Construction and Building Materials 162 (2018) 697–703

Contents lists available at ScienceDirect

Construction and Building Materials

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

The permeability of $SO4^{2-}$ and Cl^{-} in concrete under the effect of seepage flow and stress fields

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HIGHLIGHTS

- Ions erosion tests were conducted under the joint effect of seepage flow and stress fields.
- The permeability of sulfuric acid and chloride ions in concrete under different pressure head and load were analyzed.
- The ultrasonic testing results of corroded concrete are consistent with the spectrometry results.

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 11 November 2017
Accepted 9 December 2017

Keywords:
Concrete
Seepage flow and stress fields
Sulfate
Chloride
Seepage

ABSTRACT

The ultrasonic velocity in concrete and the concentrations of ions at different depths along the directional flow of ion erosion were measured under the joint effect of seepage flow and stress fields. The permeability of sulfuric acid and chloride ions in concrete under different pressure head and load were analyzed (pressure head and load are perpendicular to each other). The results show that the concentrations of chloride ion and sulfate ion in different depths of concrete were increased to a certain extent either under the water head pressure or load effect. The differences in water head can induce the variation of ions concentration in the surface layer of concrete and the influenced depth can reach up to 60 mm. The load imposed a similar effect on the ions concentration of different layers and the directions of ion erosion, respectively. The ultrasonic testing results of corroded concrete are consistent with the results of ions concentration measured by spectrometry.

1. Introduction

Concrete durability is one of the most important issues which have been extensively researched [1]. As the groundwater flow in the concrete, the permeability of chloride ions and sulfate ions in concrete is critical to concrete durability. Until now, many research works have been conducted to investigate the ions (such as chloride and sulfate) erosion of concrete and some achievements have been made. Sulfate ions can react with alkaline substances in concrete to form entringite. When the concentration of sulfate is too high, gypsum will crystallize out and the solid volume increases, resulting in an expansion, cracking and strength loss of concrete. Chloride ions are easier to react with concrete than sulfate ions. The existence of chloride ion can restrain the sulfate attack on concrete [2]. Scholars such as Mollon G [3] and Hasan Yildirim [4] have investigated the permeability of chloride ions in concrete and stressed the influence of cement types on impermeability. Poznic M [5] introduced the ion chromatography to measure the contents of chloride and sulfate in cement, Sugiyama T and Bremner [6] examined the diffusion coefficient of chloride ion in eroded concrete and obtained the relationship between chloride ion diffusion coefficient and the water-cement ratio. All the above studies focused on the erosion of concrete by either sulfate or chloride. Few studies have considered the combine effect of sulfate and chloride. K. Sotiriadis [7] studied the sulfate resistance of limestone cement concrete exposed to combined chloride and sulfate environment at low temperature. The research found that the limestone cement concretes exhibited higher deterioration degree compared to the concrete made without limestone cement. The deterioration was delayed and mitigated as the chlorides can inhibit sulfate attack on concrete. J.M. Du [8] utilized ultrasonic opposite testing method to study the sulfate corrosion thickness of concrete and proved the feasibility of this method. W.Y. Zhan [9] presented an UV spectrophotometry method to determine the macro-amounts of sulfate directly. The tested results show a good

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https://doi.org/10.1016/j.conbuildmat.2017.12.071
0950-0618/

consistence with those obtained by barium sulfate gravimetric method.

Currently, multi-field coupled erosion tests of concrete are focused on the combined effect of loading and single-factor erosive environment on the concrete structure. Studies show that load and stress have certain influence on seepage of chloride ions and sulfate ions in concrete. Schneider [10–12] performed basic research on the erosion of concrete under stress by using basic elements. Shiqing He [13] tested the content of free ions in concrete under continuous bending loads. The concrete were immersed in a NaCl solution for 30, 70, 120, or 200 days. He discovered that the diffusion rate of chloride ions and the diffusion coefficient in concrete were increased under the load. Above all, numerous researches can be found on the diffusion mechanisms of chloride ions and sulfate ions in concrete. Some researchers have studied the diffusion mechanism of corrosive ions under the effect of load and stress. However, the research towards concrete structure under the effect of seepage flow and stress fields, especially the seepage and erosions of mixed solution (with chloride and sulfate ions) in concrete, are still insufficient [14].

Among the existing durability research under the joint impact of mechanical and environmental factors, most studies performed testing by increasing the load to a certain extent, then unloaded and placed the concrete in an abrasive environment [15,16]. The real working conditions which coupling the effect of mechanics and environmental factors did not realize in these research. Some evaluation methods were used to measure the durability of concretes under stress and environment. M. Otieno [17] utilized the rapid chloride conductivity test to measure the efficacy of resistance of the concretes to chloride ion penetration. C.F. Xu [18] presented a new self-balanced loading device that can perfectly satisfy the requirements of concrete component durability test, especially under the action of both loading and environment.

In this paper, the permeation was performed according to the standard of GB50164-92 [19]. A self-balanced loading device that put forward by C. F. Xu was used to apply the load. Ions erosion tests were conducted under the joint effect of 'seepage flow and stress fields' and mixed solution (with chloride and sulfate ions) in order to be closer to the real working conditions. The non-metallic ultrasonic testing device and spectrophotometer were utilized to test the ultrasonic velocity of concrete and the concentrations of ions at different depths along the directions of ion erosion.

2. Experimental details

2.1. Materials used in the experiment

325R Normal silicate cement (manufactured by Huaihai Cement Factory, Xuzhou, China) was used for the experiment. The coarse aggregate was rubble with a diameter of 5–20 mm. The fine aggregate was natural river sand with a fineness module of 2.7. The concrete mix ratio and the compressive strength of concrete cubes measured after 28 testing days are shown in Table 1.

2.2. Equipment used in the experiment

Concrete specimens were fabricated by the self-made concrete specimen testing mold. Increasing load was applied on concrete specimens by the self-made continuous load device. A controlled pressure head was exerted by the HP-4.0 Anti-Seepage Device which equipped with auto pressurization system. The corrosion ions were permeated into concrete specimens and caused damages to the concrete performance. The thickness of corrosive layer in concrete specimens were measured by the non-metallic ultrasonic tester.

2.2.1. Self-Made concrete specimen testing mold

The concrete specimen was made of special die steel and has a mixed shape of cylinder and prism. The base of mold is a circular platform with a bottom diameter of 175 mm, upper diameter of 165 mm and height of 150 mm. The upper part of mold is a prism with a length of 200 mm, width of 200 mm and height of 300 mm, as shown in Fig. 1. Specific specimens were designed and fabricated in order to meet the requirements of erosion tests for concrete blocks. The circular table part was designed to exert the water head difference. The prism part was designed to facilitate the application of the load.

2.2.2. Self-made continuous load device

The self-made continuous load device was comprised of steel boards and bolts, as shown in Fig. 2. Two steel boards, with a length of 260 mm, width of 160 mm and thickness of 10 mm, were connected by four screw bolts. The prism section of concrete specimen was fixed between two steel boards, and load was exerted through the nuts and screws. The load direction was perpendicular to the direction of ion seepage. The magnitude of the load was displayed on the screen through the sensor.

2.2.3. HP-4.0 Anti-seepage device equipped with auto pressurization system

Fig. 3 presents the sketch map of the concrete specimen tested under the joint effect of water head pressure, load and mixed solution (with chloride and sulfate ions). HP-4.0 Anti-Seepage Device equipped with auto pressurization system was used to control the water head pressure. The bottom part of the concrete specimen

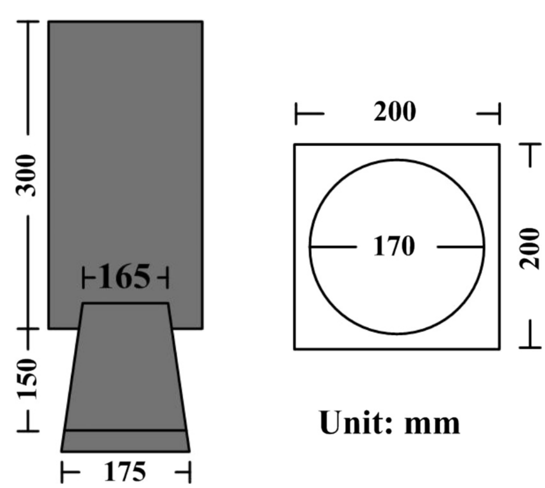

Fig. 1. Sketch map of concrete specimen mold.

Table 1
The concrete mix ratio and the mechanical function.

Grading of concrete	Concrete mix ratio			m(water)/m(cement)	Compressive strength of Concrete cubic (Mpa)
	Cement (kg*m^{-3})	Fine aggregate (kg*m^{-3})	Coarse aggregate (kg*m^{-3})		
C30R	450	610	1200	0.41	34.5