Construction and Building Materials 170 (2018) 627–636

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental study of the gas diffusion coefficient of heated concrete

Yongjiang Shen [a,*], Zhengliang Xiang [a,b], Fei Ma [a], Feilong Mi [a], Zixian Chen [a]

[a] School of Civil Engineering, Central South University, Changsha 410002, China
[b] School of Civil Engineering, Harbin Institute of Technology, Harbin 150001, China

HIGHLIGHTS

- The gas diffusion coefficient of heated concrete is investigated.
- The influence factors of the gas diffusion coefficient are investigated.
- The correlations among of the influence factors are established.

ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form 12 January 2018
Accepted 11 March 2018
Available online 23 March 2018

Keywords:
Concrete
Gas diffusion coefficient
Porosity
Density
Durability

ABSTRACT

In this paper, the effects of the water/cement (w/c) ratio and heating temperature on the gas diffusion coefficient of heated concrete are investigated. The gas diffusion coefficient of concrete increases as the heating temperature and w/c ratio increase, and the effect of the w/c ratio on the gas diffusion coefficient of concrete increases with the heating temperature. In addition, the density and porosity of heated concrete were experimentally studied, and the results exhibited a high correlation among the gas diffusion coefficient, density and porosity of heated concrete.

1. Introduction

Reinforced concrete structures combine the advantages of steel and concrete, and the cost is low. Reinforced concrete has had large-scale applications since the 1920 s, and it has become one of the preferred forms of civil engineering structural design. However, with the increase in the service period, the durability problems of reinforced concrete structures have become increasingly prominent. The corrosion of reinforcement is the most important and direct factor that causes the deterioration of reinforced concrete structures [1–3]. In a common atmospheric environment, the necessary condition for reinforcement corrosion is sufficient oxygen on the surface of the steel bars. Gaseous diffusion is the main transport process by which oxygen can reach the surface of steel bars. The diffusion rate of a gas into a uniformly permeable material is commonly determined by Fick's first law of diffusion [4]:

$$J = -D\frac{dc}{dx} \tag{1}$$

where J is the mass transport rate (g/m^{2}s), D is the diffusion coefficient (m^2/s), dc/dx is the concentration gradient (g/m^4), and x is the distance (m).

As shown in Eq. (1), the gas diffusion coefficient of a concrete cover is one of the key factors that affects the corrosion rate of the reinforcement [5]. Because concrete is a type of typical porous material [6], the gas diffusion coefficient of concrete largely depends on the porosity, pore distribution, pore tortuosity and pore connectivity of the porous media. In addition, the gas diffusion rate of concrete is affected by many other factors, such as the water content of concrete and temperature; because of the discreteness of concrete material, it is difficult to theoretically determine the gas diffusion coefficient of concrete. Except for a few theoretical studies, most studies of gas transport in concrete were performed using test methods. NIU et al. [7,8] established the relationship between the carbon dioxide diffusion coefficient of concrete and the concrete compressive strength; then, they established the relationship between the oxygen diffusion coefficient of concrete and the concrete compressive strength according to the relationship between the diffusion coefficients of carbon

* Corresponding author.
E-mail addresses: 209059@csu.edu.cn (Y. Shen), xiangzl@csu.edu.cn (Z. Xiang).

https://doi.org/10.1016/j.conbuildmat.2018.03.090
0950-0618/

dioxide and oxygen in concrete. Based on the mechanism of gas diffusion, the existing calculation formula of the gas diffusion coefficient, the compressive strength of concrete as the main parameter and the comprehensive effect of the environmental temperature, humidity and stress states of concrete, a model was introduced to calculate the effective diffusion coefficient of concrete. Zheng [9] introduced a hypothetical homogeneous medium of nonzero oxygen diffusivity and applied the general effective medium approach to obtain an analytical solution for the oxygen diffusivity of concrete.

There are two methods of determining the gas diffusion coefficient of concrete by testing: the concentration gradient method and the pressure gradient method. Figg [10] presented one of the earliest pressure gradient methods based on a simple apparatus to quickly determine the permeability of concrete. Papadakis [11], Houst and Wittmann [12] developed a device to determine the gas diffusion coefficient of concrete, but the method is complex and inconvenient for engineering applications. Based on Figg, Zhao et al. [13] proposed a quick and simple method of determining the gas diffusion coefficient of concrete. Based on the study of the gas transmission mechanism in porous media, according to the relevant theory, calculation formulas of the effective gas diffusion coefficient of concrete based on pressure gradient were derived, and a method to determine the gas diffusion coefficient of high-performance concrete and aged concrete was proposed by reasonably increasing the pressure gradient [14]. Geng et al. [15,16] developed a device to determine the oxygen diffusion coefficient of concrete based on the concentration gradient method. Then, the effect of the w/c ratio, environmental temperature and humidity on the gas diffusion coefficient of concrete was studied by tests. In addition, a prediction model of the oxygen diffusion coefficient of concrete was proposed. Villani et al. [17] investigated the repeatability/variability of an oxygen permeameter and an oxygen diffusivity instrument in two testing laboratories and found a lower variability for the oxygen diffusivity measurements than the oxygen permeability. Sercombe et al. [18] studied the effect of the w/c ratio, water saturation, pore size distribution/connectivity and total pressure on the gas diffusion properties of cement pastes by test. Zhu el al. [19] conducted orthogonal tests on the oxygen diffusion coefficient of concrete covers with different temperature, humidity and w/c ratios. Tittarelli [20] determined the oxygen diffusion coefficient of hydrophobic cement-based materials that were fully immersed in water using potentiostatic measurements on concrete and a diffusion cell on cement pastes and mortars. Khoe et al. [21] investigated the oxygen permeability of concrete and fibre-reinforced polymer (FRP) -concrete system and found a significant reduction in oxygen permeability of concrete after FRP was bonded. B.G. Salvoldi et al. [22] investigated the correlation between the oxygen permeability and carbonation coefficient, as well as the carbon dioxide diffusion coefficient of concrete, using experimental data. A. Rezagholilou et al. [23] demonstrated the compatibility and applicability of an analytical carbonation model that were initially developed for concrete in soil cement materials using experimental data. Real et al. [24] studied the effect of the w/c ratio, type of binder and aggregate, relative humidity, water content and concrete age on the oxygen permeability of lightweight aggregate concrete by tests.

However, the above studies of the gas diffusion properties of concrete were performed at room temperature. Since high temperatures can cause changes in the size and connectivity of the pore system of concrete, which extremely affects the gas diffusion rate of concrete [25], it is necessary to investigate the gas diffusion coefficient of heated concrete. In this paper, an experimental study of the gas diffusion coefficient of heated concrete was performed using four groups of concrete specimens with different w/c ratios (0.4, 0.45, 0.5 and 0.55), and the relationship among the gas diffusion coefficient, porosity and density of heated concrete was investigated.

2. Test program

2.1. Specimen preparation

To study the effect of the w/c ratio and heating temperature T on the gas diffusion coefficient of heated concrete, four groups of concrete specimens with different w/c ratios were made according to the literature [26]. The mix proportion is shown in Table 1. In the tests, tap water was used, the cement was ordinary Portland cement of strength grade 42.5 Mpa, the sand was local river sand (medium sand), and the coarse aggregate was gravel of size 8–12 mm.

Each group had 21 cylindrical concrete specimens of diameter 105 mm and height 60 mm, which were made from the same batch of fresh concrete. The molds of the specimens were made of plastic films and PVC pipes of inner diameter 105 mm, as shown in Fig. 1. The plastic films were removed one day after the specimens were cast, and the PVC molds were removed after two days. Finally, the specimens were cured at room temperature and room humidity for 28 days. The upper and lower surfaces of the specimens were polished before heating, as shown in Fig. 2.

2.2. Test equipment

The applied heating equipment in the experiment was a resistance furnace. Its working voltage is 380 V, the maximum power is 12 kW, and the maximum operating temperature is 1200 °C. The heating temperature of the resistance furnace could be manually set, and the furnace could maintain the set temperature and provide continuous heating.

According to the literature [27], a device to determine the gas diffusion coefficient of concrete was developed, as shown in Fig. 3. The inner diameter of the vacuum tube was 10 mm, the effective length between the valve and the cylinder was 1800 mm, the inside diameter of the cylinder was 200 mm, the height of the cylinder was 100 mm, and the diameter of the circular opening (the permeability section of the specimens) was 80 mm.

2.3. Test condition

To investigate the effect of the heating temperature on the gas diffusion coefficient of heated concrete, seven different temperature levels were applied in the heating tests. There were three specimens in each test condition, and the numbers of specimens are shown in Table 2.

2.4. Heating scheme

To eliminate the effect of the heating time on the test results, the heating processes were immediately stopped when the internal temperatures of the specimens became stable. The heating process inside the specimens was simulated by ANSYS before the heating tests; then, the heating times of different specimens were determined. The detailed processes are as follows:

2.4.1. Calculation parameter

According to the literature [28], the comprehensive heat transfer coefficients of the concrete surface were determined, as shown in Table 3.

According to Eqs. (2) and (3) in [29], the specific heat capacity of concrete material C (J/(kg·°C)) and thermal conductivity of