FA	260	0	112	698	1116	175	34.2	2.26



(a) (b)

Fig. 1. (a) Configuration of specimens for uniaxial tension fatigue testing (unit in mm) (b) specimens after casting.