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Chloride penetration resistance and frost resistance of fiber reinforced expansive self-consolidating concrete

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HIGHLIGHTS

- Chloride penetration and frost resistance of fiber reinforced ESCC were studied.
- Increasing fiber factor enhances chloride penetration resistance along the depth.
- The RDME of fiber reinforced ESCC decreases with the increasing fiber content.
- Increase of fiber content decreases the speed of mass change of the specimens.

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ABSTRACT

The objective of this paper is to investigate the chloride penetration resistance and frost resistance of fiber reinforced expansive self-consolidating concrete (ESCC). Fibers and expansive agent were used to decrease shrinkage, control cracks and enhance microstructure of the concrete. Steel fibers with three volume fractions (0.25%, 0.50% and 0.75%) of the total volume of concrete and monofilament polypropylene fibers with two volume fractions (0.05%, 0.10%) were used in the test. This study established levels of chloride penetration of fiber reinforced ESCC. The frost resistance was determined by rapid freezing and thawing test. Results indicated that PP shows more sensitivity on slump flow than SF but less impact on $T_{500.}$ Chloride content increased with the incorporation and increase of fibers at depths less than 17.5 mm. However, chloride penetration resistance along the depth was enhanced with increasing fiber factor. SF0.50PP0.05 exhibits the best chloride penetration resistance, and SF with a volume fraction of 0.50% and PP with a volume fraction of 0.05% show mutual beneficial effect on the chloride penetration resistance of ESCC. The relative dynamic modulus of elasticity (RDME) of ESCC in the presence of fibers decreased slightly when compared with ESCC in the absence of fibers, and decreased with the increasing fiber factor. It also shows that the increase of fiber content decreased the speed of surface spalling of the specimens as well as the mass change.

1. Introduction

Good workability, improved construction practice and performance, combined with the health and safety benefits, make self-consolidating concrete (SCC) a widely used construction material solution for civil engineering [1–4]. With low water to cement ratio, large dosage of cementitious material, high sand ratio and relatively small particle size of the coarse aggregate, SCC is subjected to significant autogenous shrinkage and plastic shrinkage. When the shrinkage is restrained, it will result in tensile stress in concrete, and crack will form if the tensile stress exceeds the tensile strength of concrete [4]. Water, chloride ion, acid, etc., hazardous substances can ingress into concrete easily, resulting in the deterioration of strength and durability of concrete. The addition of combination of fibers and expansive agent is an effective solution to this problem [5,6]. It was documented by Ding et al. [3] and Khayat et al. [7] that, to meet the requirement of workability of SCC, the fiber volume of steel fiber (SF) should not exceed 0.75%. Expansive agent can compensate the shrinkage of concrete [8]. In Li et al.'s study [4], it was found that early age shrinkage can be inhibited by fibers especially hybrid fibers under restrained conditions, and the expansion of expansive agent also can be restricted by fibers, which reduces or even prevents the formation of micro-cracks [9]. The cause of the enhanced properties of concrete containing expansive agent and fibers is the improvement of the

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pore structure, including the refinement of pores, the improvement of pore size and morphology and the decrease of porosity [10]. The permeability performance [6,9] and early age volume stability of concrete [8,11] are significantly enhanced with the addition of combination of fibers and expansive agent. Moreover, it was reported that the hybrid fibers of different types and sizes could reduce the size and amount of crack source at different scales. In the same time, the combination of hybrid fibers and expansive agent presents great enhancement for shrinkage resistance and permeability resistance of concrete [5].

Fiber addition may alter porosity and permeability of concrete. Two main viewpoints were reported in the literature. Some researchers [12–17] indicated that porosity and permeability increased with the incorporation of fibers. It was reported [12] that entrapped air content varies with the fiber type. Fiber reinforced concrete shows higher air content values compared to concretes without fiber, furthermore, polypropylene fiber (PP) reinforced concrete has the higher air content than SF reinforced concrete. It was also found that glass fiber reinforced concrete has significantly higher chloride penetration rate [12]. Karahan et al. [13] indicated that porosity increased with fiber contents. The inclusion of PP increases the volume of large capillary pores, but it does not show significant difference on total porosity, which in turn increases the permeability of the concrete [14,15]. Toutanji [16] studied the rapid chloride permeability of polypropylene fiber reinforced silica fume expansive-cement concrete and found that the addition of PP increased the permeability of concrete because fibers increased the void content. Toutanji et al. [17] found that the increase of permeability of concrete by adding PP fiber and expansive agent was due to lack of cohesiveness of the cement matrix and poor dispersion of fibers. However, other research [18–21] results indicate that fibers may decrease porosity and permeability. In Frazão et al.'s study [18], it was stated that natural immersion test in salt solution is more feasible to determine the diffusion coefficient for a steel fiber reinforced concrete than the chloride migration test under non-steady state, and the presence of SF causes the delayed setting of chloride ions on the fibers or even prevents the penetration of ions into the matrix. Abbas et al. [19] attributed the increase in chloride penetration resistance of steel fiber reinforced concrete to the lower total porosity than that of conventional reinforced concrete. It was reported by Abbas et al. [20] that steel fiber dosage rather than the fiber length presents a significant effect on the decreased permeability because SF restricts the formation and growth of the plastic and drying shrinkage cracks. In Rapport et al.'s [21] study, at crack width larger than 100 um, steel reinforcing macro-fibers can reduce the permeability of cracked concrete due to crack stitching by the SFs. Some results [22,23] indicated that the chloride penetration resistance increases and then decreases along with the increase of the fiber amount. The combination of SF and MgO-type expansive agent may decrease porosity of concrete [24], and the combination of hybrid fibers and expansive agent can enhance the permeability of concrete significantly [25].

However, very limited data is available in the literature on the frost resistance performance of fiber reinforced expansive concrete. It was demonstrated by Karahan et al. [13] that PP fiber reinforced concrete shows slight increase on frost resistance of concrete. In Yu et al.'s [26] study, it was found that the addition of aluminate expansive agent impairs the frost resistance when expansive agent accounts for 10% of the mass of the cementitious materials, however steel fiber can improve the frost resistance. Steel fiber may compensate the impairment of expansive agent to some extent when the SF and expansive agent are combined.

Nevertheless, the study of SCC containing both fibers and expansive agent in the cement matrix has been quite limited so far, especially on the frost resistance. The aim of this research is to study the effect of the combination of fibers (hybrid PP fibers and steel fibers) and expansive agent on chloride penetration resistance and the frost resistance of SCC. Tests were constructed containing the variety percentage of SFs and PP fibers. Workability test was conducted to guarantee the requirements of SCC. Chloride penetration test with wetting and drying cycles and the rapid freezing and thawing test were performed to evaluate the effects of the combination of fibers and expansive agent on durability of SCC.

2. Experimental program

2.1. Materials

Cement used in this study was ordinary Portland cement 42.5R which conforms to Chinese standard GB175-2007. Type I fly ash (FA) with density of 2.3 g/cm^3 was used as mineral additive. Properties of cement and fly ash are shown in Tables 1 and 2. Calcium sulphoaluminate hydrate-calcium hydroxide expansive agent (EA) for concrete was used, and the mass fraction of expansive agent was 8% for cementitious materials. The washed coarse aggregate was crushed limestone with density of 2.7 g/cm^3 and a 16 mm nominal maximum size. Natural river sand with fineness modulus of 2.72 was used as fine aggregate. Sieve results of the coarse aggregate and the fine aggregate are shown in Tables 3 and 4 respectively. Glycolic acid-based white powder superplasticizer (HRWRA) was used. SF was glued in bundles with hooked ends and was separated before dosed in the concrete mixture and PP is monofilament fiber. Both fibers were distributed in the concrete mixture uniformly. General properties of the fibers are given in Table 5, and the shapes are shown in Fig. 1.

2.2. Concrete mixes

The expansive self-consolidating concrete (ESCC) with strength grade of C40 was used in the study to investigate the effect of incorporating various volume fractions of steel fibers and hybrid fibers on the resistance against chloride ion penetration and frost resistance. The detailed mix design of fiber reinforced expansive concrete is shown in Table 6. The water binder ratio was 0.35 and the sand percentage was 50.8%, respectively. Expansive agent at dosage of 8% by cementitious material mass was used. Six mix designs were performed including the following: One plain concrete (ESCC8); three steel fiber reinforced concrete named as SF0.25, 0.50, 0.75 with volume fraction of 0.25%, 0.50% and 0.75%; and two hybrid fiber mixtures named as SF0.25PP0.10 and SF0.50PP0.05. The detailed fiber content information is also shown in Table 6.

2.3. Experimental procedure

According to the JGJ/T 283[27] and CECS 203-2006[28] standards, the slump flow test was performed to assess the flowability and filling ability characteristics, and T_{500} test was performed to

Table 1
Chemical composition and properties of P.O 42.5R cement.

Composition:% (mass)		80 um screen residue (%)	0.9
CaO	66.9	Initial setting time (h-min)	2–30
SiO_2	16.8	Final setting time (h-min)	3–35
Al_2O_3	4.3	MgO (%)	1.78
Fe_2O_3	4.19	SO_3 (%)	2.52
SO_3	3.88	Loss on ignition (%)	3.52
MgO	1.77	Alkali ($Na_2O + 0.658K_2O$) (%)	0.7