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Model of time-dependent and stress-dependent chloride penetration of concrete under sustained axial pressure in the marine environment

Jun Xu [a], Fumin Li [a,b,*], Jie Zhao [a], Lang Huang [a]

[a] Jiangsu Key Laboratory of Environmental Impact and Structural Safety in Engineering, China University of Mining and Technology, China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, China

HIGHLIGHTS

- Relationship between surface chloride concentration, stress and time was developed.
- Relationship between chloride diffusion coefficient, stress and time was developed.
- Chloride penetration model for coupled stress level, time was proposed.

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ABSTRACT

The effect of sustained compressive loading on the chloride penetration of concrete was investigated and a self-monitoring loading device was developed. A series of prisms were loaded under five different sustained axial stress levels and four different numbers of wet/dry chloride cycles. Both the apparent chloride diffusion coefficient D_a and the surface chloride concentration C_s values were time and stress dependent with a sudden change threshold value of approximately 0.3 f_c. A model was proposed to predict the chloride penetration profiles of concrete under sustained axial pressure, taking both the time-dependent and the stress-dependent characteristics of D_a and C_s into account.

1. Introduction

Recently, concrete engineering has increased in the marine environment, especially for durable key projects such as cross-sea bridges, submarine tunnels, and similar projects. Piers built of concrete are suffering from long-term pressure and the marine salt environment and thus, the durability of these concrete structures will change, affecting the normal use of the structure and its service life [1–6].

It has generally been accepted that the effect of load on the chloride transport properties of concrete is affected by the load type (pull, pressure, or shear), the loading speed, and the loading level [4,5,7–12]. The existence of a critical compressive stress value has also been recognized, beyond which, both the surface chloride ion concentration and the apparent chloride diffusion coefficient noticeably change. At present, many studies exist on the chloride ion transport performance of compressive stress concrete after unloading. Samaha et al. [13] reported that the sudden change critical of compressive stress was 0.75 f_c (where f_c is the compressive strength of concrete). Using similar experimental methods, Lim et al. [14] reported that this threshold stress value was about 0.8–0.95 f_c. Saito et al. [8] did not report this threshold stress value and Tegguer et al. [15] recorded stress thresholds for ordinary concrete and high performance concrete of 0.7 f_c and 0.8 f_c, respectively. The above-mentioned chloride ion transport performance tests were conducted under unloaded non-stress conditions, and the obtained results were quite different.

The actual concrete structure is usually in a state of sustained pressure. If the sustained load effect to study the durability of the structure would not be taken into account, this will lead to inadequate prediction of the service life of the structure [16–18]. Sun et al. [19] used the method of loading disc springs, and realized threshold stress of 30–40% of the compressive strength; furthermore, the chloride ion permeability model (SDWM model) was set up under the sustained axial pressure coupling of wetting-drying seawater exposure cycles. Wang et al. [20] studied the chloride diffusivity of concrete subjected to sustained axial pressure in response to seawater exposure for 224 days and concluded a

* Corresponding author at: Jiangsu Key Laboratory of Environmental Impact and Structural Safety in Engineering, China University of Mining and Technology, China.
E-mail address: lfmfm@163.com (F. Li).

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threshold value at approximately 0.3 f_c and values of the surface chloride concentration C_s and the apparent chloride diffusion coefficient D_a that strongly depended on the level of applied stress. Wu et al. [21] established the simplified permeability model of chloride ion under loads and drying-wetting saltwater cycles and did not observe such a threshold stress value.

However, the coupled effects between chloride environmental and loading actions on the sustained chloride diffusivity of concrete remain unknown. The existing chloride diffusion models of concrete that is subjected to sustained compressive loading only reflects a single stress factor and does not reflect the time factor. Furthermore, the apparent chloride diffusion coefficient model and the surface chloride concentration of concrete that has been subjected to sustained compressive loading have rarely been reported. Therefore, it remains desirable to develop a numerical model of time-dependent and stress-dependent chloride penetration of concrete under sustained axial pressure in the marine environment to predict concrete diffusivity more reasonably and efficiently.

In this study, a self-monitoring loading device was developed and a series of concrete prisms were loaded under five different sustained axial stress levels (0, 0.3, 0.4, 0.5, and 0.6 f_c) and four different numbers (25, 50, 75, and 100) of wet/dry chloride cycles. This paper aims to investigate the effects of sustained compressive loading on chloride penetration in concrete and to establish a model to predict the chloride penetration profiles of concrete under sustained axial pressure, while taking both the time-dependent and the stress-dependent characteristics of D_a and C_s into account.

2. Experimental program

2.1. Preparation of specimens

Concrete samples were prepared at a w/c of 0.57 with ordinary Portland cement P.O.42.5, as fine aggregate, we used local river sand with a fineness modulus of 2.40 and locally available crushed gravel (a maximum size of 20 mm and an apparent density of 2880 kg/m^3) was used as coarse aggregate. Concrete was mixed using tap water, and the mix proportions are listed in Table 1.

Specimens with dimensions of 100 × 100 × 300 mm were cast and compacted with a mechanical vibrator in the laboratory. Twenty-four hours after casting, all the specimens were demolded and then cured in a room at a temperature of 20 ± 5 °C at 95% relative humidity for 28 days. On the 28th day, the compressive strength of the concrete was evaluated using three cubes. The average compressive strength values of concrete were measured as 29 Mpa.

2.2. Loading of specimens

To avoid eccentric compression, the specimen, jack, and load sensor should be vertically aligned. After the specimen was put down (by applying a target load to the jack), the bolts were tightened a few times in sequence to avoid eccentric compression. Stresses were monitored and controlled by a load sensor. If stress reduction exceeded 5% of the applied stress, the bolts were tightened a few times until the stress returned to the target stress level. The setup for the loading test is shown in Fig. 1.

Table 1
Mixture proportions of concrete (kg/m^3).

Cement	Coarse aggregate	Fine aggregate	Water	W/C
360	1174	661	205	0.57

Generally accepted, concrete will be in an unstable stage of damage development when the maximum applied stress exceeds 70% of the compressive strength. Therefore, we selected 0, 10%, 30%, 40%, 50%, and 60% of the compressive strength for our exploration. The load levels and other information are shown in Table 2.

2.3. Exposure environment

To accelerate the chloride ion permeation of concrete specimens, we used a drying-wetting saltwater cycles environment [22,23]. The setup for the drying-wetting saltwater cycles is shown in Fig. 2. After the specimens were cured, only one invasive surface was left exposed, the other sides were covered with epoxy coatings. Then, the specimens were placed in a container filled with saltwater (with a 3.5% concentration by mass) and subjected to continuous drying-wetting with a cycle of 1 d (dry for 12 h and wet for 12 h) for 100 days. Considering the variation of chloride solution concentration, the samples were tested every 25 days (each sampling) to replace the chlorine salt solution. During the test, the temperature in the laboratory was maintained at a constant 25 ± 5 °C and the wind speed of the drying process was 3.5 m/s.

2.4. Chloride penetration tests

The load sensor was placed out of the saltwater during the whole penetration process, to avoid damage due to rust. Each specimen was divided into eight depths, which were 0–5 mm, 5–10 mm, 10–15 mm, 15–20 mm, 20–25 mm, 25–30 mm, 30–35 mm, and 35–40 mm, respectively. The powders of the same depth were collected as representatives of this layer. Then, the respective powder sample was ground until they passing a 0.30 mm sieve. After grinding, the powder samples were put into an oven at 105 °C for 24 h and were then mixed with nitric acid solution, following the JTJ 270-98 standard [24]. After each sampling, the pores were filled with mortar to reduce the stress concentration of the hole.

3. Results and discussion

3.1. Chloride distribution profiles of concrete specimens

Fig. 3 shows the chloride concentration profiles in both stressed and unstressed concrete specimens after various exposure periods. Fig. 3 shows that the chloride ion content of concrete decreases nonlinearly with increasing depth, while with increasing number of drying-wetting saltwater cycles, the chloride ion content in the concrete gradually increased (except for the surface convection area).

The apparent chloride ion diffusion coefficient D_a is an important index used to characterize the propagation speed of chloride ions in concrete. The ability of the concrete to resist chloride ion intrusion can be obtained via analytic solution of Fick's second law fitting Eq. (1) [25–27]. During the fitting process, the data of the first layer in the surface convection region was removed to fit all data to the pure diffusion in the saturated state as much as possible [7,28,29].

$$C = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_a t}}\right)\right] \tag{1}$$

where C_s represents the chloride concentration at the surface of the concrete and D_a represents the apparent diffusion coefficient of the concrete.

The surface chloride ion concentration C_s and the apparent chloride diffusion coefficient D_a obtained via fitting the chloride distribution profiles curve using Eq. (1) are shown in Table 3. It