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Chloride ion penetration resistance of concrete containing fly ash and silica fume against combined freezing-thawing and chloride attack

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HIGHLIGHTS

- Chloride ion penetration resistance (CPR) of concrete with FA/SF was investigated.
- Effects of FA and SF replacement level on CPR of concrete were studied.
- Effects of sodium chloride solution immersion on CPR of concrete were analyzed.
- Combining freezing-thawing and chloride attack accelerated deterioration of concrete.

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ABSTRACT

Chloride ion penetration resistance (CPR) of concrete containing fly ash (FA)/silica fume (SF) against combined freezing-thawing and chloride attack was studied. The total charge passed, immersed in tap water and sodium chloride solution, subjected to 50 freezing-thawing cycles was evaluated. It was found that immersed in tap water, SF had more evident improvement on concrete's resistance to combined effects than FA. Sodium chloride solution immersion for 41d prior to test was more aggressive than tap water. After 50 freezing-thawing cycles, CPR of concrete with FA increased, while that with SF decreased. Interaction between freezing-thawing and chloride attack accelerated concrete deterioration.

1. Introduction

Concrete is versatile and the most widely used construction material in the world. But owning to aggressive marine exposure environment and the extensive use of de-icing salts in many countries, chloride induced corrosion becomes one of the most common causes of degradation of reinforced concrete structures [1–4]. The first effect of chloride ions is physical salt attack leading to surface cracking and scaling which is similar in appearance to freezing-and-thawing damage and total disintegration of low-quality concrete [5]. Another effect is that chloride ions are the most important cause of corrosion of embedded rebar. When chloride ions penetrate concrete cover and arrive at reinforcement bars, as their amount accumulates, the passive film may break down (i.e. de-passivation) and corrosion of embedded rebar can then initiate [6,7]. The accumulation of corrosion products can build up the swelling pressure around the rebar resulting in cracking or spalling of concrete [8], which in turn facilitates the ingress of moisture, oxygen, and chlorides to the rebar and accelerates rebar corrosion

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[9]. Pitting corrosion is another threat to RC structures in a chloride environment [10] and is a type of more serious corrosion on structural safety than general corrosion [11,12], since it has resulted in quite high loss of cross-sectional area of reinforcement bars [13] and structural damages [14], or in extreme situations, the final collapse of the structure.

Chloride penetration in concrete can be characterized by the chloride diffusion coefficient and the binding ability of matrix-forming solids [15]. In concrete, chlorides can be chemically bound with cement's C3A or C4AF phases (e.g., Friedel's salt) [16], or physically hold to the surface of hydration products (e.g., adsorption on C-S-H) [3,17]. Chloride diffusion depends on pure diffusion for water-saturated concrete and capillary absorption of salty water for non-saturated concrete [18].

Recently, there are several studies reported in literature on the transport of chloride ions in concrete and numerical models developed to simulate the process [7,19–22]. Meanwhile, chloride penetration into concrete is governed by many factors. Due to the chemical and physical bond between chloride ion and hydrated product of cement changing the micro-structure, the chloride diffusion coefficient changes during the exposure period and decreases with an increased period of exposure [23–26]. Nobuaki [27] and Page [28] both studied chloride ions diffusion in concrete at different temperatures and the results reveal that the rates of diffusion of Cl^- in concrete rises with increases in temperature. In real environments, concrete structures are subjected to various environmental factors acting in a combined and possibly synergistically physical and chemical manner to accelerate the destruction process. Therefore, it is significant to study chloride resistance of concrete under combined deteriorating factors to obtain sufficient information on concrete durability. Chloride penetration and carbonation of concrete are often considered to be the most significant coupled deterioration factors and numerous studies have taken both factors into account in assessing concrete durability [29–35]. As reported by Chindaprasirt [29], Tumidajski [31] and Houst [36], carbonation decreases chloride penetration and diffusivity in ordinary Portland cement (OPC) mortar and concrete. While other test results [30,34,35] indicate that chloride penetration is accelerated when the carbonation process is combined with the chloride ingress due to liberate bound chloride. The carbonation effect on chloride penetration is controversial and considered to depend on the types and mix proportions of concretes [29,33,35]. Initial cracks in concrete significantly influence chloride penetration and the influence of crack width and depth has been experimentally and numerically studied. It is clear that chloride transport is very rapid along and across crack boundaries [37]. Concrete specimens are made with artificial cracks by means of the positioning and removal after approximately 4 h of thin copper sheets inside the specimen [38]. These copper sheets have a thickness of 0.2 mm, 0.3 mm or 0.5 mm. The copper sheets are placed at a depth in the concrete specimen of 5 mm, 10 mm, 15 mm or 20 mm. The test results also indicate that the penetration depth increases with an increasing notch depth and that the influence of notch depth is more pronounced for longer test duration while the influence of notch width is not clear [38,39]. The chloride permeability of a concrete is influenced significantly by loading style and critical stress [40–43]. The application of static loading up to 90% of the ultimate strength had little effect on chloride permeability while load repetitions at the maximum stress levels of 60% or more caused chloride permeability to increase significantly [41].

In addition, drying and wetting cycles are always identified as the most unfavorable environment condition for reinforced concrete structure subjected to chloride-induced deterioration processes and it accelerates the ingress of chloride ions and affects concrete durability [44,45].

Investigations on chloride penetration resistance of concrete have also been conducted in concrete science and engineering community, but studies on the effects of chloride ion on deterioration of concrete with FA and SF under combined freezing-thawing and chloride attack is very limited in literature. Rapid chloride permeability test (RCPT) is the most widely specified durability test method and is standardized by ASTM. The total charge passed (in Coulombs), the result of RCPT, provides a rapid indication of its resistance to the penetration of chloride ions and is calculated via Eq. (1). In this research, concrete's total charge passed, immersed in tap water and sodium chloride solutions, subjected to 50 freezing-thawing cycles was evaluated. The influence of FA and SF replacement level of OPC and sodium chloride concentration on durability of concrete under the combined freezing-thawing and chloride attack was also investigated.

2. Experimental program

2.1. Materials

42.5 R Portland cement, manufactured by Saima Cement Manufacturing Company of Ningxia, China conforming to EN197-1:2009, was used for preparing concrete in this research and its physical and mechanical properties are listed in Table 1. Table 2 presents the chemical composition of the cement, FA and SF used in this study as partial replacement of OPC. Crushed limestone aggregates were used as coarse aggregates and washed mountain sand as fine aggregates, and the sieving curves are presented in Fig. 1. The fineness modulus of fine aggregates was evaluated conforming to

Table 1
Physical and mechanical properties of OPC used for this research.

	80 μm sieving residue (%)	Water requirement of normal consistency (%)	Initial setting time (min)	Final setting time (min)	Compressive strength (MPa)		Flexural strength (MPa)		Soundness
					3 days	28 days	3 days	28 days	
Experimental result	1.60	27.3	90	135	26.0	45.9	6.0	8.3	qualified

Table 2
Chemical compositions of Portland cement, fly ash (FA) and silica fume (SF).

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	$Na_2O + K_2O$
Cement weight percent (%)	22.04	5.77	3.36	66.43	0.45	0.00	0.51
FA weight percent (%)	31.93	8.98	5.2	43.87	2.14	0.2	1.95
SF weight percent (%)	97.2	0.26	0.45	0.17	–	–	–