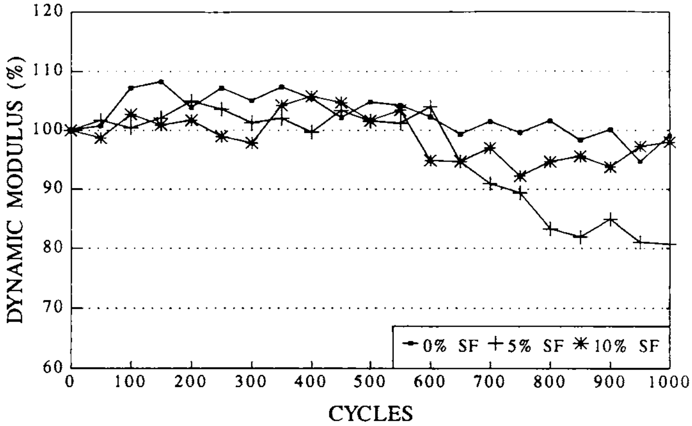

Fig. 9—Freezing-thawing durability of non-air-entrained concrete (0 percent silica fume) at 90 days

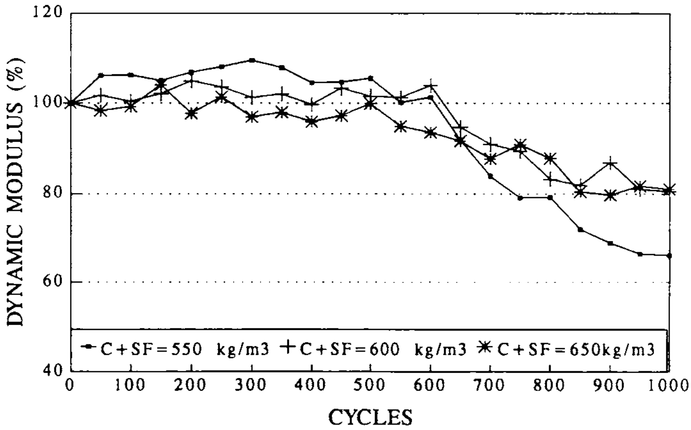

Fig. 10—Freezing-thawing durability of non-air-entrained concrete with varying silica fume contents (w/c = 0.24) at 28 days

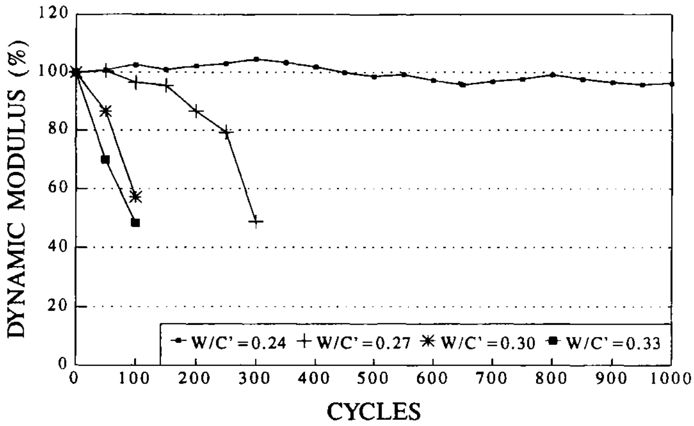

Fig. 11—Freezing-thawing durability of non-air-entrained concrete with varying total cementitious content (w/c = 0.24) at 28 days

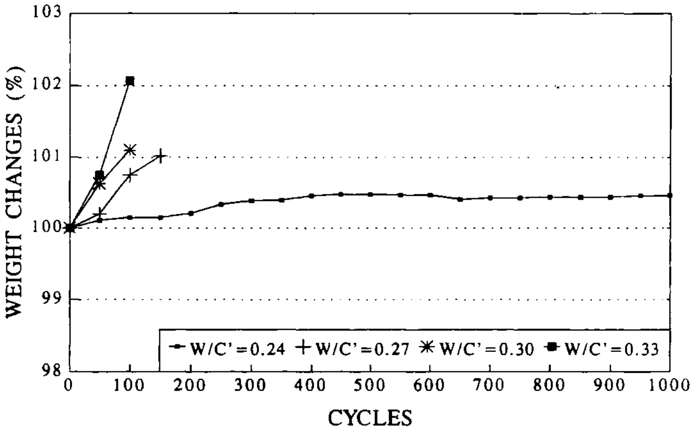

Fig. 12—Effect of freezing-thawing cycles on weight change of non-air-entrained concrete (limestone aggregate) at 28 days

SP 149-32

Effects of Silica Fume on Creep and Shrinkage of Steel Fiber-Reinforced Concrete

by J.C. Chern and C.Y. Chang

Synopsis: This paper presents the results of an investigation on the long-term deformation of steel fiber reinforced concrete containing silica fume. The influence of loading ages on the creep and ages of curing on the shrinkage of specimens was investigated. The volume fraction of steel fibers used in concrete are 0 %, 1 %, and 2 %. The addition of silica fume is 0 %, 5 %, and 10 % by weight of cement. Test results indicate that the combined effect of fibers and silica fume reduces the creep and shrinkage and enhances the development of compressive strength of concrete. At specific silica fume content, 10 %, the effect of increasing fiber content to reduce creep and shrinkage decreases gradually as the fiber content increases. This phenomena is similar to the addition of silica fume in concrete with 1 % volume fraction of steel fibers.

Keywords: Aggregates; compressive strength; creep properties; fiber reinforced concrete; mix proportioning; shrinkage; silica fume

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INTRODUCTION

Time-dependent strains in concrete can have a significant effect on the structural behviour of concrete and must be considered in engineering design. The strains may be creep due to stress, or shrinkage associated with moisture loss. Concrete containing discontinuous steel fibers, called steel fiber reinforced concrete (SFRC), has been under extensive research in recent years and has many superior engineering properties compared with conventional plain concrete [1,2]. As interest increases to apply this material in construction, such as bridge deck, concrete pavement and building floor applications, an understanding of shrinkage which often leads to cracking, and creep which may relax stress or induce excess deflection is becoming more important.

The effect of fibers on material behavior of concrete mostly comes from the interfacial bond strength between fibers and paste, the factors which influence the strength of mortar certainly influence the bond strength. The fibers have a dual role to suppress the crack initiation and propagation of cracks, and to bridge over the crack once it has advanced, to increase its ductility. Silica fume, a highly fine material, can be used to improve the mechanical property of the porous layer of the transition zone between fibers and matrix through physical densification and chemical pozzolanic process. There exists limited literature reporting creep and shrinkage of steel fiber reinforced concrete. The results available are even more limited in the area of creep according to a recent survey by Balaguru ans Shah [2]. Creep and shrinkage of steel fiber reinforced concrete with an average compressive strength of about 4,800 psi (33 MPa) at 28 days, has been investigated [4,5]. Creep of concrete containing fibers and silica fume has been presented by Houde et al. [3]. With 0%, 5%, and 10% silica fume weight replacement of cement, the 28-day compressive in concrete with or without silica fume. This results tend to contradict the results of References 4 and 8. Therefore, this study was undertaken to evaluate the effects of silica fume on the deformations of SFRC and plain concrete with higher strengths. The influence of silica fume content on creep at various loading ages and on shrinkage specimens at different ages (times of initial measurement) were investigated.

TEST PROGRAMME

The materials used were ASTM C150 Type I portland cement, steel fibers and local crushed limestone aggregate with a maximum size of 9.5 mm. Steel fibers used were 25 mm straight carbon steel fibers. The equivalent diameter of the fiber is 0.43 mm, the corresponding aspect ratio is 58. Fine aggregate used has a fineness modulus of 2.66 and a grading satisfying ASTM C33 requirements. Results of sieve analysis for coarse and fine aggregate are listed in Table 1. Type 920-U Elkem undensified silica fume with volumetric density 200 $\sim$ 300 kg/cm^3 and specific surface area 18 $\sim$ 28 m^2/g was used. The superplasticizer which conforms to ASTM C494 Type G specification is used to enhance the mixing effect and increase the workability of the mix. Concrete mix designs are shown in Table 2. Specimens for the tests were cast in watertight cast iron molds. All specimens were unsealed and cured in accordance with ASTM C 512-87, that is, in a moist room at 23°C until the day of testing. The major parameters used in the tests were age of concrete, fiber content, and the weight replacement of portland cement by silica fume. The steel fiber content ranged between 0 and 2% by volume fractions of mix. The weight replacements of portland cement by silica fume were 0, 5, and 10%.

The shrinkage tests were conducted in drying room which was automatically controlled to maintain constant temperature (23±0.5°C) and constant humidity (50±2 % R.H.). Cylindrical specimens of size 10 by 30 cm were used for the tests. Each test set included four specimens, two were specimens for drying test and two other specimens are stored in the moist room and used as control specimens. Specimens placed in drying room were sealed by foil to prevent moisture loss from the top and bottom of cylinders. Tests of concrete shrinkage were carried out according to ASTM C341-89. The specimens were exposed to 50% relative humidity on 3, 7, and 28 days after casting. The effective drying shrinkage was counted as the difference between the amount of shrinkage measured in drying room and that of control specimen.

All specimens for creep tests were 10 by 30 cm cylinders and were unsealed. Two types of creep tests were performed, which are basic creep tests conducted in the moist room at 23°C and 100% R.H., and creep tests in the drying room at 50% R.H. and 23°C . The specimens were ton jack, a load cell and a system of coil springs held in compression by a system of rods and plates between which the specimen was clamped. The desired load, which was calculated as one fourth of the compressive strength measured from companion strength cylinders, was applied by a hydraulic jack. The strain was measured at proper time intervals by Demec strain gauge. There are control specimens stored with no load in the moist room and in the drying room, and concrete cylinders for compressive strength. The size of specimens for compressive test is 10 by 20 cm cylinder.

RESULTS AND DISCUSSION

Compressive strength

Figs. 1a and 1b show the test results for compressive strength versus ages of concrete. The 28-day compressive strengths averaged from 8,000 to 10,500 psi (60 to 79 MPa). Concrete with higher volume fraction of steel fiber and higher content of silica fume yields higher compressive strength. Due to the gradual increase of bond strength between matrix and fibers, the compressive strength of steel fiber reinforced concrete increases with time. The increase of bond strength is due to the improvement of transition zone in the vicinity of fiber surface [6]. The microstructure of the transition zone (Fig. 2), mainly made of colloidal CSH particles and large crystal of CH, is gradually improved with the chemical process of packed silica fume particles. In Fig. 1a, concrete with 2% steel fibers volume fraction is 30% higher in compressive strength than that without steel fibers at the age of 28 days. For 1% SFRC, the increase of compressive strength is higher for concrete with higher silica fume content; however it is not a linear relation. The rate increase is decreasing for the concrete with higher silica fume content as shown in the Fig. 1b.

Shrinkage tests

Figs. 3a $\sim$ 3c give the shrinkage strain for specimens starting tests at various ages; it shows specimens with a earlier exposure age,t_0, yield higher shrinkage strain. In these figures, the shrinkage of 1% SFRC decreases when the silica fume is used; the more the silica fume added the less the shrinkage measured. The difference of shrinkage between 1% SFRC with and without 5% silica fume (represented by SF 5%) is larger than that between 5% and 10% silica fume as the duration of test increases.

Fig. 4 shows the effect of steel fibers on the shrinkage of 10% silica fume concrete. The more fibers added, the less shrinkage measured. The development of strength in transition zone makes steel fibers more

Creep tests

The results in Figs. 5a to 5c shows the effect of ages of concrete at time of loading on deformation in the drying room. Three ages of loading were chosen, namely, 3 days, 7 days, and 28 days. J(t,t'), shown in the ordinate of these figures, is the creep function which represents the strain at time t caused by a unit sustained load acting since time t'. The age of loading, t', is similar to the age of concrete after casting. It can be seen that creep of concrete is greater for specimens loaded at younger age. The results indicate that the use of silica fume in 1% SFRC decreases the creep of concrete; the creep progressively decreases with content of silica fume increases. It also found that silica fume has led the decrease of creep and elastic deformation at early stage of loading as shown in the Fig. 5. The difference of deformation between 1% SFRC with 5% silica fume and without silica fume is much larger than the difference between 5% and 10% silica fume concrete as the duration of test increases.

Fig. 6 illustrates the relation between time duration and creep function of 10% silica fume concrete at different volume fractions of steel fibers. The results show that the deformation is greatly reduced with the addition of steel fibers. It also shows that the fibers become more effective in restraining creep of the cement matrices as the time under load increases. This was explained due to the function of steel fibers which provide restraint to the flow characteristics of cement matrices, this effect becomes more pronounced at later times [7,8,9]. Test results of Fig. 6 are consistent with that found in References 4 and 8; but not the same as that found by Houde et al. using silica fume concrete [3]. Balaguru [2] indicated that the contradiction can be due to the low fiber fraction and higher aggregate content compared to mixes used in References 4 and 8. More research on creep and shrinkage tests on SFRC with low fiber volume fractions are needed to resolve the differences.

Fig. 7 presents the results of creep tests performed in the moist room and drying room. Creep measured at moist room, called basic creep, is much smaller than that in the drying room. The total deformation measured in the drying room includes elastic strain, shrinkage, basic creep, and drying creep [10]. The results show that creep reduction occurs when silica fume concrete was reinforced with fibers either in the drying room or moist room.

CONCLUSIONS

The following conclusions can be drawn from the results of this research:

fibers and silica fume leads to the significant increase of compressive strength and the decrease of long-term deformations of concrete; the effect is much more pronounced at later times.

2. From both the economic and engineering view points, the investigations of optimal amount of steel fibers and silica fume on the time-dependent deformations of SFRC show that 5% silica fume addition has the best merit to reduce creep and shrinkage of 1% SFRC. It also shows that 10% silica fume concrete specimens containing higher volume fraction of steel fibers yield less shrinkage, less basic creep, and less total deformation of creep test in a drying condition. The proper amount, which has the best advantages, is concrete containing 1% steel fibers volume fraction.

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TABLE 1 — SIEVE ANALYSES FOR COARSE AGGREGATE AND FINE AGGREGATE

Sieve size	3/4"	1/2"	3/8"	# 4	#8		
Cumulative percentage passing %	100	86	51	6	2		
Sieve size	# 4	# 8	#16	#30	#50	#100	F.M.
Cumulative percentage passing %	100	98	57	35	15	5.1	2.66

*1 inch=2.54 mm

TABLE 2 — MIX PROPORTION OF CONCRETE (per m^3)

Mix	Group 1			Group 2		
fiber content(%)	2	2	2	0	1	2
SF(wt. repl. %)	0	5	10	10	10	10
w/(c+SF)	0.28	0.28	0.28	0.28	0.28	0.28
cement(kg)	561	533	505	505	505	505
sand(kg)	617	617	617	617	617	617
coarse aggr.(kg)	1065	1065	1065	1065	1065	1065
silica fume(kg)	0	28	56	56	56	56
SP(kg)	8.4	8.4	8.4	8.4	8.4	8.4
slump(cm)	10 ~ 12	7 ~ 9	6 ~ 8	11 ~ 13	9 ~ 11	7 ~ 9

* SP(superplasticizer) is 1.5% weight of cement.

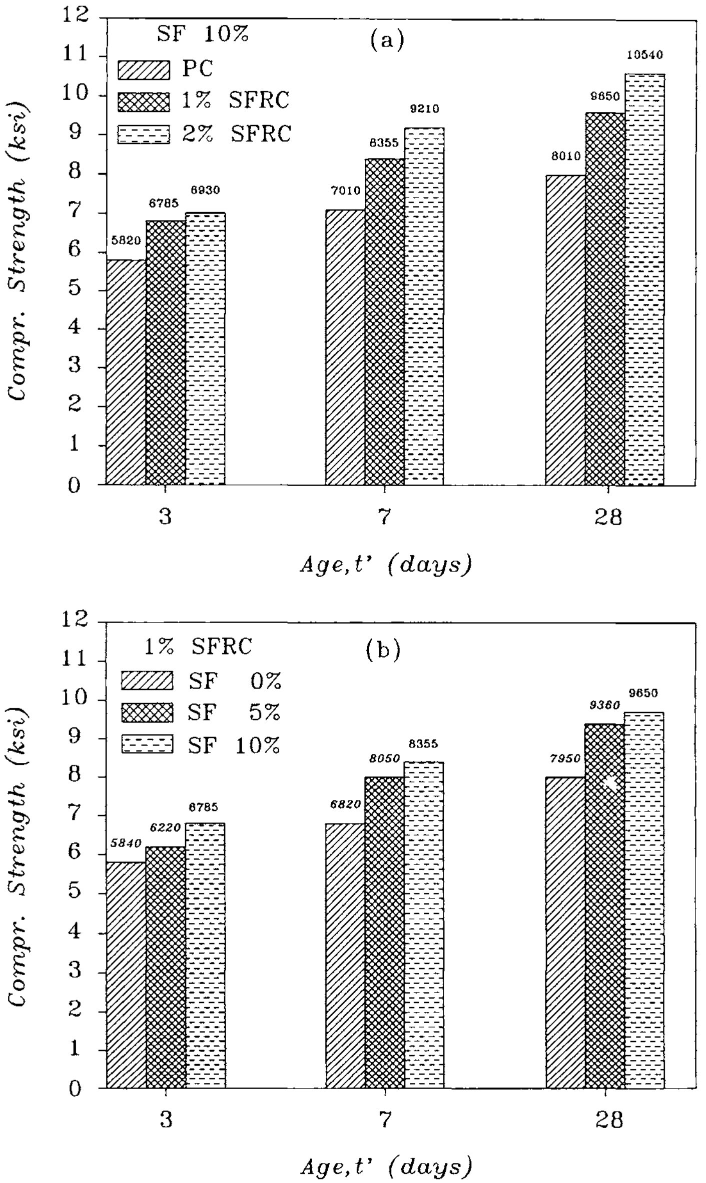

Fig. 1—Compressive strength of concrete specimens at various ages (1 ksi = 6.9 MPa)