Optimum Use of Pozzolanic Materials in Steel Fiber Reinforced Concrete

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The effects on fresh and hardened material properties for fly ash caused by substituting cement with fly ash and silica fume in steel fiber reinforced concrete were studied experimentally. The percentage substitution of cement ranged from 0 to 40 percent and from 0 to 20 percent for silica fume. The workability of fresh fibrous mixtures was characterized by measuring the inverted slump cone time. The hardened material was tested at 28 days under compression and flexural loads. The development of compressive strength with time was also assessed in steel fiber reinforced concrete incorporating fly ash. The generated test data were used to decide the optimum ranges of cement substitution with fly ash or silica fume in steel fiber reinforced concrete for achieving desirable fresh mix and hardened material characteristics.

Fly ash and silica fume are commonly used mineral admixtures capable of providing plain and fiber reinforced concrete with distinct performance advantages. Being pozzolanic materials, both silica fume and fly ash react with the calcium hydroxide produced by the hydration of portland cement. This leads to the formation of calcium silicate hydrate, which has desirable effects on the density and microstructure of concrete materials, especially at interfaces between cementitious paste and mix inclusions (e.g., aggregates and fibers), where the concentration of calcium hydroxide is generally high.

Fly ash and silica fume also have their differences. Silica fume is distinguished from fly ash by its fineness, high pozzolanic reactivity, and high silica content. The effects of the two pozzolanic materials on fresh mix workability are also different; while fly ash generally tends to improve workability, the reverse is true for silica fume.

This research was concerned with the partial substitution of cement with fly ash or silica fume in typical steel fiber reinforced concrete mixes. In this paper, the trends in the effects of pozzolan contents on fresh mix workability and hardened material mechanical characteristics are established. In addition, the optimum pozzolan contents for the specific types of fly ash and silica fume used in the mixes of this study are decided.

BACKGROUND

A brief review of the action of fly ash and silica fume in concrete, together with the outcomes of past investigations on pozzolan applications to steel fiber reinforced concrete are given below.

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Fly Ash

Fly ash is the finely divided residue resulting from the combustion of ground or powdered coal (*1*). Probably the most important consideration in the use of fly ash in steel fiber reinforced concrete is its ability to improve the fresh mix workability and fiber dispersability (*2,3*). The round particle shape and fineness of fly ash particles improve the flowability of the mix (*4*). With fly ash, the volume of cementitious paste in the mix increases due to the lower specific gravity of fly ash compared with that of cement (cement is usually replaced with fly ash on an equal mass basis). Thus, a more effective coating of fibers and lubrication of the mix inclusions is achieved (*3*). These effects improve the dispersability of fibers and the workability of the fresh mix. The improvements in fresh mix workability in the presence of fly ash are especially obvious when the fresh material is compacted through vibration (*2,3*). The improvements in fresh mix workability and fiber dispersability lead to enhanced properties of the composite material in the hardened state.

In addition to improving the fresh mix workability and fiber dispersability, the application of fly ash to steel fiber reinforced concrete imparts the following improvements to the material performance:

- Fly ash contributes to the strength of fiber reinforced concrete by reducing the water content without damaging workability, by increasing the volume of paste in the mixture, and by its pozzolanic reaction (*5*).
- The increase in cementitious paste volume in the presence of fly ash leads to a better coating of fibers by the matrix material and improves fiber-matrix interfacial bond characteristics. This may cause significant improvements in the composite material performance (*2,3*).
- All other advantages of using fly ash in plain concrete (enhanced pore system, reduced permeability and improved durability, reduced alkali-aggregate reactivity, economic and echological advantages, etc.) (*1,4,6*) would also apply to steel fiber reinforced concrete.

Certain precautions are needed to take full advantage of fly ash applications in steel fiber reinforced concrete (*1–3,6*):

- The presence of carbon in fly ash reduces the entrained air content in fly ash concrete. Hence, the dosage of the air-entraining agent used in fly ash concrete should be adjusted according to the carbon content of the fly ash.
- Fly ash generally slows down the rates of setting and hardening of concrete, and fly ash concrete is more sensitive

to temperature variations. Thus, it might need more favorable curing conditions than conventional concrete.

- Because fly ash is a byproduct, it has larger variations in chemical and physical properties than portland cement. Therefore, appropriate quality control measures should be taken depending on the specific job requirements.

Silica Fume

Silica fume is a byproduct resulting from the reduction of high-purity quartz with coal in electric arc furnaces during the production of silicon and silicon alloys (*7*). The fineness and high pozzolanic reactivity of silica fume make it highly effective in enhancing the structural density and adhesion capacity in the bulk of the cement paste, especially within the interface zones between the paste and the mix inclusions, including fibers (*8–10*). Enhanced fiber-matrix bond characteristics have important effects on the strength and ductility of fiber reinforced silica fume concrete under different stress systems.

Steel fiber concretes incorporating silica fume also benefit from the improvements imparted to plain concrete by silica fume, including (*7*)

- Increased cohesiveness and reduced segregation tendencies;
- Reduced permeability resulting from the decrease in the number of coarse pores in the cement paste incorporating silica fume, leading to enhanced durability of the material;
- The potential for developing very high strengths; and
- Greater sulfate resistance and reduced alkali-aggregate reactivity.

The optimum application of silica fume in concrete and fiber reinforced concrete would require the following precautions:

- The high surface area of silica fume requires a larger dosage of the air-entraining agent to produce the target entrained air content.
- Silica fume tends to make concrete mixtures rather sticky. Therefore, an increased water content or the use of water-reducing agents, or both, would be necessary to maintain the consistency of the mix.
- Silica fume, mainly due to its high affinity for water, does not leave adequate free water in the mixture and reduces the bleeding of concrete. This reduces the supply of water to the surface and requires the adoption of curing procedures. These procedures prevent early moisture loss from freshly placed concrete, which in turn prevents plastic shrinkage cracking.

EXPERIMENTAL PROGRAM

Different steel fiber reinforced concrete mixes with variable percentages of cement substituted with fly ash or silica fume were manufactured, and their characteristics in the fresh and hardened states were assessed.

The mixes with fly ash had a water-to-binder (cement plus fly ash) ratio of 0.42, and those with silica fume had a water-to-binder (cement plus silica fume) ratio of 0.40. The mixes with fly ash incorporated a 2 percent volume fraction of steel fibers (260 lb/yd^3), while those with silica fume had a fiber volume fraction of 1.5 percent (195 lb/yd^3). The fraction substitutions of cement with fly ash were 0 percent, 20 percent, 30 percent, and 40 percent by weight. In mixes with silica fume, 0 percent, 5 percent, 10 percent, and 20 percent by weight of portland cement were substituted with silica fume.

All the mixes had an aggregate-binder ratio of 4.0 (700–730 lb/yd^3 of binder and 2,800–2,900 lb/yd^3 of aggregates), a sand-gravel ratio of 1.0, a maximum aggregate size of ¾ in. (19 mm), and a superplasticizer-binder ratio of 0.015 by weight.

The steel fibers used in this study were straight and round. They had a length of 2 in. (51 mm), and a diameter of 0.035 in. (0.8 mm), and an aspect ratio of 57.

Type I portland cement was used and the superplasticizer was Daracem 100—a naphtalene-based high-range water reducer capable of maintaining its effectiveness over a relatively long time period. The fly ash was Type F (ASTM C618-85) and was obtained from the Eckert plant of the Lansing Board of Water and Light. Some physical and chemical properties of this fly ash (*11*) are as follows (*13*):

- Chemical composition (loss on ignition = 4.3 percent):

Component	*Percentage by weight*
SiO_2	47.0
Al_2O_3	22.1
Fe_2O_3	23.4
TiO_2	1.1
CaO	2.6
MgO	0.7
K_2O	2.0

- Gradation (lin = 25.4 mm):

Sieve (size)	*Percentage Passing*
#30 (0.6 mm, 600 μ)	100
#200 (0.074 mm, 74 μ)	92
#325 (0.045 mm, 45 μ)	84
(0.020 mm, 20 μ)	63
(0.010 mm, 10 μ)	36
(0.005 mm, 5 μ)	17

- Specific gravity = 2.245.

The silica fume used in this investigation was a product of Elkem Materials, and its chemical and physical properties are:

- Chemical composition:

Component	*Percentage by weight*
SiO_2	96.50
C	1.40
Fe_2O_3	0.15
MgO	0.20
Al_2O_3	0.15
K_2O	0.04
Na_2O	0.20

- Physical properties:

Specific gravity = 2.3
Bulk density = 14 lb/ft^3 = 225 kg/m^3
Specific surface = 200,000 am^3/g = 14 × 10^6 in.^{2}/lb
Average particle size = 0.15 micron = 6 × 10^{-5} in.
Particles smaller than 45 microns (0.018 in.) = 99.5 percent

The aggregates were natural river gravel and sand.

A rotary drum mixer was used to manufacture the steel fiber reinforced concretes with silica fume and fly ash. The fresh mix workability was measured by the inverted slump cone testing procedure (*12*). Note that a shorter inverted slump cone time indicates better workability.

Following the experiments on fresh mix, 6 × 12 in. (150 × 300 mm) cylindrical specimens for the compression test and 6 × 6 × 20 in. (150 × 150 × 500 mm) prismatic specimens for the flexural test were cast and compacted on a vibration table. All specimens were demolded after 24 hr, during which they were kept under a plastic sheet. The fly ash concrete specimens were moist cured at 100 percent relative humidity and 72°F (23°C) for 7 days and were then cured in a regular laboratory environment. A total of 6 compression and 3 flexural test specimens were constructed for each fly ash concrete mix. The three flexural specimens and two of the compression specimens were tested at 28 days. Two of the compression specimens were tested at an age of 1 day and the other two at 7 days. The silica fume concrete specimens (2 compression and 3 flexure) were all moist cured after demolding at 72°F (23°C) and 100 percent relative humidity until the test age of 28 days.

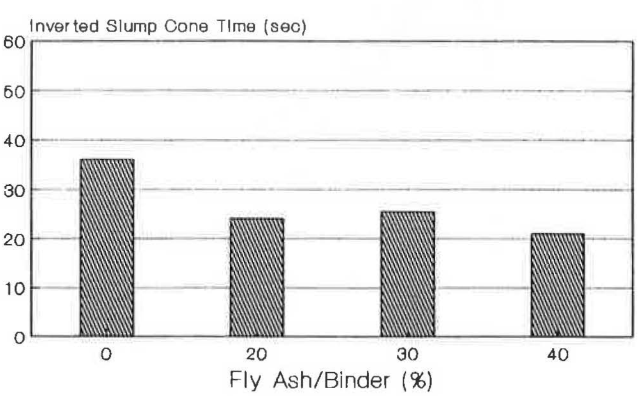
The flexural tests were performed quasi-statically using the four-point loading procedure of ASTM C1018-85 on a span of 18 in. (450 mm), and the load-deflection (at the load point) relationship was monitored throughout the test. Complete stress-strain relationships were obtained in compression tests performed at the age of 28 days.

EXPERIMENTAL RESULTS

The results of tests on the fresh mix and hardened material properties of steel fiber reinforced concretes with different fly ash or silica fume contents are discussed below.

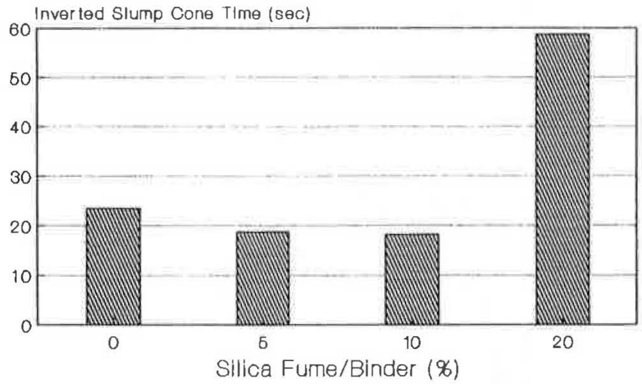
Fresh Mix Workability

The results of the inverted slump cone test on fiber reinforced concretes incorporating fly ash and silica fume are shown in Figures 1 and 2, respectively, as functions of the pozzolan content. As indicated in Figure 1, the substitution of increasing fractions of cement with Type F fly ash reduces the inverted slump cone time of steel fiber reinforced concrete, which indicates improvements in the compactibility of fresh mix under vibration in the presence of fly ash. Except for the mix without fly ash, all steel fiber reinforced concretes (with 20 percent–40 percent fly ash-binder ratios) have inverted slump cone times within the acceptable limit of 10 to 30 sec.



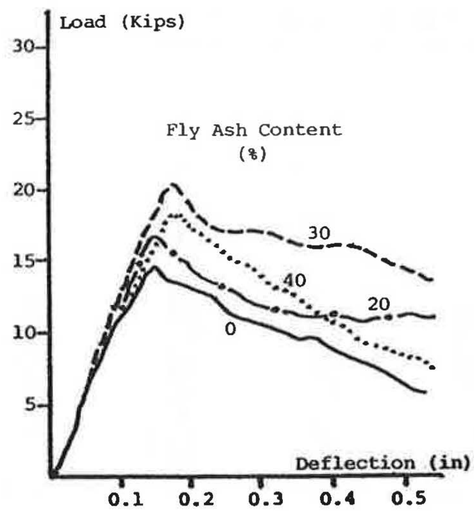
NOTE: Vf = 2 percent.

FIGURE 1 Inverted slump cone test results: fly ash concrete.



NOTE: Vf = 1.5 percent.

FIGURE 2 Inverted slump cone test results: silica fume concrete.



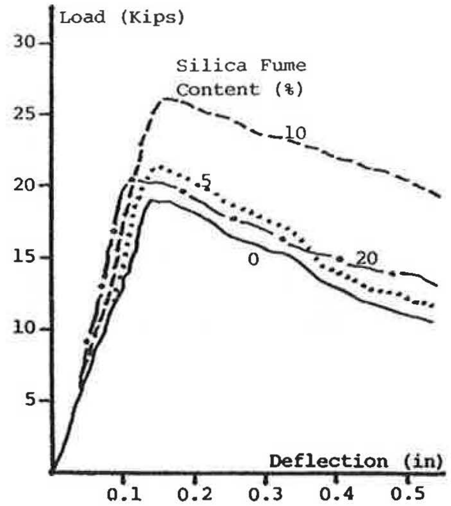
NOTE: 1 kN = 0.22 kip; 1 mm = 0.04 in.; Vf = 2 percent.

FIGURE 3 Flexural load-deflection relationships: fly ash concrete.

Figure 2 shows that the substitution of portland cement with silica fume up to 10 percent by weight has relatively little effect on the fresh mix workability of steel fiber reinforced concrete. Higher silica fume contents, however, tend to damage workability.

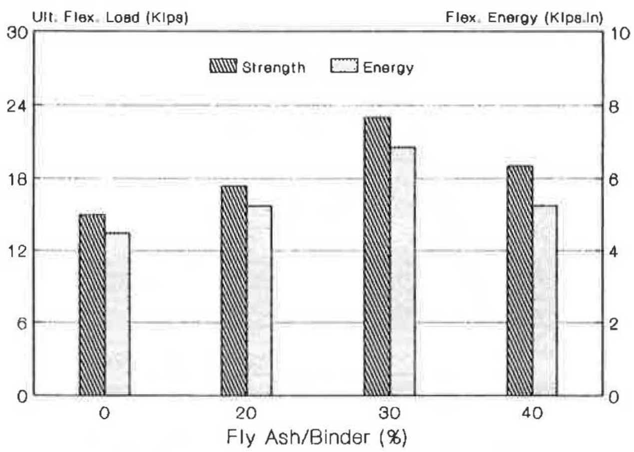
Flexural Behavior

Complete flexural load-deflection relationships are shown in Figures 3 and 4 for mixes with fly ash and silica fume, respectively. Each curve represents the average of three test results. Figures 5 and 6 summarize the trends observed in Figures 1



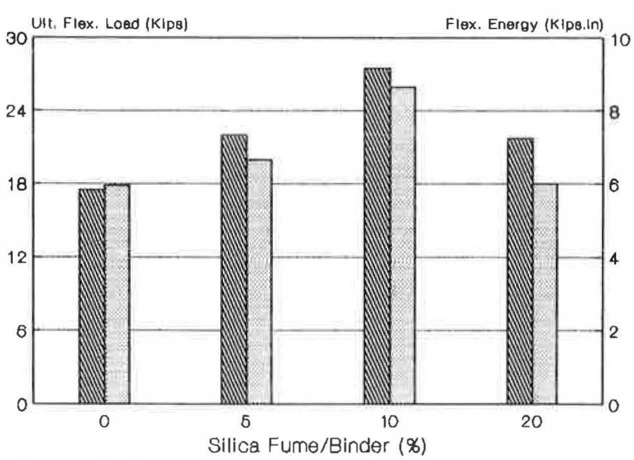
NOTE: 1 kN = 0.22 kip; 1 mm = 0.04 in.; Vf = 1.5 percent.

FIGURE 4 Flexural load-deflection relationships: silica fume concrete.



NOTE: 1 kN = 0.22 kip; 1 Nm = 8.7 (lb in.); Vf = 2 percent.

FIGURE 5 Flexural strength and energy absorption test results: fly ash concrete.



NOTE: 1 kN = 0.22 kip; 1 Nm = 8.7 (lb in.); Vf = 1.5 percent.

FIGURE 6 Flexural strength and energy absorption test results: silica fume concrete.

and 2 regarding the fly ash and silica fume effects, respectively, on flexural strength and flexural energy absorption capacity (the area under the load-deflection diagram up to a deflection 5.5 times the cracking deflection).

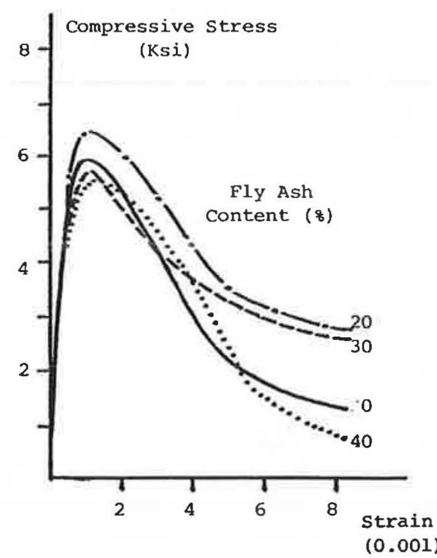
The results presented in Figures 3 and 5 indicate that the flexural strength and energy absorption capacity of steel fiber reinforced concrete tend to improve with increasing fly ash content up to a fly ash-binder ratio of 0.3 but drops at higher fly ash contents. From Figures 4 and 6 it can be concluded that the increase in silica fume-binder ratio up to 10 percent improves the flexural strength and energy absorption capacity of steel fiber reinforced concrete. This trend tends to be reversed, however, at higher silica fume contents.

Compressive Behavior

The compressive stress-strain relationships and the compressive strengths and energy absorption capacities derived from test results on steel fiber reinforced fly ash and silica fume concretes are presented in Figures 7 through 10. The compressive energy absorption capacity is defined as the area underneath the compressive stress-strain relationship up to a strain 5.5 times the strain at peak compressive stress.

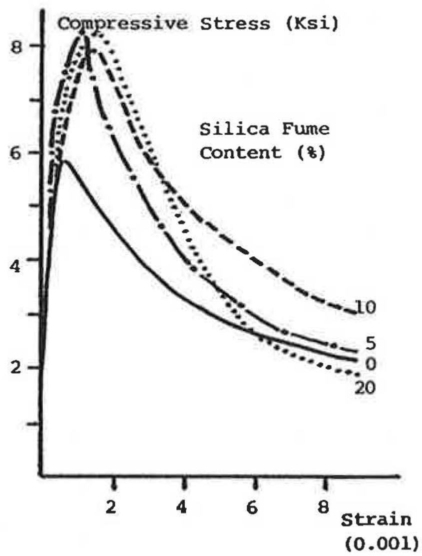
The test results on steel fiber reinforced fly ash concrete presented in Figures 7 and 9 indicate that an increase in fly ash-binder ratio up to 20 percent improves the compressive strength and energy absorption capacity of steel fiber reinforced concrete. This trend tends to be reversed at higher fly ash contents.

The trends in the effects of silica fume content on the compressive behavior of steel fiber reinforced concrete, shown in Figures 8 and 10, indicate that the increase in silica fume-binder ratio up to 10 percent improves the compressive strength and energy absorption capacity, and the increase in silica fume-binder ratio from 10 percent to 20 percent has a relatively small effect on the compressive behavior.



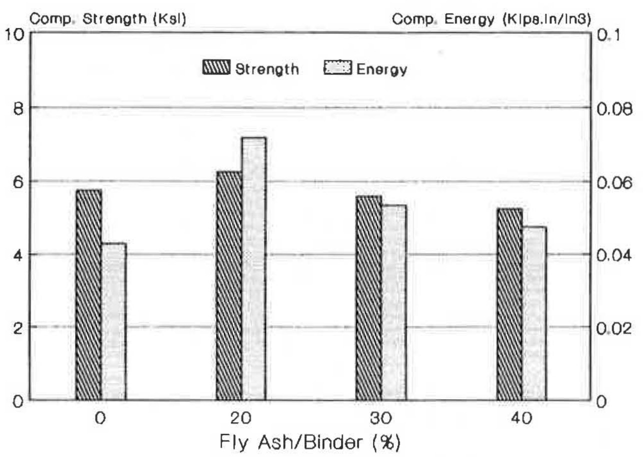
NOTE: 1 MPa = 145 psi; Vf = 2 percent.

FIGURE 7 Compressive stress-strain relationships: fly ash concrete.



NOTE: 1 MPa = 145 psi; Vf = 1.5 percent.

FIGURE 8 Compressive stress-strain relationships: silica fume concrete.

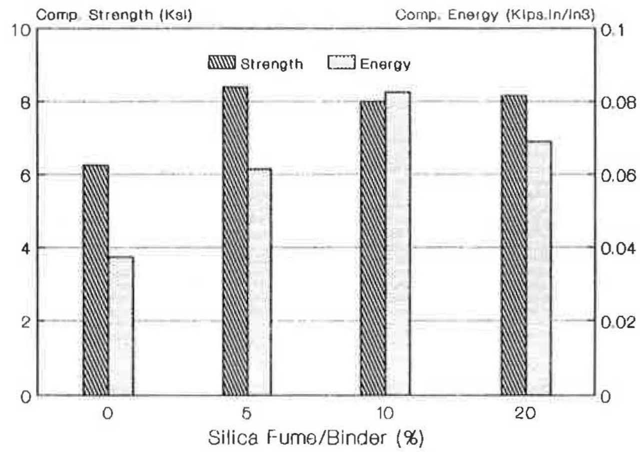


NOTE: 1 MPa = 145 psi; 1Nm/m^3 = 530,000 lb in./in.^{3}; Vf = 2 percent.

FIGURE 9 Compressive and energy absorption strength test results: fly ash concrete.

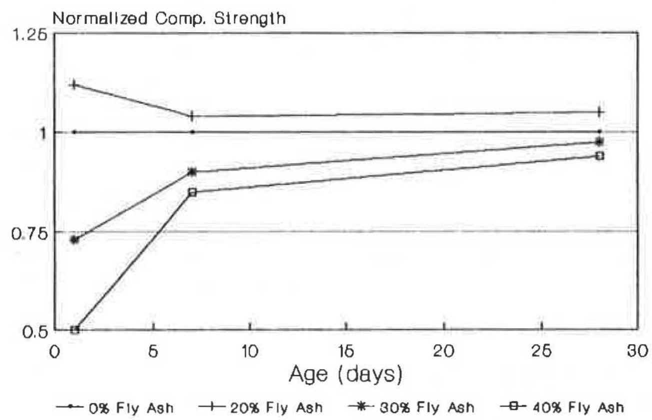
Development of Strength with Time

For the fly ash concrete mixtures, the effect of fly ash content on the development of compressive strength with time was assessed. The trends in the development of compressive strength with time for steel fiber reinforced concretes incorporating different fly ash contents are shown in Figure 11. Strength at each age has been normalized in this figure with respect to the corresponding strength of the fibrous mix with 0 percent fly ash content. It can be concluded from Figure 11 that the substitution of 20 percent of cement with fly ash increases the compressive strength of steel fiber reinforced concrete even at early ages, when compared with the corresponding mix without fly ash. When 30 percent or 40 percent of cement is substituted by fly ash, however, there seems to be a drop in the rate of strength development with time.



NOTE: 1 MPa = 145 psi; 1Nm/m^3 = 530,000 lb in./in.^{3}; Vf = 1.5 percent.

FIGURE 10 Compressive and energy absorption strength test results: silica fume concrete.



NOTE: Vf = 2 percent.

FIGURE 11 Fly ash effects on development of strength with time in steel fiber reinforced concrete.

SUMMARY AND CONCLUSIONS

The effect of silica fume and Class F fly ash contents on the properties of steel fiber reinforced concrete in fresh and hardened states were investigated experimentally. From the results it was concluded that:

Silica Fume Effects

- The compactibility of steel fiber reinforced concrete, as indicated by the inverted slump cone test results, was not much influenced by the increase in silica fume-binder ratio up to a value of about 0.10. Higher silica fume contents, however, adversely affected the workability of fresh mix.
- The flexural strength and energy absorption capacity of steel fiber reinforced concrete tended to increase with an increasing silica fume-binder ratio up to a value of about 0.10; beyond this value, the effects of silica fume on these aspects of the hardened material behavior were reversed.

- The compressive strength and energy absorption capacity of steel fiber reinforced concrete tended to increase with an increasing silica fume-binder ratio up to a value of 0.10. Further increases in silica fume content had relatively little effect on the compressive behavior of steel fiber reinforced concrete.
- For the steel fiber reinforced concrete mixes used in this study, substitution of 10 percent of cement with silica fume gave the best results with respect to the workability of fresh mix and the strength and energy absorption capacity of the hardened material under the action of flexural and compressive loads.

Fly Ash Effects

- Substitution of cement with Class F fly ash in steel fiber reinforced concrete mixes generally had positive effects on the workability of fresh mix as represented by the inverted slump cone time test results.
- The 28-day flexural strength and energy absorption capacity of steel fiber reinforced concretes tended to rise with an increasing fly ash-binder ratio up to about 0.3. An increase in this ratio from 0.3 to 0.4, however, adversely influenced the flexural performance of steel fiber reinforced concrete.
- The substitution of up to 20 percent of cement with fly ash in steel fiber reinforced concrete mixes resulted in improved 28-day compressive strength and energy absorption capacity of the material. Higher fly ash contents, however, adversely affected the compressive characteristics.
- The substitution of more than 20 percent of cement with fly ash tended to reduce the rate of compressive strength development with time at early ages in steel fiber reinforced concrete.
- The optimum fly ash-binder ratio observed for achieving desirable fresh mix workability and hardened material flexural and compressive properties in steel fiber reinforced concrete mixtures was in the range of 0.20–0.30. The use of fly ash-binder ratios above 20 percent led to a lower rate of strength development at early ages in steel fiber reinforced concrete.

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