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Influence of temperature history on chloride diffusion in high volume fly ash concrete

Peng Jiang, Linhua Jiang *, Jie Zha, Zijian Song

College of Mechanics and Materials, Hohai University, Nanjing 210098, PR China

HIGHLIGHTS

- Different temperature histories were set to determine the chloride diffusion coefficient of HVFA concrete.
- Variations of chloride diffusion coefficient with temperature histories and age were revealed.
- Relationships between chloride diffusion coefficient with Maturity were obtained.

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ABSTRACT

This paper presents the influence of temperature history on chloride diffusion of high volume fly ash (HVFA) concrete. Four different curing temperature histories, referenced as SDC (standard curing), SMC (steam curing), OC (outdoor curing) and TMC (massive concrete temperature matched curing), were set. Concretes with different replacement levels of fly ash were cast and cured under the four temperature histories, respectively. The variations of compressive strength, porosity and chloride diffusion coefficient with different ages were determined by experiment. SEM and XRD were used to analyze the microstructure and compositions of hydrated pastes. The results show that the performances of fly ash concrete were influenced by temperature histories. And the influence was more obvious with the addition of replacement level of fly ash. For ordinary concrete, higher accumulated temperature at early age got higher compressive strength, better pore structure and lower chloride diffusion coefficient, but had negative effects at later age compared to SDC. For HVFA concrete, it was beneficial for the development of performances. Although the chloride diffusion coefficient was higher than ordinary concrete at early age, it would become small even lower at later age. And higher accumulated temperature promoted this process. In addition, by utilizing the concept of maturity, good power function relations between chloride diffusion coefficient of fly ash concrete and Maturity were obtained at early age.

1. Introduction

The chloride initiated corrosion of the reinforcing steel is one of the major degeneration of reinforced concrete (RC) structures exposed to marine environments, salt lakes and de-icing salts [1,2]. Chloride diffusion coefficient is an important indicator used to quantify the chloride ingress speed in concrete, because the diffusion controls the ingress of chlorides. Thereby, the value of chloride diffusion coefficient plays a vital role in the determination of life and durability of the RC structures serviced in saline environments.

In recent decades, the output of fly ash (FA) is increasing every year, causing dust, air pollution and the damage of the ecological environment [3]. More than half of the FA was disposed as partial replacement of cement in concrete, commonly known as high volume fly ash (HVFA) concrete. This reduced the energy consumption and CO_2 emission associated with the production of Portland cement. Therefore, the use of HVFA in concrete will be highly beneficial with respect to cost, energy efficiency and environmental benefits, making concrete an environmentally sustainable material. However, due to slow pozzolanic properties of fly ash particles, low early age strength and durability properties are observed in HVFA concrete [4]. This has raised many arguments and limitations. Indeed, the small percentage is beneficial for the mechanical properties and durability but may not to any high extent [5]. Although many properties of HVFA concrete have been studied [6,7], the effect on chloride diffusion is not very clear.

It is well known that the performance of concrete is sensitive to temperature and age [8–10]. So far, researches on chloride diffu-

* Corresponding author.
E-mail address: hhulhjiang@gmail.com (L. Jiang).

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sion of concrete are mostly carried out using specimens cured in laboratory under standard curing temperature. However, in practical conditions, concrete structures will experience complex temperature variation because of ambient environment and internal hydration. For example, steam curing is used for precast concrete elements to achieve high strength at early ages [11]. Liu et al. [12] found that the temperature of concrete changed periodically like a sine curve along with atmospheric temperature. Internal temperature of massive concrete structures would rise as a result of cement hydration and slow heat dissipation [13]. The influence of these temperature histories on chloride diffusion in HVFA concrete is rarely reported.

The aim of this study is to investigate the influence of temperature history on chloride diffusion of HVFA concrete. In this work, four different curing temperature histories were set, i.e. SDC (standard curing), SMC (steam curing), OC (outdoor curing) and TMC (massive concrete temperature matched curing). Concrete specimens with fly ash contents at 0%, 30%, 50%, 70% were exposed to the four different temperature histories, respectively. The compressive strength, porosity and chloride diffusion coefficient were determined at different ages. The microstructure and compositions of hydrated fly ash - cement pastes were analyzed by SEM and XRD. Maturity concept was used to obtain the relationships between chloride diffusion coefficient and maturity.

2. Materials and methods

2.1. Materials and concrete mix

P. II 42.5 Portland cement and type II fly ash (China standard) were used. The chemical compositions of cementitious materials are given in Table 1. River sands with a fineness modulus of 3.0 were adopted as the fine aggregate. Crushed stones with the size of 5 ~ 20 mm were adopted as the coarse aggregate. A polycarboxylate superplasticizer was used to maintain the workability of HVFA concrete. The mix proportions used in the experiments are listed in Table 2.

2.2. Specimens preparation and curing temperature histories

The concrete specimens were cast with a size of 150 mm * 150 mm * 150 mm and Φ100 mm * 150 mm at room temperature (20 °C). All specimens were demoulded after 24 h and exposed to the four different curing temperature histories until the related test have been conducted. The four different curing temperature histories were set as:

(i) Standard curing (SDC): Specimens were cured in a room at 20 ± 2 °C and more than 95% relatively humidity.
(ii) Steam curing (SMC): Specimens were put into a steam curing box with the temperature procedure have been set. The maximum temperature during steam curing was 60 °C and the heating rate was 20 °C/h from room temperature. Then the duration of maximum temperature would be kept for 8 h. After that the temperature was lowered to 20 °C at a cooling rate of 20 °C/h. While all the procedure was finished, the specimens were moved to the room where SDC was conducted.
(iii) Outdoor curing (OC): Specimens were moved to an open space and covered by moist straw. The maximum, minimum and average atmospheric temperatures were recorded at every day from July to August in Nanjing City.
(iv) Temperature matched curing (TMC): Specimens were cured in a curing box whose temperature was adjusted according to real-time monitoring temperature of Three Gorges Dam [13] in China.

The profiles of temperature histories are given in Fig. 1.

2.3. Test methods

2.3.1. Porosity test

The porosity test was performed referring to evaporative water method [14]. The cylinders were cut into disks with a length of 50 ± 2 mm and immersed in deionized water more than 48 h. Then the disks were dried at 90.7% relative humidity by placing them in a desiccator containing saturated salt solution of barium chloride until constant mass. And the mass loss was calculated to the large porosity (more than 30 nm). After that the disks were placed in a drying oven heated to 105 °C for 24 h. After heat drying, the disks were moved to a vacuum desiccator for lowing the temperature down to 20 °C ~ 25 °C and weighed. Then the trials were repeated until the adjacent quality varying within 0.5%. Then took out the disks and wiped by a drying rag for weighing. Next suspended the disks in water by an iron wire and weighed the apparent mass.

The total porosity was calculated according to Eq. (1)

$$p = \frac{m_2 - m_1}{m_2 - m_3} \times 100\% \quad (1)$$

where p is the water saturated porosity(%), m_1 is the disk mass after drying, m_2 is the disk mass saturated by water, m_3 is the disk apparent mass in water.

The fine porosity was the difference between total porosity and large porosity. In addition, the large porosity was the porosity of pore lager than 30 nm and the fine porosity was less than 30 nm.

2.3.2. Rapid chloride migration (RCM) test

The RCM test was performed referring to SL352-2006 (China standard) [15]. The cylinders were cut into 50 ± 2 mm thick disks before the rapid chloride migration (RCM) test. Each disk was ultrasonic cleaned for 180 ± 20 s. In the test setup, 0.2 M KOH solution was poured to anode chamber and 0.2 M KOH with 5% NaCl mixed solution was injected to cathode side. The voltage was 30 V and the test duration was set according to the initial current. The initial and final temperatures were recorded. After that, the disks were split into two along the axial direction. 0.1 M $AgNO_3$ solution was sprayed to the fracture surfaces. Ten points were measured by a vernier caliper in the coloured area and the average value was determined to the chloride penetration depth. The chloride diffusion coefficient was calculated by Eq. (2):

$$D_{RCM} = 2.872 \times 10^{-6} \frac{Th(x_d - a\sqrt{x_d})}{t} \quad (2)$$

$$a = 3.338 \times 10^{-3} \sqrt{Th} \quad (3)$$

Table 1
Chemical compositions of cementitious materials (wt.%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	MnO_2	P_2O_5	IL
Cement	21.60	5.19	4.31	63.45	0.92	1.08	0.21	0.53	0.14	0.10	0.05	1.20
FA	47.44	29.82	4.73	3.84	0.70	0.83	1.36	0.43	1.38	–	0.26	4.56