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Communication

An experimental study on the properties of resistance to diffusion of chloride ions of fly ash and blast furnace slag concrete

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Abstract

This paper uses the Nernst–Einstein equation to calculate the diffusion coefficient of chloride ions of high-performance concrete (HPC), analyzing and discussing the property of resistance to chloride ion of HPC with fly ash or blast furnace slag. The experimental results show that the diffusion coefficient of chloride ion increases with the rise of the water–binder ratio and decreases with the rise of quantity of fly ash or blast furnace slag. That is to say, the diffusion coefficient of chloride ions is not only related to the water–binder ratio but also to the quantity and the type of additive. Both the fly ash concrete and blast furnace slag concrete have good resistance to chloride ions. Their diffusion coefficients of chloride ions are lower than 10^{-9} cm^2/s.

Keywords: Fly ash; Granulated blast furnace slag; High-performance concrete; Corrosion; Diffusion coefficient of chloride ion

1. Introduction

The problem of corrosion of steel in concrete is very important. It not only results in the waste of material, but is also one of the main factors resulting in damage or deterioration of reinforced concrete structure [1]. As a result, engineers have been attached much importance to the problem of corrosion of steel in recent years. Generally, owing to the protective film of oxide on the surface of steel, the steel is relatively passive in the alkaline environment of concrete. When concrete is carbonated, or there are enough chloride ions at the surface of steel, the protective film may be damaged.

High-performance concrete (HPC) not only can have high strength but also can have good durability. It is one of the main reasons to use HPC to solve the problem of corrosion of steel. In this paper, the resistance to chloride ions of fly ash concrete and blast furnace slag concrete has been studied.

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2. Experiments

2.1. Materials

Cement: Yidong 525# Portland cement (see Tables 1 and 2).

Additive: The class F fly ash is produced in Neimenggu Province. Blast furnace slag is produced in Shougang. The physical and chemical properties of these additives are shown in Tables 1 and 2. The coarse aggregate is crushed stone, and its diameter ranges from 5 to 25 mm. The fine aggregate is river sand, and its fineness modulus is 2.7. The superplasticizer is FDN (naphthalin-type) made in the Chengdu City of China.

2.2. Experimental program

The experimental program includes two parts. In the first part, the quantity of additives was fixed and the water–binder ratio was changed to study how the diffusion coefficient of chloride ions changes with water–binder ratio and type of additive. In the second part, quantity of additive was changed to study how the diffusion coefficient of chloride ions changes with quantity of additive. The mix proportions are shown in Tables 3 and 4, respectively.

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Table 1
Chemical composition of cement and additives (%)

	CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	SO_3	MnO	P_2O_5	Fe_2O_3	TiO_2
Cement	62.48	24.36	5.40	2.44	0.33	0.92	0.14	/	/	3.63	0.21
Fly ash	3.87	57.57	21.91	1.68	1.54	2.51	0.41	/	0.16	9.56	0.91
Blast furnace slag	40.39	33.56	11.40	11.20	0.57	0.57	/	0.09	0.05	0.33	/

Table 2
Physical properties of cement and additives

	Cement	Fly ash	Blast furnace slag
Density (kg/m^3)	3110	2300	2910
Specific surface area (m^2/kg)	360	580	410

2.3. The measurement used to determine chloride ions diffusion coefficient

If concrete is taken as solid electrolyte, the diffusion coefficient of a charged particle i is related to its partial conductance, which is the so-called Nernst–Einstein equation [2]:

$$D_i = \frac{RT\sigma_i}{Z_i^2 F^2 C_i} \tag{1}$$

where D_i is the diffusion coefficient (cm^2/s), R is the gas constant (8.314 J/mol K), T is the absolute temperature (K), σ_i is the partial conductance of charged particle (S/cm), and C_i is the concentration (mol/cm^3).

If the partial conductance and concentration of particle i are known, the diffusion coefficient can be easily derived using Eq. (1), and the partial conductance of particle i is derived using Eq. (2):

$$\sigma_i = t_i \sigma \tag{2}$$

where σ is the conductance of concrete, t_i is the transference number of particle i, which is defined by Eq. (3),

$$t_i = \frac{Q_i}{Q} = \frac{I_i}{I} \tag{3}$$

where Q is the total charge in coulombs and I is the total current in amperes.

Here Eq. (1) is used to determine chloride ion diffusion coefficient. Provided the transference number of chloride ions is 1, C_i is the chloride ion concentration in the pore solution of concrete.

2.4. Experiments and results

By using the same measurement as used in the strength experiment, samples of size 100 × 100 × 300 cm were made, cured in water under standard curing room until 28 days. Then samples were taken out of water, and cut into thin slices of thickness 3 cm. The chloride diffusion coefficient was determined by Eqs. (1)–(3). The chloride ion diffusion coefficients of concrete with variable W/C and additives are shown in Tables 5 and 6. The chloride ion diffusion coefficient changing with W/C and quantity of additives is shown in Figs. 1–3.

2.5. Analysis of experimental results

From Table 5 and Fig. 1, it is can be seen that the chloride ion diffusion coefficient increases with the rise of W/C. From Table 6, Figs. 2 and 3, it is can be seen that the chloride ion diffusion coefficient decreases with an increasing quantity of fly ash or blast furnace slag. The extent of decrease in chloride ion diffusion coefficient of blast furnace slag concrete is bigger than that of fly ash concrete.

Table 3
Mix proportion of concrete (the first part)

No.	W/C	Cement (kg/m^3)	Additive (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Superplasticizer (%)	Notes
1–1	0.34	500	/	170	640	1150	1.0	control
1–2		400	100					fly ash
1–3		350	150					blast furnace slag
2–1	0.30	550	/	165	640	1120	1.5	control
2–2		440	110					fly ash
2–3		385	165					blast furnace slag
3–1	0.26	660	/	156	620	1100	1.8	control
3–2		480	120					fly ash
3–3		120	180					blast furnace slag

Table 4
Mix proportion of concrete (the second part)

No.	W/C	Cement (kg/m^3)	Additive (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Superplasticizer (%)	Notes
2–2–1	0.30	495	55	165	640	1120	1.5	fly ash
2–2–3		385	165					
2–2–4		330	220					
2–3–1		495	55					blast furnace slag
2–3–2		440	110					
2–3–4		330	220					
2–3–5		275	275					

Table 5
Relation between W/C and chloride ions diffusion coefficient (10^{-9} cm^2/s)

W/C	0.34	0.30	0.26
Concrete with pure Portland cement	5.362	2.618	2.441
Concrete with fly ash	3.137	2.272	2.179
Concrete with blast furnace slag	2.819	1.478	1.289

Table 6
Relation between chloride ions diffusion coefficient and variable quantity of additives (10^{-9} cm^2/s)

Quantity of additive (%)	10	20	30	40	50
Concrete with blast furnace slag	4.156	2.287	/	1.595	1.452
Concrete with fly ash	3.836	/	3.595	3.162	/

3. The mechanism of fly ash concrete and blast furnace slag concrete resist penetration of chloride ions

The reasons that fly ash and blast furnace slag can result in significant decrease in chloride ion diffusion coefficient are as follows.

(1) Fly ash and blast furnace slag may improve the distribution of pore size and pore shape of concrete.

(2) More C-S-H gel may be formed when fly ash and blast furnace slag concretes hydrate, which may adsorb more chloride ions and block diffusing path.

(3) The number of total ions of Ca^{2+}, Al^{3+}, $AlOH^{2+}$ and Si^{4+} in fly ash and blast furnace slag concrete is more than that in pure Portland cement concrete, and the ion concentration of fly ash and blast furnace slag concrete is higher than that of control concrete [4]. However, ions have lower diffusing ability and may restrict the movement of chloride ions.

(4) Fly ash and blast furnace slag have more C_3A which can adsorb more chloride ions to form Friedel's salt, that is $C_3A{\cdot}CaCl_2{\cdot}10H_2O$.

As to chloride ions diffusion coefficient increasing with an increase in W/C, the reason is apparent. The diffusing paths of chloride ion into concrete have three paths [3]: the interconnected pores in cement paste, the interconnected pores in aggregate, and the interconnected pores in the interfaces between paste and aggregate. When the permeability of aggregate is significantly lower than that of hydrated paste and the interface between aggregate and paste has no apparent deficiencies, the main diffusing path exists in the paste. Thus, the compactness and volume of paste is two main causes that affect diffusing velocity of chloride ions. When the degree of hydration is a fixed value,

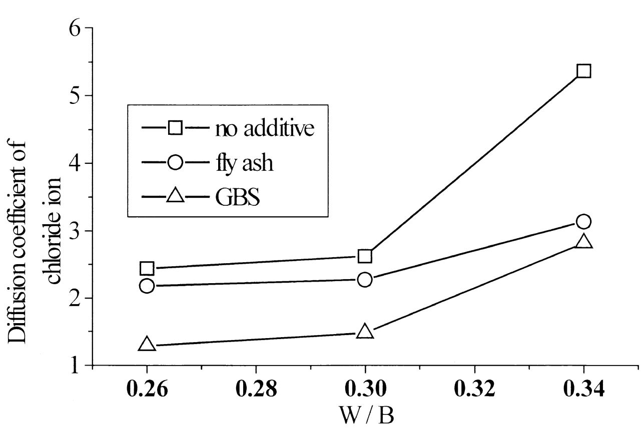

Fig. 1. Relation between chloride diffusion coefficient (10^{-9} cm^2/s) and W/C.

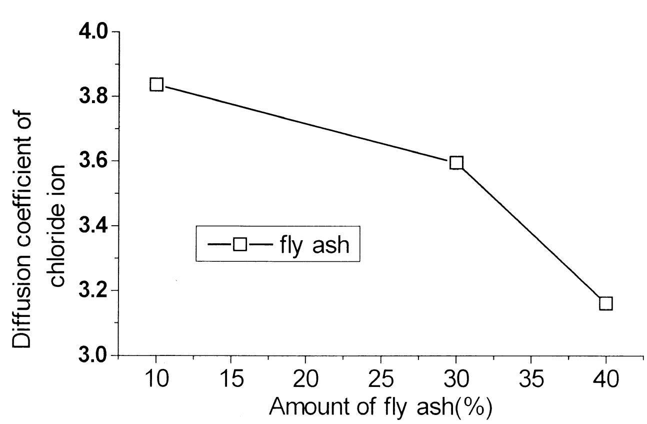

Fig. 2. Relation between chloride diffusion coefficient (10^{-9} cm^2/s) and quantity of fly ash.

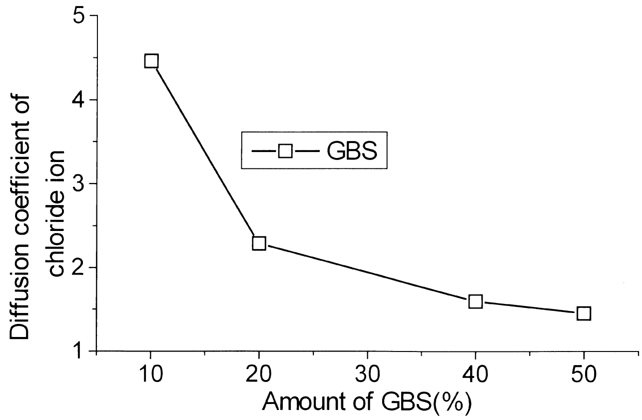

Fig. 3. Relation between chloride diffusion coefficient (10^{-9} cm^2/s) and quantity of blast furnace slag.

the volume of capillary pores is determined by W/C, which significantly affects the binding strength and interface condition between aggregate and paste. With an increase in W/C, more pores and diffusing paths may form, and the resistance to chloride ions decreases, so the chloride ion diffusion coefficient may increase.

4. Conclusions

1. The chloride ion diffusion coefficient may be determined quickly using the Nernst–Einstein equation.
2. The chloride ion diffusion coefficients of fly ash and blast furnace slag concretes may be as lower than 10^{-13} m^2/s.
3. The chloride ion diffusion coefficient of HPC increases with the rise of W/C.
4. The chloride ion diffusion coefficient of HPC may decrease with the rise of quantity of fly ash or blast furnace slag. Both fly ash concrete and blast furnace slag concrete have high resistance to diffusion of chloride ions.

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