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Workability and Freeze-thawing Performance of Fiber Reinforced Expansive Self-consolidating Concrete

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ABSTRACT

The aim of this study is to investigate the workability and freeze-thawing performance 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%, 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. The freeze-thawing performance was determined by rapid freezing and thawing test. Results indicated that polypropylene fiber shows more sensitivity on slump flow than steel fiber but less impact on T_{500}. 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. No direct relationship was found between slump flow and surface scaling of tested concrete mixtures.

Keywords: fibers; expansive agent; self-consolidating concrete; workability; freeze-thawing performance.

1.0 INTRODUCTION

Good performance of workability, improved construction practice, combined with the health and safety benefits, make self-consolidating concrete (SCC) a widely used construction material solution for civil engineering (EFNARC, 2002; EFNARC 2005; Ding *et al*., 2014; Li *et al*., 2014). 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 (Li *et al*., 2014). 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 (Sun *et al*., 2001; Sun *et al*., 1994). It was documented by Ding *et al*. (Ding *et al*., 2014) and Khayat *et al*. (Khayat *et al*., 2014) 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 (Corinaldesi *et al*., 2015).In Li *et al*.'s study (Li *et al*., 2014), 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 (Sun *et al*., 2004). The cause of the enhanced properties of concrete containing expansive agent and fibers is the improvement of the pore structure, including the refinement of pores, the improvement of pore size and morphology and the decrease of porosity (Qian *et al*., 1996).The permeability performance (Sun *et al*., 1994; Sun *et al*., 2004) and early age volume stability of concrete (Corinaldesi *et al*., 2015) are significantly enhanced with the addition of combination of fibers and expansive agent. Moreover, it was reported that the combination of hybrid fibers and expansive agent presents great enhancement for shrinkage resistance and permeability resistance of concrete (Sun *et al*., 2001).

However, very limited data is available in the literature on the freeze-thawing performance of fiber reinforced expansive concrete. It was demonstrated by Karahan *et al*. (Karahan *et al*., 2011) that PP fiber reinforced concrete shows slight increase on freeze-thawing performance of concrete. In Yu *et al*.'s (Yu *et al*., 2006) 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 freeze-thawing performance. 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 the freeze-thawing performance of SCC. Tests were constructed containing the variety percentage of SFs and PP fibers. Workability test was conducted to guarantee the requirements of SCC. The rapid freezing and thawing test was performed to evaluate the effects of the combination of fibers and expansive agent on durability of SCC.

2.0 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 2300kg/m^3 was used as mineral additive. Properties of cement and fly ash are shown in Table 1 and Table 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 2700 kg/m^3 and a 16 mm nominal maximum size. Natural river sand with fineness modulus of 2.72 was used as fine aggregate. 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 fiber were distributed in the concrete mixture uniformly. General properties of the fibers are given in Table 3, 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 freeze-thawing performance. The detailed mix design of fiber reinforced expansive concrete is shown in Table 4. 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

Table 1. Properties of P.O 42.5R cement

80 um screen residue (%)	Initial setting time (h-min)	Final setting time (h-min)	MgO (%)	SO_3 (%)	Loss on ignition (%)	Alkali (Na_2O+0.658K_2O) (%)
0.9	2-30	3-35	1.78	2.52	3.52	0.7

Table 2. Properties of fly ash

45 um square hole sieve residual (%)	Water demand ratio (%)	Loss on ignition (%)	Water content (%)	SO_3 (%)
8.9	84	4.8	0.3	1

Table 3. General properties of fibers

Type	Shape	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Modulus of elasticity (GPa)	Density (kg.m^{-3})
SF	Hooked	35	0.55	64	＞1150	200	7850
PP	Straight	19	0.07	271	568	4.35	910

Table 4. Variation of mix design

Mix No.	Fiber factor V_fL_f/d_f	Material dosage (kg/m^3)								
		SF	PP	Cement	FA	EA	Fine aggregate	Coarse aggregate	Water	HRWRA
ESCC8	0	0	0	366	157	45	795	770	200	1.84
SF0.25	0.16	19.63	0	366	157	45	795	770	200	1.84
SF0.50	0.32	39.25	0	366	157	45	795	770	200	1.86
SF0.75	0.48	58.88	0	366	157	45	795	770	200	2.00
SF0.25PP0.10	0.43	19.63	0.910	366	157	45	795	770	200	1.85
SF0.50PP0.05	0.46	39.25	0.455	366	157	45	795	770	200	1.86

SF0.25PP0.10 and SF0.50PP0.05. The detailed fiber content information is also shown in Table 4.

(a) Steel fiber

(b) Polypropylene fiber

Fig. 1. Shape of Fibers

3.0 EXPERIMENTAL PROCEDURE

According to the JGJ/T 283 (JGJ/T 283, 2012) and CECS 203-2006 (CECS, 2006) standards, the slump flow test was performed to assess the flowability and filling ability characteristics, and T_{500} time was measured to evaluate the viscosity and segregation resistance of the fresh concrete, the term T_{500} is defined as the time it takes for the outer edge of the concrete mass to reach a diameter of 500 mm from the time the mold is first raised. Combined with the CECS 203-2006 (CECS, 2006), EFNARC 2002 (EFNARC, 2002), EFNARC 2005 (EPG, 2005), BS EN 206:2013 (BSI, 2013), ACI 237R 07 (ACI, 2007) standards, the fresh properties criteria of SCC were set as follow: the slump flow is in 550 mm-850 mm, and T_{500} is between 2 s-20 s.

The rapid freezing and thawing test was performed in accordance with GB/T 50082-2009 (GB/T 50082, 2009). The specimens for use in this test method were prisms with size of 100 mm ×100 mm ×400 mm. Specimens were cured in water for another 4 days after 24 days of standard curing. Then specimens aged 28 days were used for freezing and thawing test. Within each cycle the temperature of these specimens was lowered from 5 to -18 ℃ and then raised to 5 ℃ in approximately 4 hours. Determine the mass and fundamental transverse frequency of each specimen at intervals of 25 cycles. Figure 2 shows the testing of fundamental transverse frequency. Relative dynamic modulus of elasticity (RDME) is calculated as follows:

Fig. 2. Fundamental transverse frequency test

$P_i = \frac{f_{\mathrm{ni}}^2}{f_{0\mathrm{i}}^2} \times 100$, where P_{i} = relative modulus of elasticity after n cycles of freezing and thawing (%),
f_{ni}^2 = fundamental transverse frequency after n cycles of freezing and thawing (Hz),
$f_{0\mathrm{i}}^2$ = fundamental transverse frequency at 0 cycles of freezing and thawing (Hz).

4.0 RESULTS AND DISCUSSION

4.1 Fresh Concrete Properties

The results of slump flow and T_{500} in fresh state are presented in Table 5 and Figs. 3-5. It was observed that the slump flow of fresh concrete was within the standard allowances 550 mm-850 mm, and viscosity classes of the ESCC were VS1 with all the T_{500} time greater than 2 s in accordance with JGJ/T 283-2012 (JGJ/T 283, 2012). Figure 3 shows a reduction of about 10 mm-40 mm of slump flow with every 0.25% volume fraction increase of SF. It also shows that T_{500} increases from 6.5 s to 16.8 s with the increase of steel fiber content. It indicated that the increase of single SF content decreases the workability of ESCC. As for hybrid fiber concrete, with fiber factors of 0.43, 0.46 and 0.48, the slump flow of SF0.25PP0.10, SF0.50PP0.05 and SF0.75 were 625 mm, 635 mm and 700 mm respectively. As shown in Fig. 4, when both SF and PP were mixed together, the slump flow was 65 mm and 75 mm lower than that of single SF reinforced concrete. And the reduction of slump flow increased with PP content. This is consistent with previous experiments. But the T_{500} of both hybrid fiber reinforced ESCC was almost 2-3 s less than that of SF0.75.

Table 5. Workability of fresh concrete

Mix No.	ESCC8	SF 0.25	SF 0.50	SF 0.75	SF0.25 PP0.10	SF0.50 PP0.05
Slump flow (mm)	780	740	730	700	625	635
T_{500} (s)	6.5	8	10.2	16.8	15.1	13.8

The slump flow decreases with increase in fiber factor regardless of the effect of fiber type, this conclusion is consistent with the study of Khayat (Khayat *et al.*, 2014). A distinction is observed between the workability of fiber reinforced ESCC reinforced with single SFs and that with hybrid fibers. It can be derived from Fig. 5(a) that, the PP fiber volume fraction of SF0.25PP0.10 is 0.10% than that of SF0.25, and the SF fiber volume fraction of SF0.75 is 0.50% than that of SF0.25. The fiber factor of 0.10% PP is 0.05 less than 0.50% SF. But 115 mm reduction of slump flow in SF0.25PP0.10 was observed

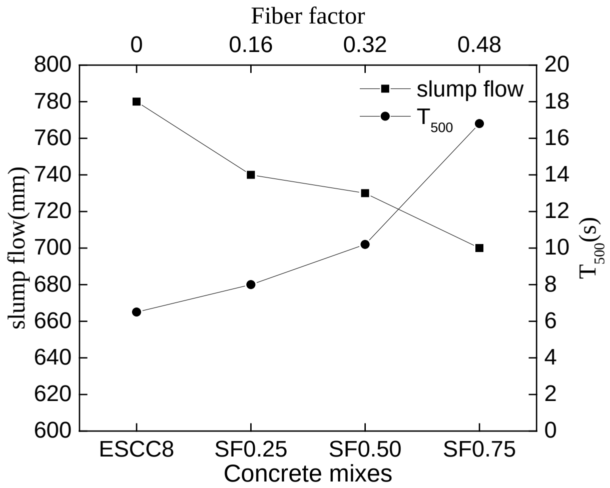


Fig. 3. Slump flow and T_{500} of fresh steel fiber reinforced concrete

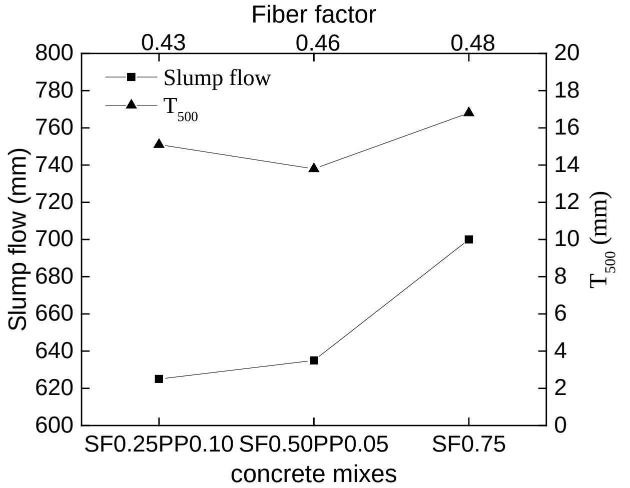
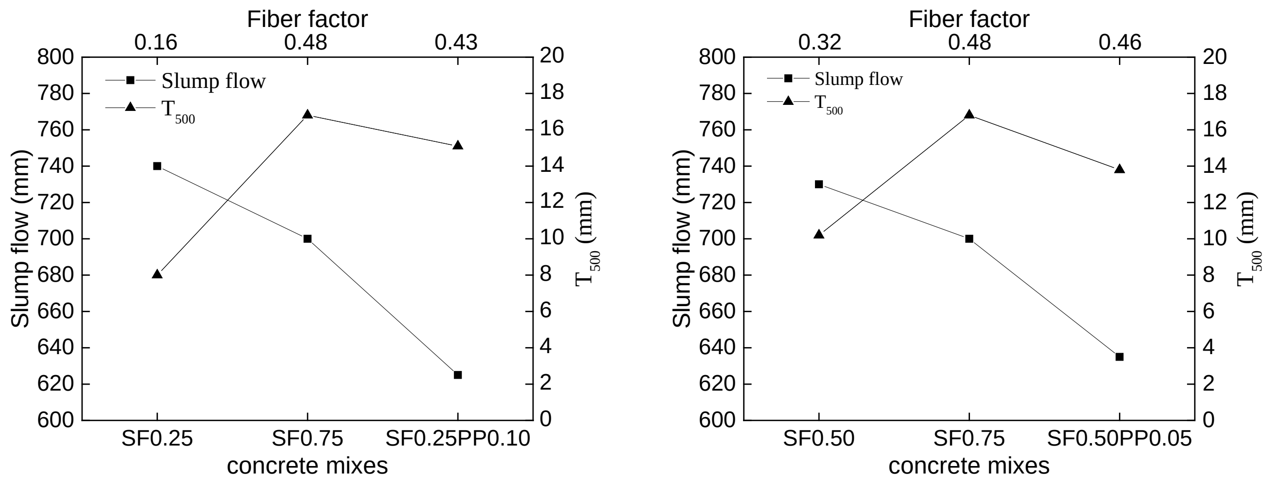


Fig. 4. Slump flow and T_{500} of fresh concrete with close fiber factor



(a) 0.25% SF mixed with 0.10% PP

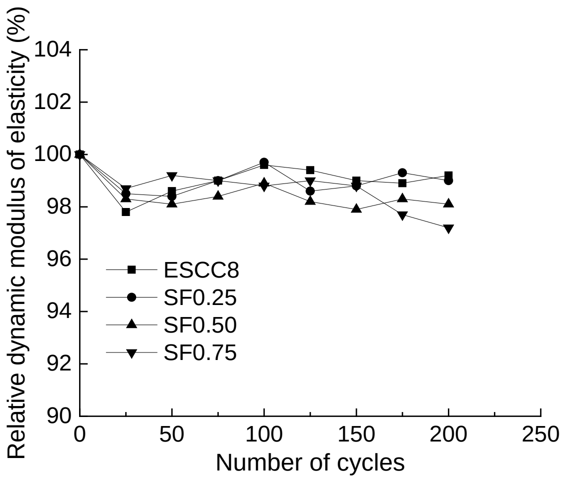
(b) 0.50% SF mixed with 0.05% PP

Fig. 5. Hybrid fiber effects on workability of fresh concrete

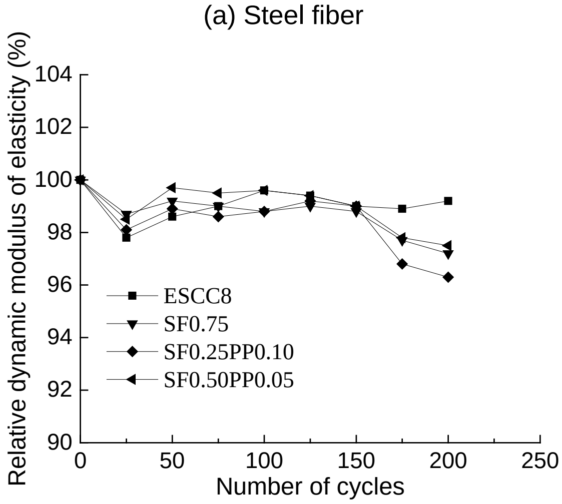
compared to SF0.25, while only 40 mm reduction in SF0.75 was observed compared to SF0.25. And the same phenomenon can be found in Fig. 5(b). It shows clearly that fiber type has a significant effect on slump flow. For close fiber factors, concrete contained both PP and SF showed a greater reduction on slump flow than concrete contained single SF. It is inferred that PP shows more sensitivity on slump flow than SF with close fiber factor. This contradicts with Khayat's and Li's (Li, 2006) researches, but is consistent with He's (He and Zhuo, 2012) research.

4.2 Freeze-thawing performance

Concrete studied was subjected to 200 freezing and thawing cycles. The combination effect of expansive agent and fibers are shown in Fig. 6 and Fig. 7. Figure 6 showed that the RDME was fluctuated with the number of freezing and thawing cycles. After 150 cycles, the RDME of expansive concrete containing fibers showed a trend of decline. After 200 cycles, the mass change of all six concrete mixes was among 0.0%-0.8%, the RDME was among 96.3-99.5%, mass change and the fundamental transverse frequency change were small, which indicates a high frost resistance performance of the concrete. In accordance with Fig. 6, SF0.25PP0.10 possesses the minimum RDME of 96.3% after 200 cycles, while ESCC the maximum of 99.2%, the RDME of SF0.25, SF0.50 and SF0.75 has presented a downward trend with numerical value of 99.0%, 98.1% and 97.2%, respectively. It was seen that the RDME of fiber reinforced ESCC was found to slightly decrease when compared to ESCC in the absence of fibers. The little decrease in frost resistance due to presence of fibers can be explained as follows. The air-entraining effect of fibers and expansion caused by expansive agent increase the porosity of concrete. When water infiltrates the pores and suffers from frost, its volume will swell 9%, thus concrete begins to expand and cause tensile stress, which will form micro cracks when it exceeds the tensile strength of concrete.



(a) Steel fiber



(b) Hybrid fiber with close fiber factor

Fig. 6. The RDME of SCC combining fibers with EA

Increasing fiber factor can cause the increase of the air-entraining effect, which will increase the internal micro cracks when suffer from freezing and thawing cycles. In spite of the combination of fibers and expansive agent presents a negative influence on the RDME, the increase of fiber content slows down the surface spalling speed of the specimens and decreases the mass change. According to Fig. 7, after 200 cycles, the mass change of ESCC, SF0.25, SF0.50, SF0.25PP0.10, SF0.50PP0.05 and SF0.75 was 0.7%, 0.6%, 0.8%, 0.3%, 0.2% and 0.1% with fiber factor of 0.00, 0.16, 0.32, 0.43, 0.46 and 0.48 respectively. Figure 8 shows the relationship between mass change rate of specimens and slump flow for the tested six concrete mixtures. It shows that the mass change becomes larger as slump flow increases. However, this might be caused by the higher fiber dosage in the concrete specimens. It is speculated that there is no direct relationship between mass change (surface scaling) and slump flow of tested concrete mixtures.

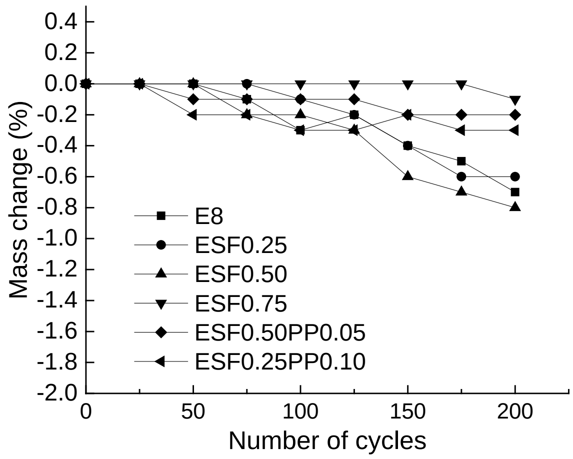


Fig. 7. The mass change of SCC combining fibers with expansive agent

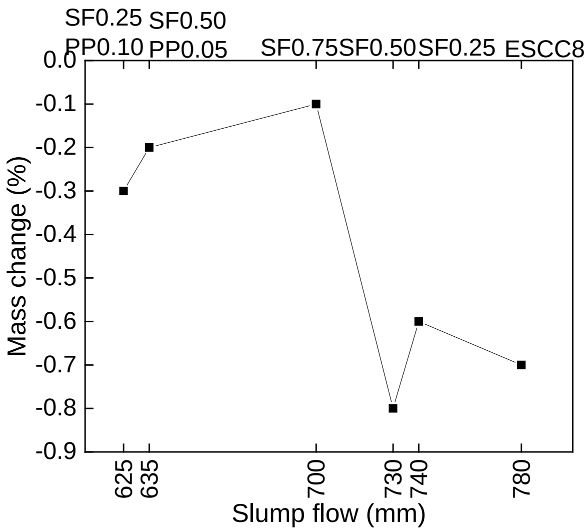


Fig. 8. The relationship between mass change and slump flow

5.0 CONCLUSIONS

This study investigated the effect of the combination of fibers and expansive agent on the chloride penetration resistance and the freeze-thawing performance of SCC. The following conclusions and inferences may be drawn from this study:

(1) Workability decreases with incorporation and increase of single SF. Hybrid fiber reinforced concretes contain SF and PP decrease the slump flow significantly as well as T_{500} compared with single SF reinforced concrete with close fiber factor. It is inferred that PP shows more sensitivity on slump flow than SF but less impact on T_{500}.

(2) The RDME of ESCC in the presence of fibers decreases slightly when compared to ESCC in the absence of fibers, and decreases with the increasing fiber factor. While the increase of fiber content slows down the surface spalling speed of the specimens and decreases the mass change.

(3) Test results show that the mass change becomes larger as slump flow increases. However, It is speculated that there is no direct relationship between mass change and slump flow of tested concrete mixtures as this might be caused by the higher fiber dosage in the concrete specimens.

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