



# Modification of chloride diffusion coefficient of concrete based on the electrical conductivity of pore solution



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## HIGHLIGHTS

- The influence of electrical conductivity of pore solution on the chloride diffusion coefficient was verified.
- A modification method of chloride diffusion coefficient was proposed.
- The modified chloride diffusion coefficient eliminated the influence of pore solution.

## ARTICLE INFO

### Article history:

Received 29 September 2016

Received in revised form 6 March 2017

Accepted 28 March 2017

### Keywords:

Chloride diffusion coefficient

Modification

Electrical conductivity

Pore solution

## ABSTRACT

To correct the influence of pore solution on the chloride diffusion coefficient and set up a comparable permeability test method with other penetration experiments based on rapid chloride migration (RCM), the influence of supplementary cementitious materials (SCMs), including grounded granulated blast furnace slag (GBFS) and fly ash (FA), on the electrical conductivity of pore solution was investigated. A modification method of chloride diffusion coefficient was proposed based on the relationship between the electrical conductivity of pore solution and chloride diffusion coefficient. It was found that the modified chloride diffusion coefficients of the same mortars with differential solution by replacing the original pore solution with NaOH solution were almost identical. The modified relative chloride diffusion coefficients of concrete with differential SCM were close to the relative water absorption content. Results indicating that the modified chloride diffusion coefficient eliminates the effect of electrical conductivity of pore solution and could reflect transport property of concrete due to the connectivity pore, thus can be used to evaluate the generally permeability of concrete.

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## 1. Introduction

The permeability of concrete is considered as the main factor affecting the durability of concrete structures [1]. Therefore, various parameters were proposed to evaluate the transport properties of concrete, such as hydraulic pressure, surface water absorption, air permeability, current capacity and resistance of concrete, chloride permeability coefficient et al. [2–5]. Among them, the chloride permeability of concrete is considered as a significant parameter describing the resistance of concrete to the transport of chlorides and widely used to evaluate the durability and service life of reinforced concrete structures.

The normally used method for chloride permeability measurement is the rapid chloride migration (RCM) test, which is a typical

accelerated non-steady-state chloride migration test method developed by Tang and Nilsson [6,7] and standardized as NT Build 492 in 1999 [8]. The chloride diffusion coefficient ( $D_{nssm}$ ) was introduced into the service life model for concrete by the European DuraCrete which puts strict requirements on the test [9], it means that the RCM was a reliability test method and the  $D_{nssm}$  was reliability or repeatability to some extent. Numerical models which take the ion interactions and the electro-coupling effect on resistivity into account were used for simulating the ionic transport under an externally electric field [10–12]. The simulation results also demonstrate that the rapid migration test is more reliable than the rapid chloride permeability test [12]. Nevertheless, there are still some concerns regarding its theoretical background [13]. The previous reported studies indicated that there was a good relationship between the chloride diffusion coefficient derived from RCM and the electrical resistivity of concrete [14–17]. The chloride diffusion coefficient of concrete increased with decreasing resistivity of concrete. However, the electrical resistivity of concrete is not

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only influenced by the pore structure but also by the ions types and concentrations of pore solution in concrete [18], thus the chloride diffusion coefficient is also influenced by the pore structure and pore solution. It is generally known that the composition of pore solution was altered when supplementary cementing materials (SCMs) were used in cement-based materials [19]. In this system, the chloride diffusion coefficient determined by RCM may not reflect the real situation due to the altered chemical composition of pore solution and electrical resistivity of concrete. To this end, it is very important to clarify the influence of pore solution on the chloride diffusion coefficient of concrete.

In this study, the influence of grounded granulated blast furnace slag (GBFS) and fly ash (FA) on the electrical conductivity of pore solution and the electrical conductivity of pore solution on the chloride diffusion coefficient of mortar determined by RCM were investigated. The measured chloride diffusion coefficient was then modified based on the electrical conductivity of pore solution. The validity of the proposed modification was validated by comparing the modified relative chloride diffusion coefficient to the relative water absorption amount of concrete.

## 2. Materials and methods

### 2.1. Materials

The chemical compositions of Portland cement (PC), fly ash (FA), GBFS and ground limestone (LS) used in this study were given in the Table 1. Two types of GBFS with Blaine specific surface areas of 400 m<sup>2</sup>/kg (G1) and 800 m<sup>2</sup>/kg (G2) were used. The Blaine specific surface areas of Portland cement, fly ash and ground limestone were 360 m<sup>2</sup>/kg, 340 m<sup>2</sup>/kg and 340 m<sup>2</sup>/kg, respectively. River sand with a fineness modulus of 2.7 and crushed granite with size of 16.0–31.5 mm were used as aggregates. NaOH (chemical quality) was used to alter the electrical conductivity of pore solution. Polycarboxylate superplasticizer was used to maintain the same workability.

### 2.2. Methods

#### 2.2.1. Preparation concrete pore solution

Since it was difficult to extract pore solution from long-term cured concrete [20], the pore solutions extracted from cement paste (with a water/binder ratio of 5.0 by weight) with a curing age of 28 days were used as the simulate concrete pore solutions (SCPS) in this study. The mixtures include PC-GBFS, PC-FA, PC-GBFS-FA and PC-GBFS-FA-LS, the content of GBFS and FA in the binary system was range from 0% to 50% respective, and the detail mixture proportions of multi system were listed in Table 2. The blended cementitious materials was mixed with deionized water, and the fresh slurry were immediately filled into the plastic bottles; the plastic bottles were then sealed and stored at 20 °C for 28 days. The pore solutions were extracted from cement slurry and the electrical conductivity was measured by a conductivity meter (DDS-308A).

**Table 1**  
Chemical compositions of raw materials (wt%).

Material	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	LOI
PC	21.60	4.35	2.95	1.76	63.81	0.16	0.51	1.06	1.19
GBFS	35.22	12.15	0.25	11.25	37.08	0.25	0.49	1.19	–
LS	0.80	0.30	0.30	1.80	55.00	0.01	0.01	0.05	43.40
FA	49.27	28.33	6.38	1.63	5.43	0.53	1.10	1.22	3.60

Note: LOI, Loss on ignition.

**Table 2**  
The mixture proportions of blended cement system (wt%).

ID	PC	GBFS	FA	LS	W/B ratio
P0	100	–	–	–	5.0
P1	64	16(G1)	10	10	5.0
P2	38	35(G1)	14	13	5.0
P3	25	36(G1)	39	–	5.0
P4	25	36(G2)	39	–	5.0

Note: W/B ratio, water to binder ratio by mass.

**Table 3**  
The mixture proportion of mortar (kg/m<sup>3</sup>).

PC	GBFS	FA	Water	Sand
183	262(G1)	285	365	1060

**Table 4**  
The mixture proportions of concretes (kg/m<sup>3</sup>).

ID	PC	GBFS	FA	LS	Water	Crushed granite	Sand
C0	440	–	–	–	160	1044	756
C1	282	70(G1)	44	44	160	1044	756
C2	167	154(G1)	62	57	160	1044	756
C3	110	158(G1)	172	–	160	1044	756
C4	110	158(G2)	172	–	160	1044	756

#### 2.2.2. Preparation of mortar specimen

The mixture proportion of the mortar specimen was given in Table 3. The fresh mortar mixtures with W/B of 0.50 were cast in steel moulds (Φ100 × 100 mm). The mortar specimens were demoulded after 24 h and subsequently cured in water at 20 ± 1 °C for 28 days.

#### 2.2.3. Preparation of concrete specimen

The mixture proportions of the concrete specimen were given in Table 4. The W/B for all the mixtures was 0.36. The polycarboxylate superplasticizer was used to adjust the slump to the targeted value (190 mm). The fresh concrete mixtures were cast in steel moulds (Φ100 × 100 mm and 100 × 100 × 100 mm). The specimens were demoulded after 24 h and then cured in water at 20 ± 1 °C for 28 days.

#### 2.2.4. Adjustment of electrical conductivity of mortar pore solution

The electrical conductivity of mortar pore solution was altered by absorbing NaOH solution with concentrations of 0.0%, 0.7%, 1.4% and 2.0% (wt%) into the pre-dried specimens: Before the RCM test, the mortar specimens (Φ100 × 50 mm) were dried in an oven at a temperature of 60 °C for 24 h, and then cooled at room temperature of 20–25 °C. After drying, the specimens were placed in a vacuum container for vacuum treatment. The absolute pressure in the vacuum container was reduced to the value in the range of 10–50 mbar (1–5 kPa) within a few minutes and maintained for 3 h, NaOH solution with different concentrations was then filled in the vacuum container. After that, the vacuum maintained for one more hour before air was allowed to re-enter the vacuum container. The specimens were kept in NaOH solution for 18 h, and the chloride diffusion coefficients of the specimens were subsequently measured.

#### 2.2.5. Measurements of the chloride diffusion coefficient and electrical resistivity

The chloride diffusion coefficients of the prepared mortars and concretes specimens were measured according to Standard NT Build 492 [8]. The electrical resistivity of the prepared mortars were calculated by Eq. (1) according to Ohm's Law based on the initial voltage and initial current used during the RCM test.

$$\rho = R \times A/l \quad (1)$$

where  $\rho$  is the electrical resistivity of specimens (Ω·cm);  $R$  is the electrical resistance of specimens (Ω);  $A$  is the cross sectional area of specimens (cm<sup>2</sup>);  $l$  is the thickness of specimens (cm).

## 3. Results

### 3.1. Effect of SCMs on the electrical conductivity of pore solution

The influence of SCMs on the electrical conductivity of pore solution is shown in Fig. 1. When the SCMs content was less than 20%, the electrical conductivity of SCPS was only slightly reduced; however, when the SCMs content was greater than 20%, the electrical conductivity of SCPS dramatically decreased with the increase of SCMs content (Fig. 1a). Further, the influence of fly ash on the electrical conductivity of mortar was more pronounced, compared to furnace slag. For example, compared to the pore solution prepared with pure Portland cement, the electrical conductivity of pore solution prepared with 50% fly ash decreased about 35%, and the electrical conductivity of pore solution prepared with 50% GBFS decreased only about 23%. The influence of SCMs in binary system was also similar to that in multi system (Fig. 1b), the electrical conductivity of pore solution decreased with the

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