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Properties of polypropylene fiber reinforced silica fume expansive-cement concrete

Houssam A. Toutanji

Department of Civil and Environmental Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, USA

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Abstract

This paper reports on a comprehensive study on the mechanical properties of expansive-cement concrete containing silica fume and polypropylene fibers. Properties studied include those of the fresh mix properties, length change, rapid chloride permeability, compressive strength, flexural behavior, and bond of hardened concrete. Silica fume content used was 5 and 10% and fiber volume fraction was 0.10, 0.30, and 0.50%. Results show that the use of 5% silica fume combined with 0.30% fiber volume fraction results in optimum mixture design for repair applications from the standpoints of workability, bond, strength, length change and permeability.

Keywords: Compressive strength; Expansive cement; Flexural strength; Permeability; Polypropylene fibers; Shrinkage; Silica fume; Volume change

1. Introduction

Polypropylene fibers, produced by the fibrillation of polypropylene films, have been used in Portland cement concrete since the late 1960s [1]. Polypropylene and other synthetic fibers are added to concrete as secondary reinforcement to control plastic shrinkage [2]. The most common application is slab-on-grade construction where the constraint of the foundation or other parts of the structure produces tensile stresses when the concrete shrinks due to moisture loss. These stresses may exceed the concrete strength at early age leading to shrinkage cracks. Polypropylene fibers mitigate plastic and early drying shrinkage by increasing the tensile concrete and bridging the forming cracks.

The effect of polypropylene fibers on the properties of hardened concrete varies depending on the type, length, and volume fraction of fiber, the mixture design, and the nature of the concrete materials used. The general results are that permeability, abrasion and impact resistance are all significantly improved by the addition of polypropylene fibers [2]. The effect of polypropylene fibers on flexural, compressive and tensile strength as well as on toughness and elastic modulus is not quite clear. Most work shows either no effect or modest improvements in these properties. However, in some cases the addition of polypropylene fibers has been known to decrease the ultimate strength of hardened concrete.

Expansive-cement concrete is similar to ordinary Portland cement concrete except that expansive-cement has properties which enable it to expand upon initial hydration. Such an initial expansion tends to counteract the effect of the drying shrinkage that occurs in expansive-cement concrete. As a result, the net shrinkage of expansive-cement concrete is small compared to conventional concrete.

The phenomenon of near zero shrinkage is potentially very beneficial for concrete structures such as highways and bridges. Problems develop in these structures when surface cracks occur. In addition to being

[1] Tel.: +1-205-890-6370; fax: +1-205-890-6724.

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unsightly, these cracks serve as conduits for salt and water. The saline solution comes in contact with reinforcing steel and promotes corrosion. Corrosion causes expansion of steel and inevitably pop-outs occur in the concrete cover, thereby reducing the strength and service life of the concrete (pavement section). It has previously been well documented that by eliminating or reducing the drying shrinkage cracks, the integrity, and service life of concrete paving will be enhanced [3–5]. Also, the reduction of shrinkage of repair materials is beneficial for: (1) bond to the substrate; and (2) service life of the repair.

Research in expansive-cement concrete has focused on application in pavements and bridge decks. Cusick and Kesler [6] investigated the use of expansive-cement concrete in repair of bridge decks. Gaskill and Jacobs [7], Gruner and Plain [8], Lower [9], Rosenlund [10] and Russel [11] studied the use of expansive-cement concrete in pavements and bridge decks. Further research by Vondran and Webster [12] indicated that the use of silica fume and polypropylene fibers enhanced the impermeability and durability of concrete which is advantageous for new constructions of bridge decks and pavements as well as for repair. Moreover, ACI Committee 226 [13] and Cohen and Olek [14] indicated that the use of silica fume as a replacement of ordinary Portland cement on an equal mass basis improved the compressive strength and decreased rapid chloride permeability of concrete.

An area that has not been previously examined is the effect of polypropylene fiber additions on the mechanical properties of silica fume expansive-cement concrete. Researchers have studied expansive-cement concrete and fiber reinforced concrete, however, considering reinforcing fibers and silica fume in expansive-cement concrete is an innovative approach. The purpose of this research is to study the properties of expansive-cement concrete that pertain to applications in highways and bridge decks.

In this research project, nine mixtures were prepared for studying the properties of fiber reinforced silica fume expansive-cement concrete (FRSFEC). The tests conducted included determinating the properties of fresh concrete, shrinkage, interfacial bond strength, compressive strength, and permeability. The results of this study can provide important information on the properties of FRSFEC and its use in highway pavements and bridge decks.

2. Experimental program

2.1. Materials

Nine mixtures that contained different fiber volume fractions and silica-fume percentages were fabricated and tested in order to assess fresh and hardened properties of FRSFEC. Materials, specimen fabrication, curing conditions, and testing methods used in this investigation were designed to stimulate potential repair applications of FRSFEC in practice.

Materials used included Type K expansive cement, silica fume, coarse aggregate with a maximum nominal size aggregate of 9.5 mm, concrete sand, tap water, naphthalene formaldehyde sulfonate-based high-range water-reducing admixture (HRWRA), and fibrillated polypropylene fibers. The fiber lengths used ranged between 6 and 51 mm. The purpose that Type K expansive cement was used in this study was due to its widespread availability in the US. The silica fume contains 96.5% SiO_2 with an average particle size of 0.15 μm. The mixture design proportions are listed in Table 1.

All mixes were prepared in a drum mixer with a capacity of 0.0651 m^3. Mixing sequence was as follows:

- Place the sand and gravel in the mixer and start the mixer.

Table 1
Mixture design proportions of fiber reinforced silica fume expansive-cement concrete[a]

Mixture no.	W/B	C/B	SF/B	G/B	S/B	SP/B	Fiber volume fraction (%)
1	0.50	1.00	0	2.30	1.80	0.02	0.10
2	0.50	0.95	0.05	2.30	1.80	0.02	0.10
3	0.50	0.90	0.10	2.30	1.80	0.02	0.10
4	0.50	1.00	0	2.30	1.80	0.02	0.30
5	0.50	0.95	0.05	2.30	1.80	0.02	0.30
6	0.50	0.90	0.10	2.30	1.80	0.02	0.30
7	0.50	1.00	0	2.30	1.80	0.02	0.50
8	0.50	0.95	0.05	2.30	1.80	0.02	0.50
9	0.50	0.90	0.10	2.30	1.80	0.02	0.50

[a] B = C + SF = binder; C = Type K expansive cement; SF = silica fume; G = gravel; S = sand; SP = high-range water-reducing admixture (HRWRA); and W = water. All ratios are by mass.

- Add one-third of the mixing liquids (water + HRWRA) to the running mixer.
- Add the cementitious materials (expansive cement + silica fume) slowly with another one-third of the mixing liquids to preserve fluidity and workability of the mixture.
- Add the polypropylene fibers.
- Add the remaining mixing liquids.
- Continue mixing for 5 min, stop the mixer for 3 min, and then continue mixing for an additional 2 min.

Upon completion of mixing, place the fresh concrete into the molds and vibrate simultaneously. Then cover the specimens with plastic sheets for 24 h.

After the specimens were covered with plastic sheets for 24 h, they were demolded and placed in a curing box (72°F and 100% relative humidity) for 2 days. Then the specimens were kept in laboratory conditions until they were tested at the age of 30 days. In order to measure the shrinkage effect; shrinkage specimens were submerged in a saturated lime solution for 2 days after demolding.

2.2. Testing methods

2.2.1. Fresh mix properties

Experimental investigation of fresh mix properties of FRSFEC was conducted based on ASTM C 995 [15] using an inverted slump cone, slump by ASTM 143 [16], and air content ASTM C 231 [17].

2.2.2. Shrinkage determination

Length change was measured using ASTM C 490 [18]. Four specimens of each mixture were tested using a length compactor with a precision of 2.5 μm. Each specimen measured $25 \times 25 \times 280$ mm. Upon demolding, the specimens were submerged in a saturated lime solution for two days to encourage the expansive reaction of the Type K cement. The specimens were then placed in an incubator, which was kept at 12.5°C, and 0% relative humidity for 14 days after casting. The purpose of incubator drying was to simulate ultimate drying shrinkage. Compactor readings were made at 24 h, at every 3 days, and at 14 days of age.

2.2.3. Bond strength

The bond strength of the test concrete to normal concrete was measured using ASTM C 882 [19]. The bond specimens were cast using a combination of normal concrete substrate and test concrete along an inclined bond surface. The test concrete mixture was placed on top of a 102-mm diameter concrete cylinder with a 102-mm average height and an inclined top surface at a 30° angle to the cylinder's axis. The tapered 102-mm cylinders were made of conventional concrete to stimulate the substrate in repair projects. Three specimens of each mixture were tested to determine bond strength.

2.2.4. Compressive strength

Compressive strength of each specimen was determined using ASTM C 39 [20]. Three specimens of each mixture were tested to determine the average compressive strength. Each specimen measured 102 mm in diameter and 204 mm in height.

2.2.5. Flexural load and deflection test

Flexural load–deflection behavior was studied based on three specimens per mixture. The specimens were tested in third-point loading over a span of 305 mm in accordance with ASTM C 1018 [21]. Specimen dimensions were $102 \times 102 \times 356$ mm. A yoke with two LVDTs was used to measure the deflection at midspan. Load and deflection were continuously monitored during flexural testing.

2.2.6. Permeability test

Permeability test was performed in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T 277 [22]. By measuring the total charge passed (coulombs) through a standard specimen, the rapid chloride permeability of the specimen can be evaluated. The electrical current is based on the reaction between a 3.0% sodium chloride (NaCl) solution and a 0.3% sodium hydroxide (NaOH) solution. Two specimens, each measuring 102 mm in diameter and 51 mm in height of each mixture were tested.

3. Experimental results

3.1. Properties of fresh concrete

The test results of the inverted slump cone, slump, and air content are listed in Table 2. Results showed

Table 2
Fresh properties of fiber reinforced silica fume expansive-cement concrete

Mixture no.	Inverted slump cone (s)	Slump (cm)	Air content (%)
1	12	14.0	2.0
2	14	7.6	2.0
3	16	6.4	3.0
4	13	7.0	2.5
5	15	7.6	2.5
6	17	6.4	3.5
7	20	4.4	3.0
8	24	3.8	5.0
9	28	2.5	7.0

that inverted slump cone time increased as the percentage of fiber increased, since reinforcing fibers are disadvantageous for concrete workability. The addition of silica fume will normally densify the mixture by filling voids in the cement matrix. This will produce a stiffer mixture and a corresponding increase in the inverted slump cone time as shown in Table 2. Slump values appeared to be inversely related to the inverted slump cone time as anticipated. The addition of fibers and silica fume exhibited detrimental effects on the workability of fresh expansive-cement concrete, as may be seen in Table 2 (mixtures 8 and 9).

Air content of fresh concrete increased with increasing volume of fibers or with silica fume content, as shown in Table 2. This behavior appeared to be more prominent at the maximum fiber volume fraction of 0.30% and at the maximum silica fume percentage of 10%.

3.2. Shrinkage

Shrinkage test results are shown in Figs. 1–3. Results showed that shrinkage varied with silica fume addition rate. Fig. 1 represents the shrinkage of mixtures 1–3 which contained 0.10% fibers and variable amounts of silica fume. The initial expansion of all three mixtures was overcome entirely by the subsequent drying shrinkage. The maximum shrinkage occurred in mixture 3, which contained 10% silica fume. Initial expansion and drying shrinkage for mixtures 1 and 2 were approximately equal. Fig. 2 shows the results of length change for mixtures 4–6, which contained 0.30% fiber volume fraction. As shown in Fig. 2, shrinkage test results of mixtures 4–6 were similar to the test results of mixtures 1–3 with respect to the silica-fume effect. Drying shrinkage of mixtures 4–6 overcame initial expansion for every mixture. Length changes of mixtures 7–9 with 0.50% fiber volume fraction are presented in Fig. 3. From Fig. 3, one may conclude that the relatively high air content of mixtures 7–9 resulted in an increase of the initial expansion, which was probably caused by the easier passage of curing water into the shrinkage specimens. Length change test results of this study appeared to be inconclusive with respect to effects of variation in volume fraction of fibers.

3.3. Bond strength

The bond strength of FRSFEC cured to conventional concrete was calculated by testing the bond specimens up-to-failure, then determining the ultimate load carrying capacity. The failure plane for all specimens was at the bond interface. Based on ASTM C 882 [19], bond strength is obtained by dividing ultimate vertical compressive load by the elliptical area. Fig. 4 represents bond strength of FRSFEC as a function of silica fume

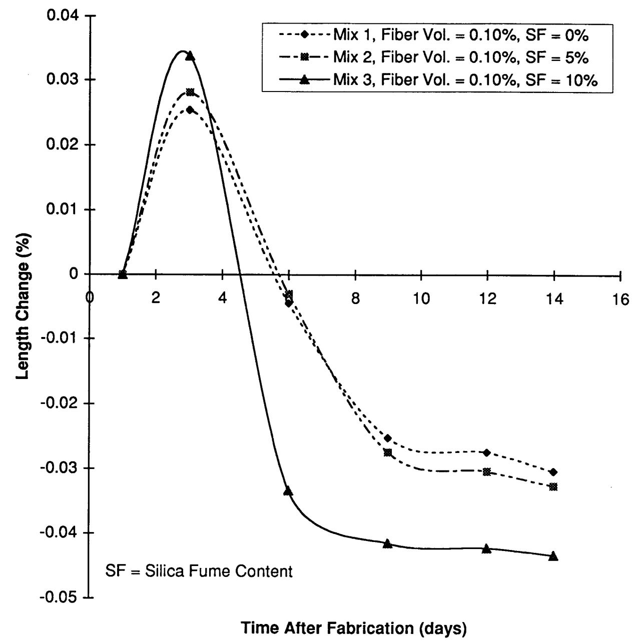

Fig. 1. Shrinkage of fiber reinforced silica fume expansive-cement concrete as a function of time (mixes 1–3).

content. For the mixtures with 0.10% and 0.30% fiber volume fractions, the bond strength increased significantly with the addition of 5% silica fume. Further increase in bond strength was practically constant irrespective of the silica fume content. It can be concluded that silica fume and polypropylene fibers improve bond strength of expansive cement concrete.

3.4. Compressive strength

Compressive strength test results are presented in

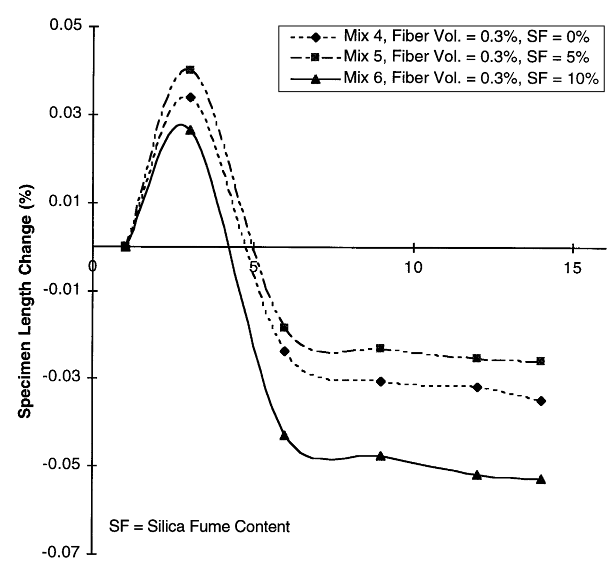

Fig. 2. Shrinkage of fiber reinforced silica fume expansive-cement concrete as a function of time (mixes 4–6).

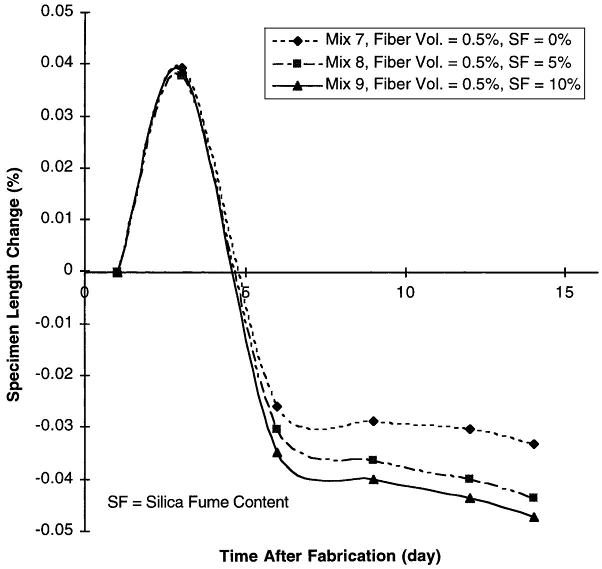

Fig. 3. Shrinkage of fiber reinforced silica fume expansive-cement concrete as a function of time (mixes 7–9).

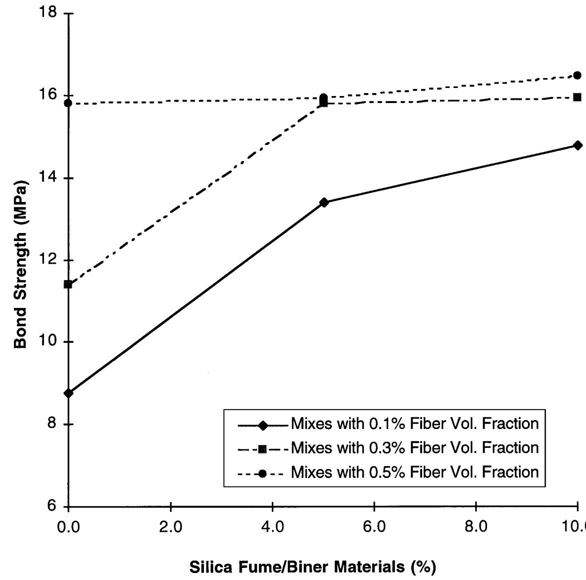

Fig. 4. Bond strength of fiber reinforced silica fume expansive-cement concrete as a function of silica fume to binder ratio.

Fig. 5. The mixtures that did not contain silica fume exhibited compressive strength ranging from 32.4 to 35.0 MPa. The addition of 5% silica fume resulted in an increase in the compressive strength between 5 and 10%, whereas 10% silica fume caused further increase of up to 35%. The increase in strength values can be linked to silica fume particles filling the micro-voids among the cement grains in the paste fraction of the concrete. Effect of fibers on compressive strength appeared to be inconclusive.

3.5. Flexural behavior

Flexural load–deflection curves for the mixtures with 0%, 5%, and 10% silica fume are shown in Figs. 6–8, respectively. Test results showed that silica fume had no effect on the flexural behavior or post-peak resistance (Table 3) of polypropylene fiber reinforced concrete. However, increasing fiber volume fraction resulted in improving post-peak flexural resistance. A pronounced effect was noted upon increasing fiber volume fraction from 0.10 to 0.30% and a relatively smaller increase was observed when increasing fiber content to 0.50%.

3.6. Chloride permeability

Table 4 provides the average chloride permeability values of two specimens for each mixture. Results show that the addition of polypropylene fibers increased the permeability of concrete. This was apparently caused by the voids created by fiber addition. Consequently, the advantageous effect of fiber restraint formation of micro-cracks was not observed. The addition of silica fume decreased permeability by filling the micro-voids among cement particles. With adequate silica fume percentage, the adverse effect of fibers on permeability was reduced. Optimum mixture proportions appeared to have 0.30% fiber volume fraction and 5% silica fume. The addition of silica fume resulted in decreased permeability while maintaining adequate workability.

4. Conclusions

Results of the experimental study on the properties of fiber reinforced silica fume expansive-cement concrete (FRSFEC) were presented in this paper. The following conclusions can be drawn:

1. Silica fume appeared to have an adverse effect on the workability of fiber concrete.

Table 3
Post-peak strength of fiber reinforced silica fume expansive-cement concrete

Mixture no.	Silica fume content (%)	Fiber volume fraction (%)	Post-peak strength (MPa)
1	0	0.10	1.21
2	5	0.10	1.31
3	10	0.10	0.80
4	0	0.30	2.37
5	5	0.30	2.72
6	10	0.30	2.15
7	0	0.50	3.23
8	5	0.50	3.40
9	10	0.50	3.34

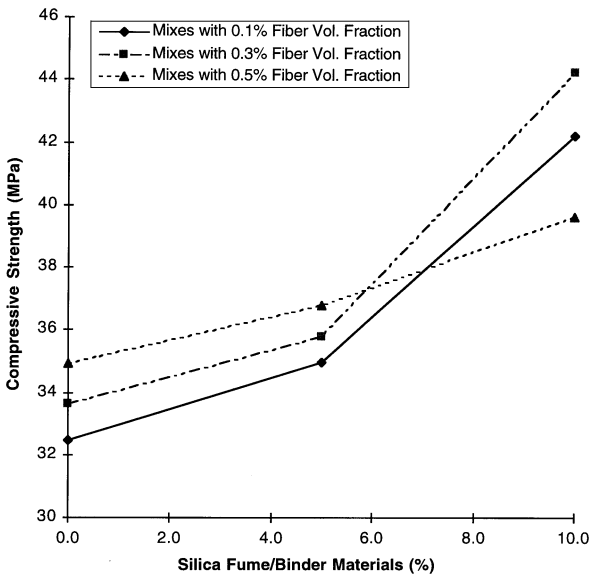

Fig. 5. Compressive strength of fiber reinforced silica fume expansive-cement concrete as a function of silica fume to binder ratio.

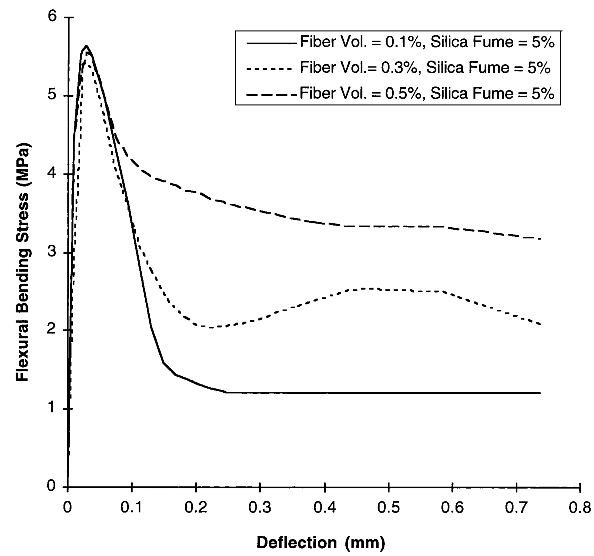

Fig. 7. Flexural behavior of fiber reinforced expansive-cement concrete with 5% silica fume.

2. The addition of 5% silica fume caused a small decrease in expansion and a similar increase in drying shrinkage. This effect was more pronounced with the addition of 10% silica fume.
3. The use of 5% silica fume resulted in improving the bond strength between the new expansive cement–concrete (as a repair material) to the old conventional concrete (as a substrate). The rate of increase in bond strength decreased with increasing silica fume content from 5 to 10%. However, the use of polypropylene fibers resulted in an increase in bond strength especially for the mixtures with 10% silica fume.
4. Silica fume exhibited a significant effect on the lexural behavior of fiber reinforced expansive-cement concrete. Increasing polypropylene fiber volume fraction resulted in an improvement in post-peak flexural strength of fiber reinforced silica fume expansive-cement concrete.
5. The addition of polypropylene fibers caused an adverse effect on the chloride permeability of expansive-cement concrete. However, the addition of silica fume resulted in a significant decrease in permeability.
6. Based on the test results presented in this paper, it was concluded that a mixture design with 5% silica

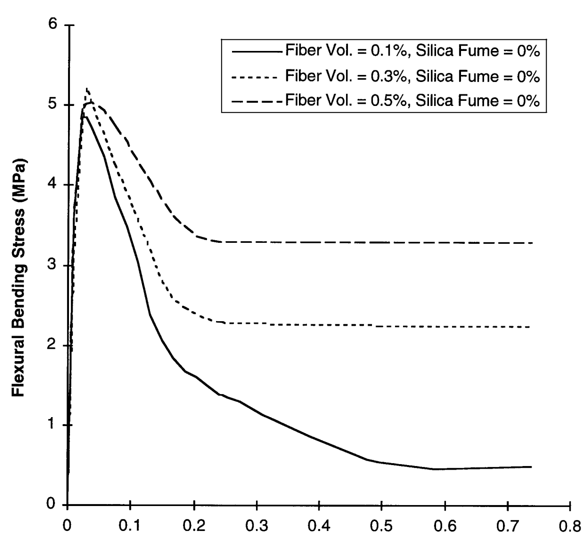

Fig. 6. Flexural behavior of fiber reinforced expansive-cement concrete.

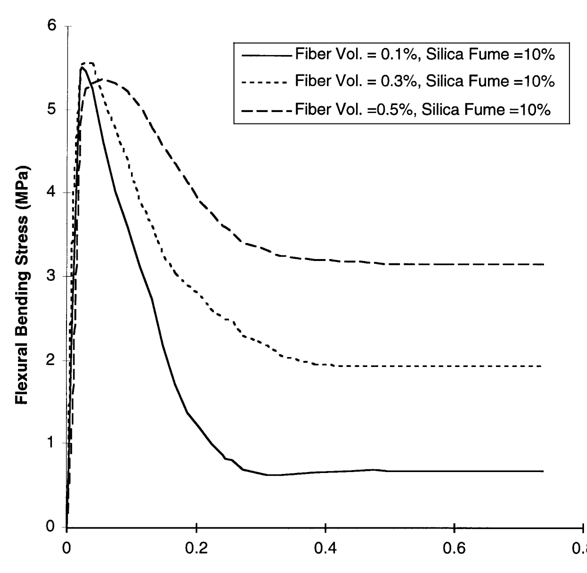

Fig. 8. Flexural behavior of fiber reinforced expansive-cement concrete with 10% silica fume.

Table 4
Rapid chloride permeability of fiber reinforced silica fume expansive-cement concrete

Mixture no.	Silica fume content (%)	Fiber volume fraction (%)	Max. charge passed (C)
1	0	0.10	4629
2	5	0.10	2874
3	10	0.10	1163
4	0	0.30	10 772
5	5	0.30	1560
6	10	0.30	1174
7	0	0.50	11 255
8	5	0.50	3537
9	10	0.50	1273

fume and 0.30% fiber volume fraction was optimal in decreasing permeability while maintaining an adequate workability.

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