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Research on Chloride Penetration Resistance of Hybrid Fiber Reinforced Self-Compacting Concrete

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ABSTRACT

The properties of chloride penetration of hybrid fiber reinforced self-compacting concrete (SCC) were investigated in this study. The results show that the chloride penetration resistance of concrete can be improved by single incorporation either carbon or cellulose fibers. The concrete chloride diffusion coefficient D_{RCM} of 12-cm length carbon SCC with fiber content of 1.7, 2.72, and 3.4 kg/m^3 decreases by 10.3, 25.5, and 18.2% compared to reference concrete without any fibers, respectively. Moreover, the concrete chloride diffusion coefficient D_{RCM} of cellulose SCC with fiber content of 1.2, 1.6, and 2.0 kg/m^3 decreases by 18.8, 22.4, and 26.7% compared to reference concrete, respectively. Based on the results of orthogonal experimental design, the chloride diffusion coefficients D_{RCM} of hybrid fiber reinforced SCC are listed in order of importance, as follows: length of carbon fiber > content of carbon fiber > content of cellulose fiber; furthermore, the hybrid of 2.72-kg/m^3 carbon fiber with length of 12 mm and 2.0-kg/m^3 cellulose fiber exhibits the most significant effect on chloride diffusion coefficients D_{RCM} of SCC.

Keywords: carbon fiber, cellulose fiber, hybrid fiber, self-compacting concrete, impermeability

1. INTRODUCTION

Resistance to chloride ion penetrability is an important index for measuring durability of concrete (Neville, 1996), so it is one of critical means for strengthening durability of concrete by increasing its impermeability. At present, related research has suggested that chloride ion migration and damage to concrete cover are major causes of reinforcement corrosion for reinforced concrete (Aïtcin, 1998; Neville, 1996). The corrosion of reinforcing bars and changes in corrosion current depend largely on the impermeability of the concrete and the cover thickness over the reinforcement.

Limited information is available regarding the influence of SCC on *in situ* corrosion performance (ACI Committee 237, 2004). The lack of static stability of plastic SCC can lead to bleeding and segregation, and weaken the quality of the interface between cement paste and embedded reinforcement with direct influence on corrosion resistance (Long, Khayat, Lemieux, Hwang, & Han, 2014). Densification of the cement matrix and increase in concrete cover in well-cured and uncracked concrete can reduce the risk of corrosion due to ingress of chloride ions.

Using different reinforcing fibers in concrete to make fiber reinforced concrete (FRC) is an effective method in preventing crack propagation and compensating shrinkage induced by low tensile strength (Barluenga & Hernández-Olivares, 2007; Cao, Zhang, & Lv, 2014; Farhad & Shami, 2013; Pająk & Ponikiewski, 2013; Sivakumar & Santhanam, 2007). The most important properties of fiber concrete are energy absorption, formability, and resistance against strikes. These characteristics help FRC to play an important role in concrete technology and to be a cost-effective material in structural issues (Alberti, Enfedaque, & Gálvez, 2014; Ardanuy, Claramunt, Dias, & Filho, 2015; Banthia, Majdzadeh, Wu, & Bindiganavile, 2014; Jiang, Fan, Wu, & Chen, 2014; Khayat & Roussel, 2000; Nehdi and Ladanchuk, 2004).

2. EXPERIMENTS

2.1 Raw materials

In this experiment, P.O. 42.5R ordinary Portland cement manufactured by China Resources Cement (Fengkai) Co., Ltd. was used. Its physical and chemical indices are shown in Table 1. Class II Fly ash was supplied by Guangzhou Zhujiang Cement Co., Ltd. Coarse aggregate was from Antuo Shan, Shenzhen, and continuously graded with a fineness module of 3.59. Made from sea sand of Shenzhen, fine aggregate was flushed by clear water and its fineness module equaled to 3.59. WS-PC set retarder and polycarboxylates high range water-reducing admixture (HRWRA) was produced by Shenzhen Wushan New Materials Co., Ltd.

Table 1. Performance index of Portland cement.

Specific surface area (m^3/kg)	Normal consistency (%)	Ignition loss (%)	Chloride ion (%)	Alkali content (%)
370	25.5	4.01	0.01	0.4
SO_3 (%)	**MgO (%)**	**Amount of admixture (%)**	**Content of gypsum (%)**	
2.21	1.54	10.1	5.5	

In this experiment, chopped carbon fiber with different length (including 6, 12, and 20 mm) manufactured by Nanjing Weida Composite Materials Co., Ltd, was used. Its physical and mechanical properties are shown in Table 2. Cellulose fiber was Duline UF500 cellulose from Beijing Ronel Engineering Materials Co., Ltd. Its physical and mechanical properties are shown in Table 3.

Table 2. Physical and mechanical properties of carbon fiber.

Filament diameter (μm)	Tensile strength (GPa)	Tensile modulus (GPa)	Carbon content (%)
15.0–20.0	3.6–3.8	240–280	≥95%
Extensibility (%)	**Density (g/cm^3)**	**Volume resistivity (ω·cm)**	
1.50%	1.6–1.76	1.5×10^{-3}	

Table 3. Physical and mechanical properties of cellulose fiber.

Filament diameter (μm)	Specific gravity (g/cm^3)	Fiber length (mm)
19.2	1.0–1.2	2.2
Tensile strength (MPa)	**Elasticity modulus (MPa)**	**Denier (g/900 m)**
751	9.2×10^3	2.5

2.2 Mix proportion

In this experiment, concrete was mixed with water at 212.8 kg/m^3, cement at 448 kg/m^3, fly ash at 448 kg/m^3, coarse aggregate at 870 kg/m^3, and fine aggregate at 712 kg/m^3. An experimental scheme was designed through an orthogonal experiment to investigate resistance of hybrid fiber reinforced SCC to chloride ion penetrability. Level and factors of the orthogonal experiment are shown in Table 4. Orthogonal level and factor design are shown in Table 5.

Table 4. Factors and levels of orthogonal test.

	Factors		
Levels	A (Carbon fiber length/ mm)	B (Carbon fiber content/ kg/m^3)	C (Cellulose fiber content/ kg/m^3)
1	6	1.7	0.60%
2	12	12	0.80%
3	20	1.70%	1.00%

Table 5. Orthogonal trial.

	Factors		
No.	A (Carbon fiber length/ mm)	B (Carbon fiber length/ kg/m^3)	C (Cellulose fiber content/ kg/m^3)
11	1 (6)	1 (1.7)	1 (1.2)
12	2 (12)	1	2 (1.6)
13	3 (20)	1	3 (2.0)
14	1	2 (2.72)	2
15	2	2	3
16	3	2	1
17	1	3 (3.4)	3
18	2	3	1
19	3	3	2

In this experiment, there were mainly 19 groups, among which the first group was the Control Group, the 2nd to 7th groups were mainly about single-doped carbon fiber for focusing on exploring length and doping amount of carbon fiber, the 8th to 10th groups were about single-doped cellulose fiber mainly for investigating doping amount of cellulose, the 11th to 19th groups were about orthogonal experimental design primarily for examining impacts of doping amount of cellulose fiber, length, and doping amount of carbon fiber on properties of hybrid fiber reinforced SCC. Experiment number and doping amount of fiber are shown in Table 6.

2.3 Experimental procedure

This experiment was performed according to Chinese Standard GB/T 50082 – 2009 “Standard for Test Methods of Long-term Performance and Durability of Ordinary Concrete.” The 100-mm high molds with a diameter of 50 mm were used. The specimens were demolded at 24 h and then submerged in a pond of a standard curing room. These specimens were processed 7 days ahead of the chloride ion penetration test. In this experiment, middle parts (50 ± 2 mm) of specimen were taken.

Table 6. Serial number and fiber content.

No.	Carbon fiber length (mm)	Carbon fiber length (kg/m³)	Cellulose fiber content (kg/m³)
1	–	–	–
2	6	1.7	–
3	6	2.72	–
4	6	3.4	–
5	12	1.7	–
6	12	2.72	–
7	12	3.4	–
8	–	–	1.2
9	–	–	1.6
10	–	–	2.0
11	6	1.7	1.2
12	6	2.72	1.6
13	6	3.4	2.0
14	12	1.7	1.6
15	12	2.72	2.0
16	12	3.4	1.2
17	20	1.7	2.0
18	20	2.72	1.2
19	20	3.4	1.6

Steady-state chloride ion migration coefficient of concrete was calculated as follows:

$$D_{RCM} = \frac{0.0239 \times (273+T)L}{(U-2)t}\left(X_d - 0.0238\sqrt{\frac{((273+T)L)X_d}{U-2}}\right)$$

where D_{RCM} was steady-state chloride ion migration coefficient and accurate to 0.1×10^{-12} m²/s;

V was absolute value of voltage (V);

T was mean of initial and final temperature of anode solution (°C);

L was thickness of specimens and accurate to 0.1 mm;

X_d was mean penetration depth of chloride ions (mm) and accurate to 0.1 mm;

t was duration of the experiment (h).

In each group, arithmetic mean of chloride ion migration coefficient of three specimens was considered as migration coefficient of that group of chloride ions.

Water tank used in the experiment on chloride ion penetrability experiment is shown in Figure 2.

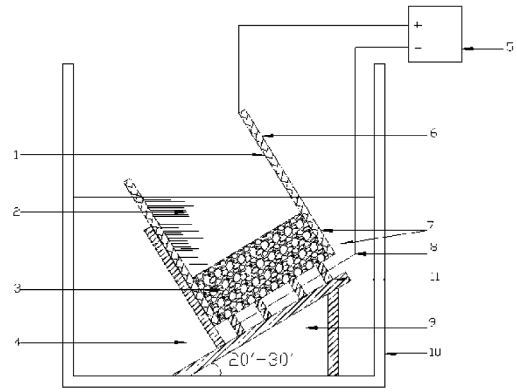

Figure 1. Test setup of RCM. 1 – anode plate; 2 – anode solution; 3 – specimens; 4 – cathode solution; 5 – stable DC power source; 6 – organic silicon rubber bushing; 7 – hoop; 8 – cathode plate; 9 – bracket; 10 – test pit; and 11 – end support.

Figure 2. Tank of RCM equipment.

Figure 3. Chloride ion penetration depth of RCM test.

Chloride ion migration depth of RCM experiment is shown in Figure 3.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In this range of experiments, D_{RCM} (chloride ion migration coefficient) is shown in Table 7.

Table 7. Chloride ion penetration coefficient D_{RCM}.

Experiment group	1	2	3	4	5	6	7
D_{RCM} (×10–12 m²/s)	16.5	15.3	13.9	14.7	14.8	12.3	13.5
Experiment group		**8**	**9**	**10**	**11**	**12**	**13**
D_{RCM} (×10–12 m²/s)		13.4	12.8	12.1	12.5	13.1	11.7
Experiment group		**14**	**15**	**16**	**17**	**18**	**19**
D_{RCM} (×10–12 m²/s)		11.4	12.8	12.3	12.7	11.5	11.6

3.1 Impacts of carbon fiber on penetrability

Impacts of carbon fiber with different lengths (6 and 12 mm) and doping amount (1.7, 2.72, and 3.4 kg/m³) on D_{RCM} of SCC chloride ion are shown in Figure 4.

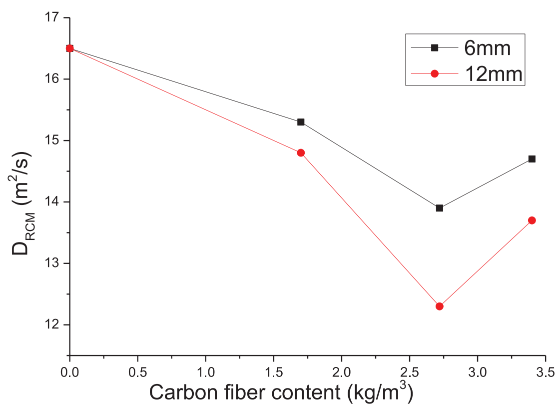

Figure 4. The impact of carbon fiber length and content on D_{RCM}.

From Figure 4, it may be known that D_{RCM} decreases with the increase in doping amount of chloride ions ranging from 0 to 2.74 kg/m³ for carbon fiber of two different lengths (namely, 6 and 12 mm), whereas resistance of concrete to chloride ion penetrability increases. As the fiber is doped at a volume above 2.74 kg/m³, D_{RCM} increases with the increase of doping amount, but the resistance of concrete to chloride ion is weakened.

As shown in Figure 4, impacts of carbon fiber on D_{RCM} of SCC differ in case of different lengths. As such fibers of two different lengths were doped with 1.7, 2.72, and 3.4 kg/m³, the coefficient declined by 7.27, 15.76, and 10.91%, respectively, for 6-mm carbon fiber, but fell by 10.30, 25.45, and 18.18%, respectively, for 12-mm long carbon fiber. From the figure, it may be known that when in case of the same doping amount, 12-mm long carbon fiber has weaker impacts on D_{RCM} of concrete than 6-mm long carbon fiber.

3.2 Impacts of cellulose fiber on penetrability

Impacts of doping amount of cellulose fiber on D_{RCM} of SCC are shown in Figure 5.

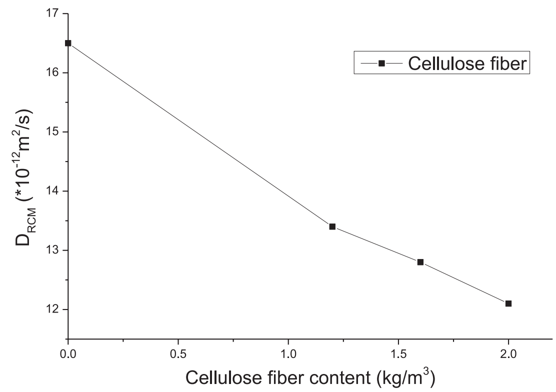

Figure 5. The impact of cellulose fiber content on D_{RCM}.

It may be found from Figure 5 that cellulose fiber imposes different impacts on D_{RCM} when it is applied at 1.2, 1.6, and 2.0 kg/m³, respectively. Compared with reference concrete, the coefficient of concrete doped with cellulose fiber decreased by 18.79, 22.42, and 26.67%, respectively. It may be seen from Figure 5 that D_{RCM} declined with the increase in doping amount of cellulose fiber within a volume from 0 to 2.0 kg/m³.

3.3 Orthogonal experimental results and analysis

Impacts of length of carbon fiber, and doping amount of carbon fiber and cellulose fiber on D_{RCM} of concrete were mainly examined. Table 8 shows results about the D_{RCM} and the intuitive analysis.

Table 8. Test results and analysis of D_{RCM}.

No.	Carbon fiber length (mm)	Carbon fiber content (kg/m³)	Cellulose fiber content (kg/m³)	D_{RCM} (×10–12 m²/s)
11	6	1.7	1.2	12.5
12	6	2.72	1.6	13.1
13	6	3.4	2	11.7
14	12	1.7	1.6	11.4
15	12	2.72	2	10.8
16	12	3.4	1.2	12.3
17	20	1.7	2	12.7
18	20	2.72	1.2	11.5
19	20	3.4	1.6	11.6
K1	37.3	36.6	36.3	
K2	34.5	35.4	36.1	
K3	35.8	35.6	35.2	
k1	12.43	12.20	12.10	
k2	11.50	11.80	12.03	
k3	11.93	11.87	11.73	
Range	0.93	0.40	0.37	
Order	A>B>C			
Optimization levels	A_2	B_2	C_3	
Optimal combination	$A_2B_2C_3$			

According to intuitive analysis of Table 8, length of carbon fiber had the most significant impacts on D_{RCM} of hybrid fiber reinforced SCC when the concrete was doped with 6, 12, and 20-mm long carbon fiber at 1.70, 2.72, and 3.40 kg/m^3 and cellulose fiber at 1.20, 1.60, and 2.00 kg/m^3, respectively, followed by doping amount of carbon fiber and cellulose fiber successively. In case of only considering impermeability of concrete, it is best to dope the concrete with 12-mm long carbon fiber at 2.72 kg/m^3 and cellulose fiber at 2.0 kg/m^3. Under this situation, hybrid fiber has the most significant impacts on D_{RCM} of concrete.

4. ANALYSIS ON MECHANISM OF FIBER

Cellulose fiber is highly dispersive, so it is effective for cellulose fiber to effectively scatter in cement-based materials to form an effective support system by doping SCC with the fiber. The fiber may not only reduce undesirable phenomena such as water extraction and aggregate separation but also effectively reduce bleeding and strengthen cohesiveness of SCC. Therefore, it does not only decrease internal bleeding passage of concrete but also reduces its connected pore channel. Microscopically, it decreases porosity and enhances compactness of concrete, thereby greatly increasing impermeability of the concrete.

It is effective for obstructing connected pores by doping the concrete with carbon fiber and cellulose fiber to transform originally connected pores into closed holes. However, current pertinent research has suggested that apart from internal porosity of concrete, its internal connected pores also have close associations with chloride ion migration. Thus, it is not only effective for controlling migration of chloride ions inside fiber reinforced SCC but also favorable for decreasing its migration coefficient, finally strengthening its impermeability.

The acting mechanism of doping SCC is the same for enhancing resistance to chloride ion penetrability and early crack resistance, because it is effective to generate crack-resistant effect and thus inhibit formation of early plastic cracks by doping concrete with fiber. According to theories of composite materials, early crack resistance of SCC is strengthened when it is doped with fiber which may bear stress. As fiber is resistant to crack, hardened SCC will have higher crack resistance. As a result, cracks will be effectively inhibited and formation of penetrating cracks may be reduced.

5. CONCLUSION

(1) Carbon fiber has different impacts on D_{RCM} of SCC in case of different lengths. When the doping amount is the same, the coefficient is lower for 12-mm carbon fiber than that for 6-mm carbon fiber, and the impermeability of concrete is better for 12-mm carbon fiber than 6-mm long carbon fiber.

(2) Carbon fiber affects D_{RCM} of concrete differently when the doping amount differs. When concrete is doped with 6 and 12-mm carbon fiber at a volume ranging from 0 to 2.74 kg/m^3, D_{RCM} of concrete will decline with the increase in doping amount, whereas the resistance to chloride ion penetrability is strengthened. As the concrete was doped with carbon fiber at a volume higher than 2.74 kg/m^3, D_{RCM} will rise with the increase in doping amount and the resistance to chloride ion penetrability will be weakened.

(3) As the concrete was doped with cellulose fiber at 1.2, 1.6, and 2.0 kg/m^3, the D_{RCM} will decline by 18.79, 22.42, and 26.67%, respectively.

(4) According to analytical results of orthogonal experiments, D_{RCM} of hybrid fiber reinforced SCC is influenced by length of carbon fiber to the largest extent, followed by doping amount of carbon fiber and cellulose fiber, respectively.

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