Application of Silica Fume in Synthetic Fiber–Reinforced Concrete

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The effect of silica fume on the properties of synthetic fiber–reinforced concrete was assessed. Two fiber types were used: fibrillated polypropylene fibers and polyethylene-terphalate polyester fibers. Various fiber volume fractions were examined. Fiber volumes ranged from 0 to 0.6 percent, and fiber length was 12 mm (½ in.). Silica fume was used as partial replacement of portland cement on an equal-mass basis at 0, 5, 10, and 25 percent. The fresh mixtures were tested for slump, inverted slump cone time, and air content. The hardened concrete material was tested for compressive and flexural behaviors as well as impact resistance. Rapid chloride permeability was also measured. The purpose of the experimental investigation was to assess the suitability of synthetic-fiber silica-fume concrete for application in bridge-deck overlays and other applications for which the mechanical properties and permeability are important. The results indicate that silica fume is useful in improving the effectiveness of fiber reinforcement of concrete and reducing its permeability.

Silica fume is a by-product in the manufacture of silicon and ferrosilicon alloys. It is composed of fine particles with high silica (SiO_2) content (average particle size of the order of 0.1 micron = 4×10^{-6} in.). The use of silica fume in concrete as an admixture is common (*1*). Silica fume reacts with hydrated lime existing in cement paste, and calcium silicate hydrate is obtained. Calcium silicate hydrate contributes to the improvement of concrete properties, including strength, impermeability, and durability (*1*).

Various types of synthetic fiber are used for concrete reinforcement. They reduce shrinkage and cracking and enhance impact resistance and toughness (*2*). Silica fume has been found to have beneficial effects on the performance of steel fiber concrete (*3,4*). It was found that silica fume helped to enhance the interfacial bond between fibers and cement paste. As a result, the reinforcement effect of fibers in concrete was improved (Figure 1). The use of silica fume as a part of binder in concrete significantly reduces workability, air content, and permeability, but it increases compressive and flexural strengths (*1–3,5*). Optimum addition of silica fume reduces bleeding of concrete—a reduction that prevents early moisture loss from freshly placed concrete, which in turn reduces plastic shrinkage cracking.

The fineness and high pozzolanic reactivity of silica fume contribute to the enhancement of the density and adhesion capacity of cement paste, especially with other additives including fibers (*1–3,5*). Enhanced bonding between fibers and the cement matrix contributes to the strength and ductility of steel fiber–reinforced silica-fume concrete. One type of fiber commonly used is polypropylene fiber. Compared with unmodified concrete, concrete reinforced with polypropylene fiber has significantly less bleeding, less segregation, and lower plastic shrinkage cracking. Furthermore, polypropylene fiber–reinforced concrete shows increases in flexural fatigue strength and impact resistance, and it has shown reduced drying shrinkage cracking (*2,6*).

Polyester fibers have also been used to reinforcement concrete. Increases in flexural strength, toughness, and impact resistance were among the benefits of such reinforcement.

EXPERIMENTAL

Materials

Mix Type A: Monofilament Polyester Fiber–Reinforced Concrete

Type II portland cement was used for Mix A; coarse aggregate was pea stone with a maximum size of 9 mm (⅜ in.). The

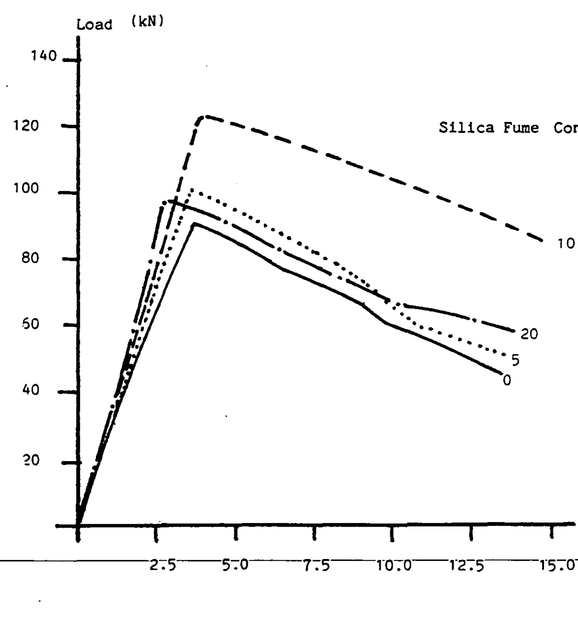

FIGURE 1 Flexural load-deflection relationships of silica-fume concrete.

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fine aggregate was sand with a modulus of 3.8. A naphthalene formaldehyde sulfonate-based superplasticizer was used; this superplasticizer has been found to be compatible with silica fume and maintains its effectiveness over a long period (*7*).

Polyethylene-terphalate (PET) polyester fibers with the following characteristics were commercially available (*8*):

- Diameter = 50 microns (0.002 in.)
- Specific gravity = 1.3
- Tensile strength = 380 MPa (55 ksi)
- Elastic modulus = 1.9 × 10^4 MPa (2,800 ksi)
- Fiber length = 12.5 mm (0.5 in.)

The chemical composition of the commercially available silica fume is given in Table 1; the physical properties are as follows (*9*):

- Specific gravity = 2.3
- Bulk density = 225 kg/m^3 (14 lb/ft^3)
- Specific surface = 200 000 cm^2/g (14 × 10^6 $in.^2$/lb)
- Average particle size = 0.14 microns (4 × 10^{-5} in.)
- Particles smaller than 45 microns (0.018 in.) = 99.5 percent

Mix proportionings were performed by the mass batching method. Silica fume was used as a partial replacement of cement on an equal-mass basis. For all the mixes in this series, the ratio of aggregate (fine and coarse) to binder (cement and

TABLE 1 Chemical Composition of Silica Fume

Chemical Compound	Percentage of Total Mass
SiO_2	96.5
C	1.40
Fe_2O_3	0.15
MgO	0.20
Al_2O_3	0.15
K_2O	0.04
Na_2O	0.20

TABLE 2 Mix Design Program

Mix No.	Designation	Fiber Volume %	Silica Fume /Binder (%)	Mix Type
1	Standard 1	0.0	0.0	A
2	Series	0.15	0.0	A
3	No. 1	0.35	0.0	A
4		0.60	0.0	A
5	Series	0.00	5	A
6	No. 2	0.15	5	A
7		0.35	5	A
8		0.60	5	A
9	Series	0.15	10	A
10	No. 3	0.35	10	A
11		0.60	10	A
12	Series	0.15	25	A
13	No.4	0.35	25	A
14		0.60	25	A
15	Standard 2	0.00	0.0	B
16	Series	0.10	0.0	B
17	No.5	0.30	0.0	B
18		0.50	0.0	B
19	Series	0.00	5	B
20	No. 6	0.10	5	B
21		0.30	5	B
22		0.50	5	B
23	Series	0.00	10	B
24	No. 7	0.10	10	B
25		0.30	10	B
26		0.50	10	B

Note: Mix Type A contains more filament polyester fibers while Mix Type B contains fibrillated polypropylene fibers.

silica fume) was 3.0, and the ratio of sand to gravel was 1.0. This proportioning results in a binder content of 520 kg/m^3 (870 lb/yd^3). The water-binder ratio was 0.45. The amount of superplasticizer was 1.0 percent of the binder by mass. Volume percentages of fiber ranged from 0.0 to 0.60 percent of the total volume.

Mix Type B: Fibrillated Polypropylene Fiber Concrete

The aggregates in Mix B were natural river sand and gravel with a maximum size of 9 mm (3/8 in.). Type I portland cement was used, as were fibrillated polypropylene fibers with the following characteristics (*10*):

- Specific gravity = 0.91
- Tensile strength = 550 to 760 MPa (80 to 110 ksi)
- Elastic modulus = 3500 MPa (500 ksi)
- Fiber length = 12.5 mm (½ in.)
- Melting point = 160°C (320°F)

The mix proportioning technique was also based on mass batching. Silica fume was considered as a partial replacement of cement on an equal-mass basis. In these mixes, the ratio of aggregate (fine and coarse) to binder was 4.0, and of water to binder, 0.41; this resulted in a binder content of 430 kg/m^3 (720 lb/yd^3). The amount of superplasticizer used was 1.0 percent of the binder by mass. The sand-gravel ratio was 1.0. Fiber concrete ranged from 0.0 to 0.50 percent as a volume percentage.

The variations in both Type A and B mixes are given in Table 2; Type A consisted of four series, and Type B had three series.

TABLE 3 Fresh Mix Results

Mix No.	Slump (mm)	Inverted Slump Cone Time (S)	Air Content %
1	250	*	1.0
2	190	9	1.8
3	125	17	3.0
4	45	13	1.7
5	200	*	2.5
6	190	9	2.2
7	125	12	3.0
8	40	13	2.7
9	125	10	2.5
10	50	22	2.7
11	25	24	1.5
12	0	21	3.4
13	0	36	3.2
14	0	55	3.2
15	215	*	2.0
16	235	*	1.5
17	200	*	2.5
18	190	14	4.5
19	200	*	3.0
20	235	*	4.0
21	175	*	4.2
22	50	13	6.0
23	165	*	3.0
24	165	6	3.8
25	65	12	5.2
26	50	14	6.0

* Fresh mixtures flows freely through the inverted cone. Therefore test not applicable.
25.4mm - 1in

Mixing and Testing

A conventional rotary-drum mixer was used to produce the concretes. The workability of the freshly mixed concretes was assessed using the slump and inverted slump methods (*11*). Air content was measured using the pressure method according to ASTM C231. The following specimens were cast and tested for each series:

1. Three prismatic flexural specimens 100 × 100 × 350 mm (6 × 6 × 16 in.) for four-point (⅓ point) flexural load-deflection behavior test over a span of 300 mm (12 in.) according to ASTM C78 and C1018. Load and load-point deflection were measured using a servocontrolled loading machine and two displacement transducers.
2. Two cylindrical specimens 150 × 300 mm (6 × 12 in.) for the compressive stress-strain test using a compressometer (ASTM C39 and C469).
3. Three cylindrical specimens 150 mm (6 in.) in diameter and 62 mm (2.5 in.) in height for the impact strength testing as reported by the American Concrete Institute (*11*).
4. Two cylindrical specimens 100 × 200 mm (4 × 8 in.) for the rapid chloride permeability test according to AASHTO T277.

Curing was under 22°C (77°F) and 100 percent relative humidity for 7 days and under ambient conditions until the testing age of 28 days.

DISCUSSION OF RESULTS

Fresh Mix

The properties of the freshly mixed concrete are given in Table 3. It can be concluded that the use of plastic fibers

TABLE 4 Impact Results

Mix No.	Mix Type	First Crack Strength (No. of blows)	Ultimate Strength (No. of blows)
1	A	16	22
2	A	46	58
3	A	70	90
4	A	87	120
5	A	28	33
6	A	117	129
7	A	75	101
8	A	59	87
9	A	95	121
10	A	73	106
11	A	68	97
12	A	37	59
13	A	66	70
14	A	19	31
15	B	10	14
16	B	17	28
17	B	47	60
18	B	50	71
19	B	9	15
20	B	92	110
21	B	101	112
22	B	144	160
23	B	10	20
24	B	50	66
25	B	65	82
26	B	69	87

decreases the workability of concrete as indicated by the results of the slump and inverted slump cone tests. Polyester fibers appear to have no significant effect on air content. However, polypropylene fibers appear to increase the air content significantly. Silica fume appears to reduce the workability of concrete, as shown by the decrease in slump and the increase of inverted slump cone time.

Impact Resistance

Impact test results are listed in Table 4. It can be seen that plastic fibers in both types of mixes significantly enhance the impact resistance of concrete. Furthermore, adding silica fume at 5 and 10 percent increases the impact resistance even more. It is postulated that this increase is attributed to the improvement in fiber dispersion and in bond between fibers and concrete caused by silica fume. The data indicated that a silica-fume content of 5 percent is optimal for impact resistance. It can also be postulated that the adverse effects on workability, caused by high contents of silica fume or fibers, resulted in the reduction in the impact resistance of the material.

Permeability

Table 5 gives the data obtained from permeability testing. The data indicate that adding synthetic fibers to plain or silica-fume concrete increases the permeability. However, with an increasing silica fume–binder ratio (25 percent for Mix A and 10 percent for Mix B), the effects of fiber on permeability are reversed. The result is that adding fiber to concrete with a high content of silica fume can be beneficial for impermeability. It is thought that this reversal occurred via the improved fiber dispersion caused by the stickiness and cohesiveness of concretes with high silica-fume contents. This advantageous effect of silica fume diminishes as fiber content increases and consolidation becomes a difficulty.

TABLE 5 Permeability Results

Mix No.	Mix Type	Permeability (couloumbs)
1	A	5961
2	A	8384
3	A	6596
4	A	5743
5	A	1692
6	A	2960
7	A	3228
8	A	3962
9	A	978
10	A	768
11	A	1317
12	A	1144
13	A	278
14	A	329
15	B	3162
16	B	6770
17	B	4510
18	B	6796
19	B	1723
20	B	1167
21	B	1160
22	B	1904
23	B	841
24	B	752
25	B	737
26	B	493

Compressive Behavior

Table 6 gives the obtained compressive properties of both types of mix. The compressive toughness index is defined as the total compressive energy absorption (area under the stress-strain curve) divided by the pre-peak energy absorption (area under the stress-strain curve up to the peak stress).

The effects of various contents of polyester fibers and polypropylene fibers on the compressive stress-strain relationships of concrete are shown in Figures 2 and 3, respectively. Each curve represents the average test of three test specimens. Within-batch variations were less than 5 percent.

From Table 6 and Figures 2 and 3, it can be concluded that both polyester and polypropylene fibers improve the compressive toughness of concrete. The polyester fibers appear to cause a slight increase in the compressive strength of concrete, but polypropylene fibers appear to have no significant effect on compressive strength. Furthermore, both types of fiber appear to increase the strain at peak compressive stress.

Figures 4 and 5 illustrate the relationships of compressive strength with silica-fume content for plastic fiber concrete with various fiber volumes. From Figure 4, it can be concluded that silica fume at 5 to 10 percent increases the compressive strength of polyester fiber concrete; at 25 percent, however, no increase is observed, which is attributed to inadequate workability. Optimum silica-fume content appears to be 5 or 10 percent, and optimum fiber content appears to be 0.35 percent. Figure 5 shows that silica fume caused an increase in the compressive strength of polypropylene fiber–reinforced concrete. Optimum silica-fume and fiber contents are as shown in Figure 5: 5 percent and 0.30 percent, respectively.

Flexural Behavior

Figures 6 and 7 present the effects of polyester and polypropylene fiber volume fractions on the flexural load-deflection

TABLE 6 Compression Characteristics

Mix No.	Compressive Strength (MPa)	Compressive Strain at Failure (0.001)	Compressive Toughness Index	Mix Type
1	38.5	16	2.1	A
2	43.5	24	2.1	A
3	41.5	24	2.2	A
4	43.5	33	2.8	A
5	50.5	22	1.5	A
6	51.0	27	2.0	A
7	52.0	32	2.1	A
8	44.0	30	2.2	A
9	49.0	22	2.4	A
10	50.5	26	2.9	A
11	50.0	30	3.3	A
12	43.0	29	2.8	A
13	39.5	21	2.8	A
14	45.0	31	3.3	A
15	39.5	16	1.2	B
16	42.0	19	1.3	B
17	41.0	22	2.0	B
18	38.5	32	1.4	B
19	41.5	21	1.3	B
20	46.5	17	1.8	B
21	50.5	30	1.5	B
22	45.0	32	1.6	B
23	40.0	23	1.4	B
24	45.0	26	1.4	B
25	45.5	29	1.6	B
26	45.5	30	1.5	B

1ksi = 6.89 MPa

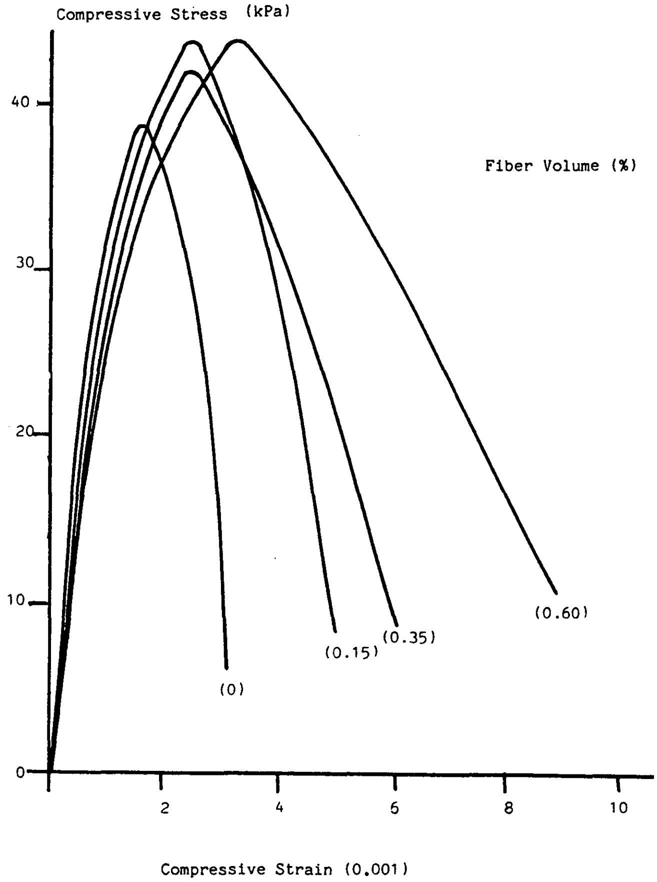

FIGURE 2 Compressive stress-strain behavior of polyester fiber concrete.

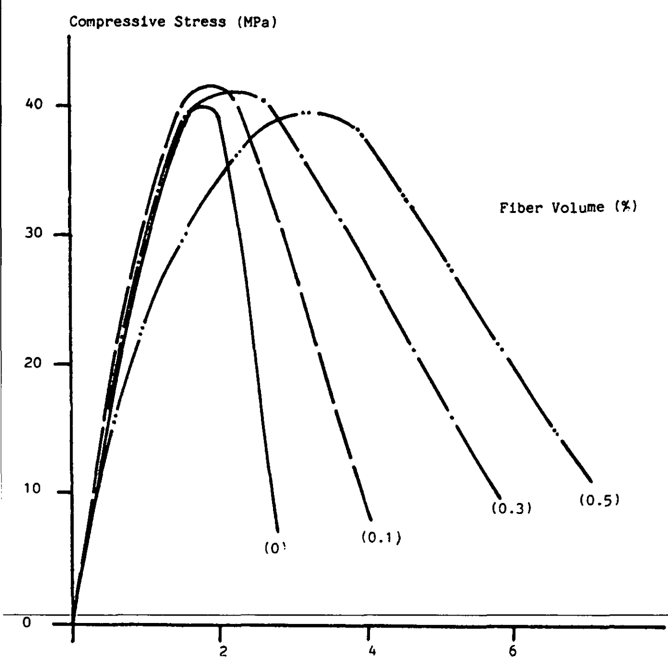

FIGURE 3 Compressive stress-strain behavior of polypropylene fiber concrete.

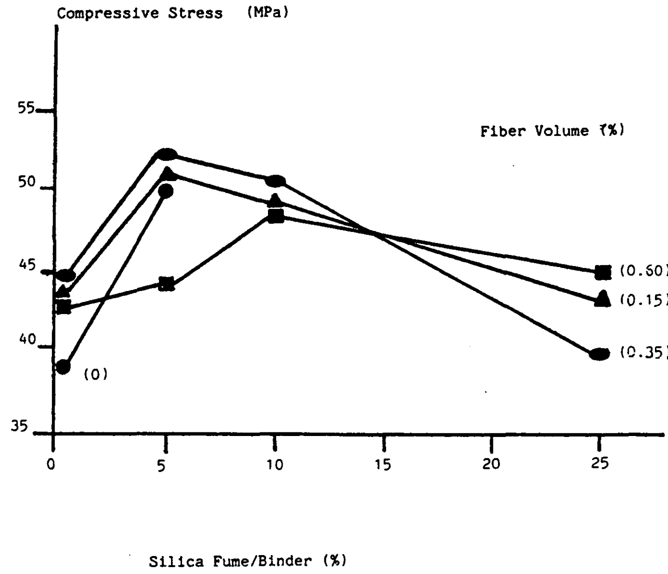

FIGURE 4 Compressive strength of polyester fiber concrete.

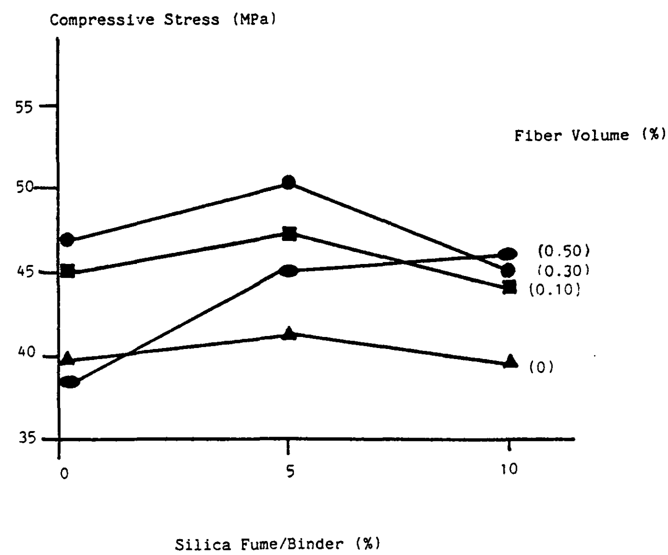

FIGURE 5 Compressive strength of polypropylene fiber concrete.

behavior of fiber-reinforced concrete. Each curve is the average of testing on three specimens. Within-batch variations were less than 10 percent. The characteristic flexural properties are listed in Table 7. Ultimate strength is defined as the maximum elastic flexural stress; post-peak strength, as the elastic flexural stress sustained by the specimen in the range beyond the peak load (which remains to some extent constant); and the toughness index, as $I_{5.5}$, according to ASTM C1018.

From Table 7 and Figures 6 and 7, it can be concluded that both polyester fibers and polypropylene fibers affect the flexural strength of concrete. Fibers significantly enhance the ductility of concrete, illustrated by changes in post-peak resistance and flexural toughness. This effect generally continues

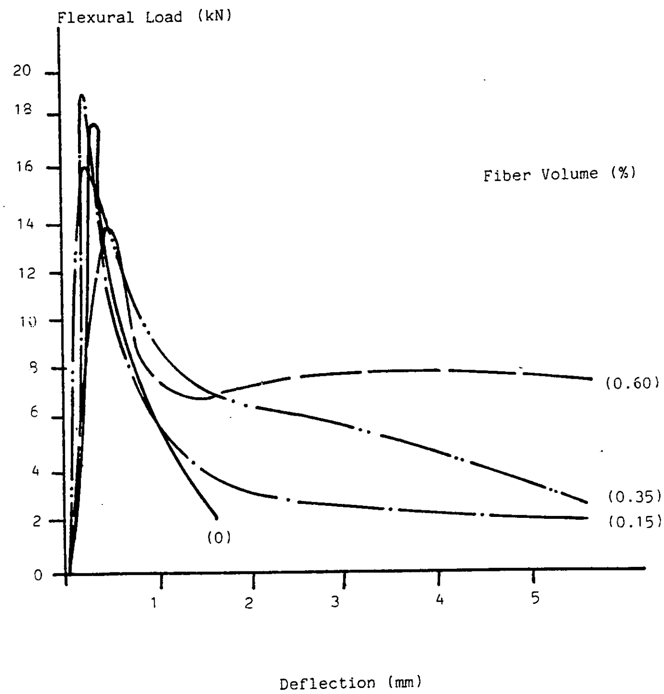

FIGURE 6 Flexural behavior of polyester fiber concrete.

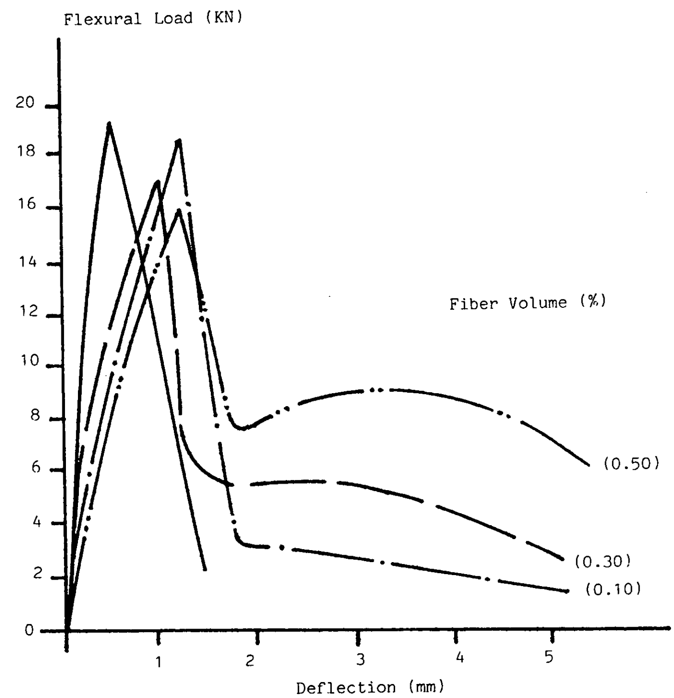

FIGURE 7 Flexural behavior of polypropylene fiber concrete.

TABLE 7 Flexural Characteristics

Mix No.	Ultimate Strength (kPa)	Post-Peak Strength (kPa)	Toughness Index	Mix Type
1	4510	-	2.5	A
2	5510	950	3.9	A
3	4650	1800	4.2	A
4	4270	2090	4.9	A
5	4605	-	2.6	A
6	4415	760	4.2	A
7	4750	1710	4.6	A
8	4270	1950	4.6	A
9	5220	1570	5.3	A
10	4130	2280	5.0	A
11	4510	2470	4.6	A
12	4840	1425	5.0	A
13	4370	1805	4.9	A
14	4035	2330	4.9	A
15	5600	-	1.5	B
16	5175	670	3.1	B
17	5220	1500	4.2	B
18	4415	2060	4.3	B
19	5840	-	1.7	B
20	4370	610	3.0	B
21	4795	1350	4.3	B
22	4795	1990	4.8	B
23	5935	-	1.8	B
24	4320	740	3.5	B
25	4415	1490	4.3	B
26	5030	2430	4.4	B

- Not applicable
1ksi = 6.89 MPa

to increase with increases in fiber volume fraction. Silica fume also appears to have a slight effect on increasing the ductility of fiber concrete. Figures 8 and 9 illustrate the effect of fibers and silica fume in post-peak resistance of concrete.

CONCLUSIONS

From the results of this investigation, the following can be concluded:

1. Both polyester and polypropylene fibers reduce the workability by increasing inverted slump cone time and decreasing slump. This effect is more obvious at higher contents of fibers (0.3 percent or more).
2. There is an increase in the air content of polypropylene fiber–reinforced fresh concrete, especially at a fiber content of 0.5 percent. However, there is an inconsistent effect of polyester fiber on the air content of fresh concrete.
3. Silica fume generally increases inverted slump cone time and decreases slump, which indicates adverse effects on workability.
4. Both types of fiber improve the impact resistance of concrete dramatically.
5. Optimum improvements of impact resistance for polyester fibers occur at a fiber volume of 0.15 percent and a silica-fume content of 5 percent. On the other hand, optimum improvements of impact resistance for polypropylene fibers were observed at 0.50 percent of fiber content and 5 percent of silica-fume content.
6. Fibers have a relatively small favorable effect on compressive strength. Both fibers slightly improve compressive behavior of concrete by enhancing toughness.
7. Use of silica fume enhances the compressive strength and toughness of fiber concrete with an optimum content of 5 to 10 percent.

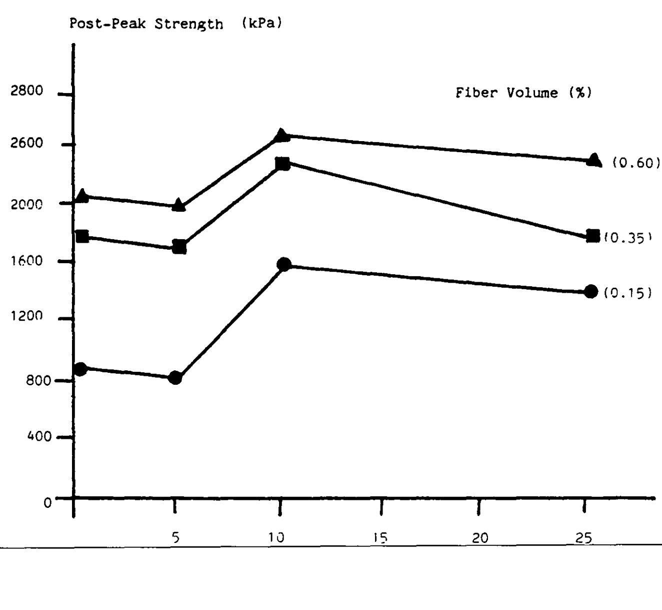

FIGURE 8 Post-peak flexural strength of polyester fiber concrete.

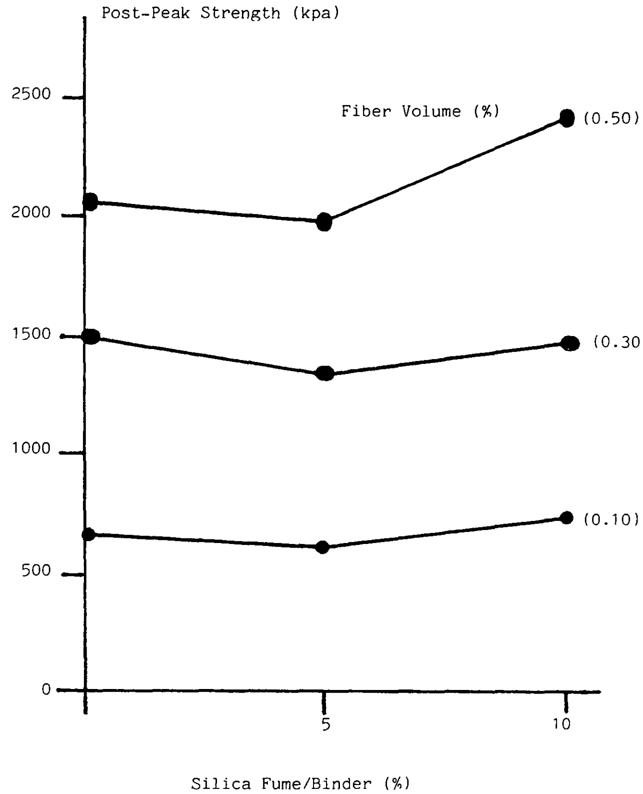

FIGURE 9 Post-peak flexural strength of polypropylene fiber concrete.

8. Polyester fibers and polypropylene fibers have an inconsistent effect on the flexural strength but significantly increase the flexural toughness and post-peak resistance of concrete. These improvements continue as fiber volume increases, except in ultimate strength, for which it starts to decrease beyond fiber volume of 0.35 percent.
9. Silica fume slightly enhances flexural toughness and post-peak strength of plastic fiber concretes.
10. Synthetic fiber–reinforced silica-fume concrete compared with plain concrete shows increases in impermeability, toughness, post-peak flexural strength, and impact resistance. These improvements indicate that such concrete is an alternative for use in pavements, overlays, slabs, grades, and other such applications.

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