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Transport model of chloride ions in concrete under loads and drying-wetting cycles

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HIGHLIGHTS

- The chloride transport in concrete influenced by drying-wetting cycles, stress ratios and exposed ages was studied.
- The relationship between chloride concentration in concrete and exposed ages was presented.
- The simplified transport model of chloride ion in concrete was established.

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ABSTRACT

Alternation of drying and wetting led to the worst corrosion of the engineering structures in marine environments. In this paper, the transport of chloride ions in concrete under loads and drying-wetting cycles was investigated. The influences of drying-wetting cycles, stress ratios and exposed ages of concrete on chloride ions transport in concrete were studied. The relationships between the coefficient of chloride ion diffusion and stress ratios of concrete under the loads and drying-wetting cycles were obtained. The relationship between the chloride ion concentration of concrete surface and exposed ages of concrete was studied. And the simplified transport model of chloride ions in concrete under loads and drying-wetting cycles was established, of which the validity was verified through the good agreement with the experimental data.

1. Introduction

Chloride-induced corrosion of the reinforcing rebar is one of major causes for deterioration in reinforced concrete structures [1]. So the resistance to chloride penetration is important to concrete structures subjected to simultaneous chloride attack and service loads [2].

The transport of chloride ions in concrete included a variety of mechanisms, which basically has the following several kinds: the diffusion due to the action of concentration gradient [3], the diffusion due to the pressure [4,5], and capillary suction under the action of humidity gradient [6]. Actually, the chloride penetration into concrete is a complex phenomenon. The main reason is that concrete is a kind of inhomogeneous material, and the micro defect or damage was formed during the service period. The chloride ions diffusion in concrete was accelerated due to the micro defects of the structures caused by the action of loads, environment and climate conditions [7]. The continuously hydration of cement led to the internal structure of concrete denser, therefore the chloride ion diffusion coefficient is a function of time, and the chloride ion diffusion coefficient was reduced with the increasing of time [8,9]. The chloride ion diffusion coefficient was also related to the ion concentration in pore fluid of concrete [10]. It was concerned that the movement of ions was speed up due to the rise of temperature. As a result, the chloride ion diffusion process was accelerated [11].

Based on Fick's second law of diffusion, a new multi-components diffusion equation was deduced by Yu et al. [12]. In that equation, the influences of chloride ion binding capacity of concrete, time-dependence of chloride diffusivity and micro-defect of concrete structures were taken into consideration. The mechanism of concrete durability under uniaxial compressive loads has been studied through chloride penetration experiments by Jiang et al. [13]. It has been found that there was a good corresponding relationship between chloride penetration resistance of concrete and the applied compressive stress levels. The effects of cyclic flexural loads on the chloride diffusion characteristics of plain concretes were investigated, and a model to predict the chloride penetration in plain concrete subjected to both tidal

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environments and different cyclic flexural load levels was also proposed [14].

Under the chloride salt environment, the drying-wetting cycle zone often corresponded to the worst corrosion position of the rebar in reinforced concrete structures. In order to obtain the simplified calculation model, many researchers studied the chloride ion transport process in concrete based on Fick's second law. The constant boundary conditions were determined by the drying-wetting environment, and the chloride ion diffusion model was established in accordance with transport process of chloride ion in concrete [15,16].

At present, the transport model of chloride ions in concrete under only loads or drying-wetting cycles has been addressed by many researchers. But very few information are available about the transport model of chloride ions in concrete under both loads and drying-wetting cycles. The objective of this study is to establish the transport model of chloride ions in concrete under both loads and drying-wetting cycles.

2. Experimental procedure

2.1. Materials and mix proportion

The cement used in this study was a 42.5R Ordinary Portland cement (specific surface: 385 m^2/kg), which was supplied by the China Jiangnan Cement Co., Ltd. The mineral admixtures used as partial cement replacement materials were Class I FA (specific surface: 405 m^2/kg, specific density: 2.27 g/cm^3) and Class S95 BFS (specific surface: 402 m^2/kg, specific density: 2.90 g/cm^3). The available crushed gravel with a maximum size of 30 mm and specific density of 2690 kg/m^3 was used as the coarse aggregate. The locally available natural river sand with a fineness modulus of 2.44 and specific density of 2600 kg/m^3 was used as the fine aggregate. The high range water reducer was used and the industrial salt was used as the chlorine salt. Three mix proportions were designed, and the details of the mixture proportions were shown in Table 1.

2.2. Design of specimens

The drying-wetting cycles, the exposed age of concrete and the compressive stress ratio were considered to research the transport model of chloride ion in concrete. The test matrix is shown in Table 2. The specimens were divided into nine groups. In order to investigate the chloride ion concentration of concrete surface, the specimens with the full immersion and drying-wetting cycles were tested, respectively. Three water-cement ratios were designed to consider the influence of different mix proportions, and it can be found from Group [A] and Group [D], Group [B] and Group [H], Group [C] and Group [H], respectively. In order to investigate the influence of concrete exposed age on the content of chloride ions, the content of chloride ions was measured at the age of 30, 60, and 90 days, respectively. Four kinds of stress ratio were considered in Group [D] to Group [G]: $p = \sigma_c / f_{cuk} = 0,\ 0.3,\ 0.5,\ 0.7$, where σ_c is the compressive stress of concrete, f_{cuk} is the cubic compressive strength of concrete, and 28-day cubic compressive strength of concrete was 43 MPa. Taking account for tidal conditions in Bohai Sea, East Sea and Yellow Sea in China, the drying and wetting cycle scheme was eight hours for wet condition and eight hours for dry condition.

2.3. Test setup and instrumentation

The loading test is shown in Fig. 1. From top to bottom, the compressive stress on concrete specimens is 70%, 50%, 30% of concrete compressive strength, respectively. Thus the size of each specimen can be calculated, which is $45 \times 100 \times 50$ mm, $60 \times 100 \times 50$ mm, $100 \times 100 \times 50$ mm, respectively. When the specimens were tested, one surface was chosen for the working surface, the other five surfaces were sealed.

The setup for loading test is shown in Fig. 1(a). In order to guarantee sufficient strength and stiffness for the frame, the size of the steel plates was set to 50 mm × 50 mm × 210 mm and the diameter of the steel bars to 28 mm. The disc springs were used in order to minimize stress loss during the experiment. The external load was controlled by the displacements of the disc springs. To maintain the load level on concrete, the displacements of the disc springs was measured by the vernier caliper, and the loading values were calibrated by pressure machine, as shown in Fig. 1(b).

After the specimens were cured, they were subjected to different external loads, as shown in Table 2. Compressive stress was applied by two top nuts after three specimens fixed completely to the steel plates by epoxy glue. The stress level was maintained by monitoring the displacements of the disc springs. Then the setup and concrete specimens were immersed in salt water for drying and wetting cycles. The chloride concentration of the salt water was 3%.

2.4. Measurement of chloride ion content in samples

Each specimen was divided into four depths, which were 0–5 mm, 5–10 mm, 10–15 mm, 15–20 mm, respectively. The powder of the same depth was collected as the representative of this layer. Then the powder was grinded until they can get through the 0.60 mm sieve. After grinding, the powder samples were put into the oven at 105 °C ± 5 °C for two hours and then taken out to be titrated by silver nitrate. The chloride ion content in concrete can be calculated by the following equation [17].

$$P = \frac{C_{AgNO_3} V_3 \times 0.03545}{G \times V_2 / V_1} \times 100\% \tag{1}$$

where P—water soluble chloride ion content in concrete samples (%); C_{AgNO_3}—standard solution concentration of silver nitrate (mol/L); G—weight of Concrete samples (g); V_1—water amount used for immersion (mL); V_2—extracted filtrate volume each titration (mL); V_3—consumed amount of silver nitrate each titration (mL).

3. The experiment results and analysis

3.1. The influence of drying-wetting cycles on chloride ion content

Fig. 2 shows distributions of the chloride ion content in concrete changed with ages in full immersion and drying-wetting cycles. It

Table 1
Mixture proportions of concrete.

W/C	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	BFS (kg/m^3)	FA (kg/m^3)	Water reducer agent (g)
0.33	185	696	1043	153	185	94	4.64
0.39	160	719	1078	156	160	80	4.0
0.45	160	709	1064	180	160	80	4.0

Table 2
Experiment matrix.

Group	Number of specimens	Compressive stress ratio	Water cement ratio	Drying-wetting cycles system	Exposed age of concrete (d)
[A]	S0I3, S0I6, S0I9	0	0.33	Full immersion	30, 60, 90
[B]	P4I3, P4I6, P4I9	0	0.39		30, 60, 90
[C]	P5I3, P5I6, P5I9	0	0.45		30, 60, 90
[D]	S0W3, S0W6, S0W9	0	0.33	Dry/wet = 1:1, 8 h wet and 8 h dry	30, 60, 90
[E]	S3W3, S3W6, S3W9	30%	0.33		30, 60, 90
[F]	S5W3, S5W6, S5W9	50%	0.33		30, 60, 90
[G]	S7W3, S7W6, S7W9	70%	0.33		30, 60, 90
[H]	P4W3, P4W6, P4W9	0	0.39		30, 60, 90
[K]	P5W3, P5W6, P5W9	0	0.45		30, 60, 90