



Understanding the interacted mechanism between carbonation and chloride aerosol attack in ordinary Portland cement concrete



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ABSTRACT

An experimental study is carried out with the aim to understand the interacted mechanism between carbonation and chloride aerosol attack in ordinary Portland cement (OPC) concrete. Effects of carbonation on the chloride profile, the chloride binding capacity and the chloride diffusion coefficient are evaluated. Besides, effect of chloride aerosol attack on the carbonation rate is investigated. Concrete specimens with three water-to-cement ratios (0.38, 0.47 and 0.53) are fabricated in this work. Tested results demonstrate that carbonation remarkably affects the chloride profile, reduces the chloride binding capacity, and also accelerates the rate of chloride ion diffusion of concrete. Besides, the presence of chloride aerosol can lead to lower the carbonation depth and increase the pH value of carbonated concrete. Microscopic properties such as morphology, porosity, and pore size distribution for the contaminated concretes are explored by scanning electron microscope and mercury intrusion porosimetry, which provide strong evidence to these research findings.

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1. Introduction

Durability of reinforced concrete structures is of a great major concern across the world especially in the coastal regions where structures suffer from the steel rebar corrosion due to the ingress of carbon dioxide and chloride ion. The penetration of carbon dioxide can initiate the carbonation reaction in concrete materials. Concrete carbonation is a neutralization phenomenon which involves in the reaction between the carbon dioxide and the hydrated cement compounds, resulting in a reduction of the pH value of concrete pore solution [1–3]. The alkalinity reduction of concrete can lead to destroy the initially-formed passive film around the steel reinforcement, causing the steel corrosion in the presence of both moisture and oxygen [4–7]. In addition to carbon dioxide ingress, the steel corrosion can be occurred when a sufficient quantity of chloride ions are accumulated on the steel rebar surface [8,9]. The chloride-induced steel corrosion reduces the cross-sectional area of reinforcing bar, accelerates the crack formation in concrete, and even results in the spalling of concrete cover, which declines the residual service life of concrete structures [10,11]. In some environmental regions like atmospheric marine zone, both carbon dioxide and chloride ion can be interacted and this coupled effect may lead to a faster material degradation than if either one acts alone [12]. From the review of previous research work, some studies have been conducted to

investigate the effect of carbonation on chloride ingress for cement and concrete materials. For instance, Lee et al. [13] have reported that a higher ratio of water-soluble (free) chloride to acid-soluble chloride (total) content can be formed under the presence of carbonation. Backus et al. [14] have indicated that carbonation causes the liberation of bound chloride and a sudden increase of free chloride concentration in concrete material. A recent study taken by Ye et al. [12] has also pointed out that carbonation can increase the chloride content at carbonation fronts. Additionally, the rate of chloride diffusion in concrete material can be significantly increased by carbonation, as demonstrated by Ngala et al. [15], Chaoming et al. [16], and Ditao et al. [17] in their articles. On the other hand, it has been reported by Kuosa et al. [18] that the presence of chloride ion lowers the carbonation depth. This research finding is also supported by an experimental investigation concerning the effect of chloride ion on carbonation of cement paste by using X-ray computed tomography technique [19]. The researchers have found that increasing the chloride ion in cement paste can refine the porous structure and decrease the porosity. As a result, the resistance against carbon dioxide penetration for cement paste is improved. Yoon et al. [20] have stated that the risk of steel corrosion due to carbonation (given that both the moisture and oxygen are present) is not as serious as that caused by chloride attack, when concrete structures are subjected to double environmental effects of carbonation and chloride ingress. Besides the above experimental reports, the combined action of carbonation and chloride ion penetration has been investigated by numerical simulation work, which can be found in these literatures [21–24].

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Many studies on the subject of carbonation and chloride attack are generally conducted by using carbon dioxide and chloride solution, considering the situation where the concrete structures are constructed under seawater or in a splash zone. However, the relative humidity is quite high in such marine regions, which does not allow the carbonation to occur. Hence, the combined action of carbonation and chloride attack is rarely existed in these coastal environments. Nevertheless, in the atmospheric marine zone, carbon dioxide and chloride aerosol do exist concomitantly and the combined attack of carbonation and atmospheric chloride on the offshore concrete structures can be occurred. In general, chloride aerosol is generated along the seashore by breaking wave movement and transported inland by wind [25]. The combination of carbonation and chloride aerosol attack may cause a severe deterioration of concrete structures over their designed service life. However, little research work has been done on concretes subjected to the combined effect of carbonation and atmospheric chloride ingress. The role of chloride aerosol in the presence of carbon dioxide and that of carbon dioxide in the presence of chloride aerosol on degradation of concrete material have not been well clarified. Understanding the coupled physical-chemical interaction between carbonation and chloride aerosol attack in concrete is of great significance for prediction of service life for reinforced concrete structures situated in atmospheric marine environment.

The objective and originality of this research work is to investigate the interacted mechanism between carbonation and chloride aerosol attack in ordinary Portland cement concrete material. The ionic transport characteristics of concrete under the combined action of carbon dioxide and chloride aerosol are explored by evaluating both the effect of carbonation on the chloride profile, the chloride binding capacity and the chloride diffusion coefficient, and the opposite, the effect of chloride aerosol on the carbonation depth and the pH value. Microscopic properties of concrete under the coupled effect are also explored by using the scanning electron microscope (SEM) and mercury intrusion porosimetry (MIP) techniques.

2. Experimental work

2.1. Materials and specimen preparation

In this research work, type I ordinary Portland cement, made in Shenzhen Haixing Onoda Cement Co. Ltd., was used as concrete component. The chemical composition and the physical property of cement are listed in Table 1. The contents of calcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetra-calcium aluminoferrite (C_4AF) in cement were 59.36%, 18.25%, 9.82%, and 10.18%, respectively. Crush stone with the density of 2700 kg/m^3 was used as coarse aggregate, which was obtained from a quarry of AnTuo Mountain in Shenzhen city, China. The maximum size and the minimum size for the coarse aggregate were 20 mm and 5 mm, respectively. River sand with the fineness modulus of 2.61 and the density of 2632 kg/m^3 was

Table 1
Chemical composition and physical characteristics of ordinary Portland cement.

Item	Cement
Composition (mass % as oxide)	
Calcium oxide (CaO)	64.67
Silica (SiO_2)	18.59
Alumina (Al_2O_3)	4.62
Iron Oxide (Fe_2O_3)	4.17
Magnesium oxide (MgO)	2.35
Sulfur trioxide (SO_3)	3.32
Potassium oxide (K_2O)	0.92
Physical characteristics	
Loss on ignition (LOI)	1.03
Specific surface area (m^2/kg)	345
80 μm sieving fineness (%)	4.15

used as fine aggregate. Distilled water was used in the fabrication of concrete mixtures. Three water-to-cement ratios of 0.38, 0.47 and 0.53 were considered. Table 2 shows the mix proportion of concrete specimen.

All concrete mixtures were cast into 100 mm cube steel mold, and then consolidated on a vibration table with the purpose to force out the air bubbles. After demoulding, the mixtures were cured in a moisture room at 20°C and 95% relative humidity for 28 days. Prior to environmental conditioning, only one surface of concrete was allowed to be penetrated by carbon dioxide or chloride aerosol while the other surfaces were coated with epoxy resin. This was to realize one-dimensional diffusion. The concrete specimens were separated into four groups representing different exposure conditions, namely, group A (pure chloride aerosol attack), group B (combined carbonation and chloride aerosol attack), group C (pure carbonation) and group D (combined chloride aerosol ingress and carbonation). More details of the experimental scenarios for these four groups of specimens are described in Table 3.

2.2. Accelerated carbonation test and measurement of pH value and carbonation depth

The carbonation test was conducted in the accelerated carbonation chamber, following the Chinese National Standard GB/T 50082-2009 “Standard for test methods of long-term performance and durability of ordinary concrete” [26]. The concrete samples were conditioned with 20% CO_2 concentration, $35 \pm 2^\circ\text{C}$ temperature, and $70 \pm 2\%$ relative humidity. The tested period for carbonation was 28 days. In order to evaluate the alkalinity variation of concrete under carbonation, the pH value of carbonated concrete sample was measured. In this work, the pH measurement was carried out within the 0–16 mm depth interval of concrete. The method of pH measurement was based on mixing powdered samples with distilled water as a solvent and measuring the pH of the suspension, which was proposed and validated from a literature [27]. The concrete specimen was powered by a grinding machine from the surface to the interior, and the concrete powders were separately collected with an interval of 1 mm for the first 10 mm away from exposed surface and with an interval of 2 mm in the range from 10 mm to 16 mm. Then, 1 g powder and 50 g distilled water were weighted, and mixed together for 24 h prior to the pH value measurement. A device of pH meter was adopted to determine the pH value of carbonated concrete layer at different depths. Additionally, a 1% phenolphthalein solution was sprayed on the split cross section to determine the carbonation depth, in accordance with the testing standard [26]. The carbonation depth was captured and recorded by a digital caliper on a split face, perpendicularly from the carbonation front to the end edge.

2.3. Chloride aerosol conditioning and measurement of chloride content

To simulate the chloride aerosol exposure in marine atmospheric environment, concretes were conditioned in an environmental chamber (from Wuxi Sunan Experimental Equipment Limited Company) which was designed to spray the chloride-contained aerosol from the top down. Considering the deposition of salt fog in the environmental chamber, the concrete specimens were positioned with a manner that the top surface was upward and exposed to atmospheric chloride. A

Table 2
Mix proportions of OPC concrete.

Mixture ID	Water-to-cement ratio	Composition (kg/m^3)			
		Cement	Sand	Crush stone	Water
C38	0.38	454	729	1094	173
C47	0.47	409	720	1079	192
C53	0.53	396	718	1076	210

Note: The mass ratio of the fine aggregate to total aggregate (fine aggregate + coarse aggregate) used in all concrete specimens was kept as 0.4.

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