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INFLUENCES OF FIBER CONTENT ON PROPERTIES OF SELF-COMPACTING STEEL FIBER REINFORCED CONCRETE

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ABSTRACT

This paper deals with the mix design and mechanical properties of self-compacting steel fiber reinforced concrete (SFRC). By using superplasticizers and mineral admixtures such as slag and fly ash, three SFRC of different fiber contents (0.5, 1.0 and 1.5%) and one plain concrete with high fluidity (slump ≈250mm) have successfully been developed without bleeding or segregation. The compressive and flexural strengths, flexural toughness as well as shrinkage and creep of the four mixes of concrete were studied. It has been shown that increasing steel fiber content can improve the flexural strength and toughness of self-compacting SFRC even though its compressive strength could be reduced due to the increase of air content. It has also been found that the addition of steel fibers can efficiently reduce both the autogenous and drying shrinkages of the self-compacting SFRC. The models of ACI Committee 209 accurately predicted the autogenous shrinkage of the plain self-compacting concrete but they overestimated its drying shrinkage and creep.

Key Words: steel fibers, self-compacting concrete, flexural strength, drying shrinkage.

I. INTRODUCTION

Since its invention in the early 1960s, steel fiber reinforced concrete (SFRC) has been successfully used in various types of construction: airport and highway pavements, slabs and floors, bridge decks, tunnel linings, shotcrete coverings, seismic-resistant and explosion-resistant structures, etc. (Vondran, 1991; Shah and Skarendahl, 1986; ACI, 1984) Such a success is essentially due to the fact that adding steel fibers improves the durability and mechanical properties of hardened concrete, notably flexural strength, toughness, impact strength, resistance to fatigue, vulnerability to cracking and spalling (Williamson, 1965; Shah and Baston, 1987; Johnston, 1980). However, the addition of steel fibers also reduces the workability of fresh concrete, hence the use of SFRC becomes inappropriate in cases where a good workability of concrete is needed.

Self-compacting concrete has recently been successfully developed in several countries (Aitcin and Miao, 1992; Miao, 1996; Okamura, 1997; Chern *et al.*, 1995). In addition to its high workability and superior mechanical properties over normal strength concrete, self-compacting concrete reduces the energy expense and time required for consolidation at job site. Nevertheless, two problems remain unsolved, they are: (1) SFRC is as brittle as normal strength concrete and (2) it is more susceptible to spall under elevated temperatures (Noumowe *et al.*, 1996).

An extensive four-year collaborative research program between the National Taiwan University (Taipei, Taiwan) and University of Moncton (New Brunswick, Canada) was started in 1996 to study self-compacting SFRC which combines the ductility of SFRC with the workability of self-compacting concrete. The scope of the overall research program includes mix design, mechanical properties (compressive strength, modulus of rupture, flexural toughness), creep and shrinkage, and behavior under high temperatures. This paper presents the mix design and the effects of steel fibers on compressive strength and flexural behavior of self-compacting SFRC.

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Table 1 Chemical composition and physical characteristics of the cement, slag, and fly ash

Constituent	Cement	Slag	Fly ash
SiO_2, %	21.7	34.8	46.7
Al_2O_3, %	5.10	13.7	27.8
CaO, %	65.0	41.2	6.27
Fe_2O_3, %	3.20	0.34	5.23
MgO, %	1.40	7.50	1.63
SO_3, %	2.27	1.98	0.79
Na_2O equivalent, %	0.59	0.29	–
Loss on ignition, %	0.91	–	5.02
Specific gravity, g/cm^3	3.15	2.86	2.12
Specific surface (Blaine), cm^2/g	3150	4450	–

II. MIX DESIGN

A self-compacting SFRC should be a very fluid concrete without bleeding or segregation. The slump loss should also be well controlled. To satisfy those requirements, materials had to be carefully selected and their proportion optimized.

In addition to the control concrete (no fiber), three different volume fractions (0.5, 1.0, and 1.5%) were chosen to study the effect of fiber content. To facilitate the presentation of the experimental results, each concrete mix was identified by the letter *F* followed by its fiber content in percentage, i.e. F-0, F-0.5, F-1.0, and F-1.5.

1. Material Selection

Dramix Type ZP 30/.5 (30 mm in length and 0.5 mm in diameter) steel fibers and an ASTM Type I portland cement were selected for their large availability on the local market. The fibers used were hooked-end steel fibers with an aspect ratio (Length/Diameter) of 60. Details on the physical and mechanical properties of this kind of fibers can be found in the manufacturer's catalogue. The chemical composition and some physical properties of the cement used are presented in Table 1.

Concrete with high fluidity generally requires a high dosage of superplasticizer. In a pure portland cement concrete, bleeding often occurs under high superplasticizer dosages. Until now, two techniques have been used to solve this problem: 1) use of mineral admixtures and 2) use of a viscosity agent. The first technique was chosen in this investigation. A locally available ground blast furnace slag and an ASTM Class *F* fly ash (c.f. chemical composition and physical properties in Table 1) were chosen to improve the workability of fresh concrete. The experience of this research has shown that this technique is also efficient in reducing slump loss.

The fine aggregate was natural sand with a fineness modulus of 2.76. The coarse aggregate was crushed siliceous gravel with a maximum size of 25 mm. The gradation of both the fine and coarse aggregates satisfies ASTM *C* 33 requirements. A coarse aggregate of 10 mm was first chosen following the guidelines of the ACI Committee 544 (ACI, 1993).

Finally, a naphthalene-based ASTM *C* 494 Type *G* superplasticizer with a solid concentration of 42% was chosen to obtain the high fluidity as designed.

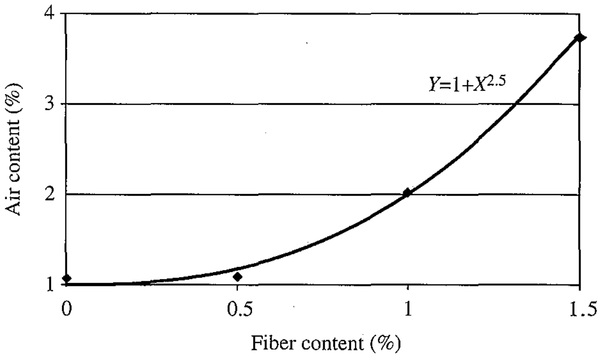

Fig. 1 Entrapped air content versus fiber content

2. Mixture Proportioning

No standard proportioning method is presently available for self-compacting SFRC. Based on the guidelines of ACI Committee 363 (1992) and on other methods for proportioning high strength and ultra high strength concretes, the following procedure was used in the mixture proportioning for this study:

(i) *Water/Binder ratio*: The Water/Binder ratio was fixed as 0.32 to assure high strength of concrete.

(ii) *Fine/Coarse aggregate ratio*: The most dense aggregate packing with a minimum content of voids requires the least amount of cement paste and produces the most fluid concrete mix for a given amount of cement paste. In order to find

Table 2 Mix proportion and properties of fresh concrete

Materials	Mix			
	F-0	F-0.5	F-1.0	F-1.5
Cement (kg/m^3)	244	244	244	244
Water (kg/m^3)	174	174	174	174
Slag (kg/m^3)	128	128	128	128
Fly ash (kg/m^3)	170	170	170	170
Fine aggregates (kg/m^3)	777	768	759	750
Coarse aggregates (kg/m^3)	842	832	822	812
Steel fibers (kg/m^3)	0	39	78	117
Superplasticizer (kg/m^3)	11.7	11.7	11.7	11.7
Slump (mm)	270	260	250	170
Flow (mm)	680	670	600	550
Unit weight (kg/m^3)	2364	2364	2366	2369
Air content (%)	1.07	1.09	2.02	3.74

the optimal Fine/Coarse aggregate ratio corresponding to the most dense aggregate packing, oven dried sand and gravel were mixed at various proportions. The unit weight of each mix was measured following the procedure of ASTM *C* 29. The fine/coarse aggregate ratio 48/52 (by weight) gave the highest unit weight and was therefore used in this study.

(iii) *Mineral admixtures and superplasticizer dosage*: A cement/slag/fly ash mass ratio of 45/25/30 was found to get the most dense paste by optimizing the grain size distribution of the binder (cement + slag + fly ash) using several particle-packing models (de Larrard, 1987; Caquot, 1937; Feret, 1892). Experiments on fresh concrete showed that this ratio also gave the most workable mix without bleeding when using a high superplasticizer dosage of 2.2% (mass ratio of solid superplasticizer/cement) (Shah and Baston, 1987). The slump loss at 45 minutes after mixing was less than 20 mm.

(iv) *Paste/Aggregates ratio*: As compared to normal strength concrete, high-performance concrete generally requires a higher paste volume to provide good workability. A volume ratio of 38/62 between paste (cement + slag + fly ash + water) and total aggregate (sand + gravel) was found to be suitable to obtain a self-compacting concrete without segregation.

3. Mixing Procedure

The following mixing procedure with a total mix time of 10 minutes was found to be satisfactory to produce self-compacting SFRC and was used during all the batches in this study:

(i) Loading and mixing aggregates for 1.5 minutes;
(ii) Adding and mixing cement, slag, and fly ash for 1.5 minutes;
(iii) Adding water premixed with superplasticizer and mixing for 3 minutes;
(iv) Carefully adding (to prevent balling) and mixing steel fibers for 4 minutes.

III. TEST PROCEDURES

The following procedures were used during this study:

Slump – ASTM *C* 143
Unit weight – ASTM *C* 138
Air content – ASTM *C* 231
Compression tests – ASTM *C* 039
Flexion tests – ASTM *C*-1018.

For each compression test, three 100×200mm cylinders were prepared according to the specifications of ASTM *C*192-90, cured in their molds during 24 hours, and then moist cured at 23±1°C until testing.

For each flexion test, three 75×75×300mm beams were prepared and cured in the same manner as the specimens for compression tests. A Yoke type frame was used to eliminate the effect of support settlement on deflection.

IV. PROPERTIES OF FRESH CONCRETE

1.Workability

In addition to the traditional slump value, the minimum and maximum widths of concrete spread, called flow values, were also measured and are reported in Table 2 for the four concretes studied. Highly fluidity (slump > 250 mm) and balling free fibrous concrete was obtained without bleeding or segregation at a maximum fiber content of 1.0%. For the concrete *F*-1.5 containing 1.5% steel fibers, good workability was too difficult to obtain and the air

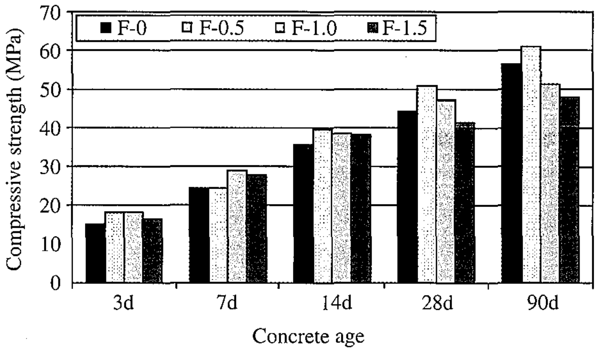

Fig. 2 Compressive strength of concrete

content increased dramatically.

2.Unit Weight and Air Content

The results for unit weight and air content tests are presented in Table 2. The air content of the concretes increased with increasing fiber content. Because no air-entraining agent was used, the air in concrete was entrapped during mixing.

V. MECHANICAL PROPERTIES OF HARDENED CONCRETE

1. Compressive Strength

Figure 2 shows the results of compression tests (average of three specimens). Notice that the within batch variations of compressive strength were higher for the fibrous concretes (*F*-0.5 to *F*-1.5) than for the plain concrete (*F*-0). A strength improvement of 15 to 30% can be observed from 28 to 90 days, likely due to pozzolanic reaction.

It has been reported Shah and Baston (1987) and ACI Committee 544.3 (1993) that adding steel fibers to a normal strength concrete has little, if any, effect on its compressive strength. To illustrate the effect of fiber content on the compressive strength of self-compacting SFRC used in this study, the fibrous to plain strength ratios are shown in Fig. 3 as a function of concrete age. As compared to the plain concrete (*F*-0), the concrete *F*-0.5 containing 0.5% steel fibers showed a strength improvement (up to 20% at early ages) for all the test ages. However, a strength improvement of 10 to 20% was noted for the fibrous concretes *F*-1.0 and *F*-1.5 at early age (3, 7, and 14 days), followed by a decline of up to 15% at 90 days.

Figure 3 also shows that the fibrous to plain concrete strength ratio decreases with increasing fiber content. This can be attributed to the increase of entrapped air content due to fiber addition (see Table 2). In fact, two factors affect the compressive strength of concrete: fiber content and entrapped air content. The former slightly increases the compressive strength of concrete if it does not change the air content, while the latter leads to a decrease in the compressive strength of concrete. According to Aitcin and Lessard (1993), an increase of 1% in air content in high-performance concrete can reduce the compressive strength by 4%.

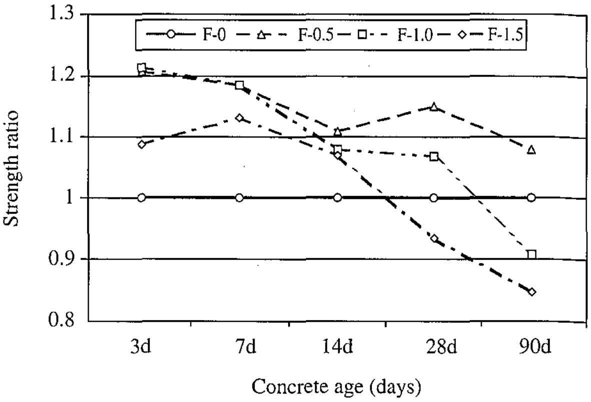

Fig. 3 Fibrous/plain concrete strength ratio

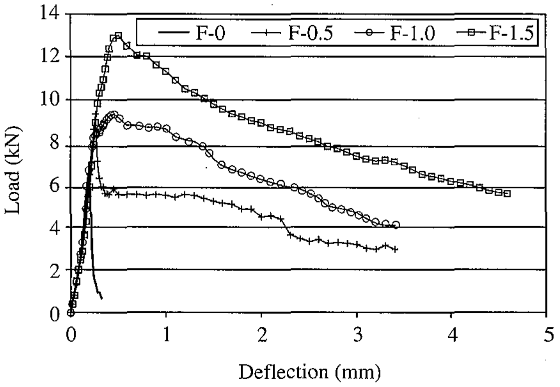

Fig. 4 Typical load-deflection curves from flection tests at 28 days

Figure 3 also indicates that, even though the compressive strength of concrete increased with increasing concrete age, the fibrous to plain concrete strength ratio decreased. This is probably due to the increasing strength of the concrete matrix in the fibrous concrete making the fibrous reinforcement less effective.

2. Flexural Strengths

Flexural tests were performed for the four concretes (*F*-0, *F*-0.5, *F*-1.0, and *F*-1.5) at four ages (3, 7, 14, and 28 days). Representative load-deflection plots for the plain (*F*-0) and fibrous (*F*-0.5, *F*-1.0 et *F*-1.5) concretes are shown in Fig. 4. It indicates that the self-compacting SFRC behaved similarly to normal SFRC.

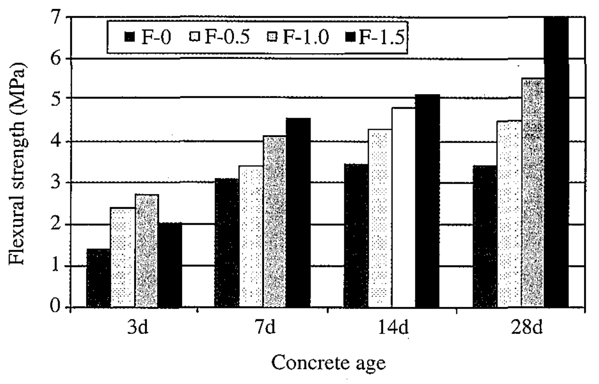

Fig. 5 Flexural strength of concrete (MOR) from flection tests

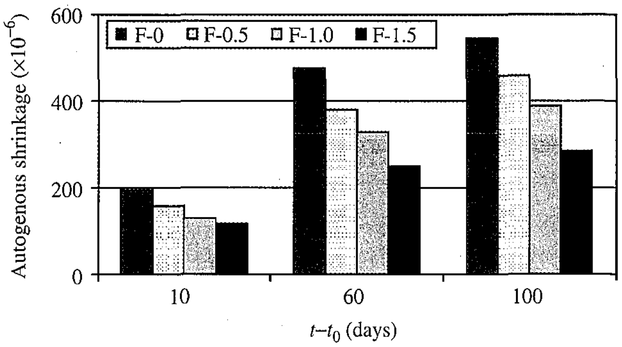

Fig. 7 Autogenous shrinkage of concrete

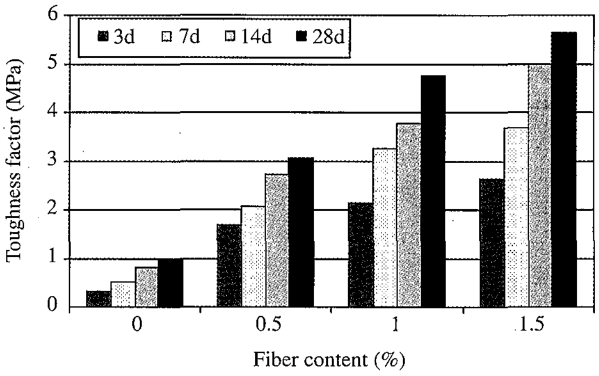

Fig. 6 Japanese flexural toughness factors

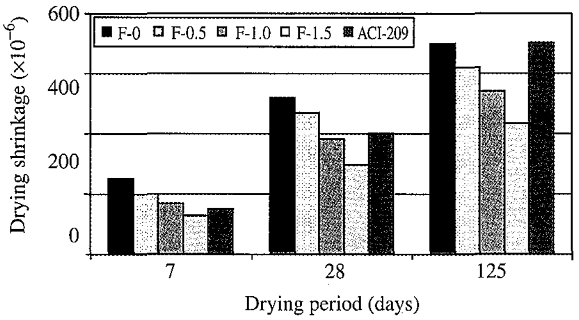

Fig. 8 Drying shrinkage of concrete

Flexural strengths (modulus of rupture), averaged over three specimens for the concretes at different test ages are shown in Fig.5. The flexural strength increased with increasing concrete age and the increases were more substantial for the fibrous concretes (F-0.5 to F-1.5) than for the plain concrete (F-0). At a given age, the flexural strengths increased with increasing fiber content despite the decrease of matrix strength due to increase of air content by adding steel fibers. These increases were higher at more advanced concrete ages (14 and 28 days). The improvement of fiber-matrix interfacial bond due to pozzolanic reaction has probably contributed to this increase.

3. Flexural Toughness

The peak loads, the computed toughness indices (ASTM C1018), and the flexural toughness factors (Japanese Concrete Institute Standard SF-4) are shown in Table 3. The within batch variations of the toughness indices I_5 and I_{10} were lower than that of the index I_{30}. The indices appeared not to be very sensitive to either fiber content or to concrete age.

It is interesting to note that the Japanese flexural toughness factors as defined in JCI-SF4 varied less and were more sensitive to both fiber content and concrete age as compared to the ASTM toughness indices studied. The flexural toughness factors increased both with increasing concrete age and with increasing fiber content (Fig. 6).

4. Shrinkage

Autogenous and drying shrinkages were performed on 100×300 mm cylinders for the four concretes. The specimens were prepared according to the specifications of ASTM C192-90 and cured in the mold during 24 hours. After having been removed from the mold, the specimens for autogenous shrinkage were sealed with sticky aluminum sheets to prevent water loss and then kept at a temperature of 23°C, while those for drying shrinkage were moist cured at 23°C during 7 days before being exposed to drying (23°C, 50% RH). The length change of each specimen was recorded using two 200 mm ELE Demec strain gages attached on opposite sides.

Autogenous shrinkage and drying shrinkage after 90 days are shown in Figs. 7 and 8 for the four concretes. Unlike the behavior of fiber reinforced normal strength concrete as reported in the literature (Shah and Baston, 1987; ACI, 1993), steel fibers have

Table 3 Toughness test results

Mix	Concrete age	Peak load (kN)	ASTM Toughness indices			JCI flexural toughness factor (MPa)
			I_5	I_{10}	I_{30}	
F-0	3d	2.63 (0.20)*	1.00	1.00	1.00	0.32 (0.01)
	7d	5.76 (0.09)	1.00	1.00	1.00	0.51 (0.01)
	14d	6.45 (0.54)	1.00	1.00	1.00	0.81 (0.01)
	28d	6.43 (0.81)	1.00	1.00	1.00	0.96 (0.03)
F-0.5	3d	4.33 (0.11)	4.51 (0.31)	8.08 (0.34)	18.41 (0.53)	1.68 (0.04)
	7d	6.38 (0.25)	4.28 (0.21)	8.12 (0.35)	21.34 (0.83)	2.07 (0.04)
	14d	8.03 (0.56)	4.13 (0.35)	7.72 (0.72)	23.69 (4.05)	2.71 (0.23)
	28d	8.46 (1.27)	4.09 (0.50)	7.48 (1.06)	19.11 (2.65)	3.07 (0.22)
F-1.0	3d	5.08 (0.79)	4.74 (0.53)	8.99 (1.05)	23.02 (2.16)	2.13 (0.26)
	7d	7.73 (1.09)	5.37 (0.21)	9.81 (0.53)	21.35 (2.70)	3.26 (0.32)
	14d	9.04 (0.89)	4.95 (0.46)	9.45 (1.14)	23.40 (3.64)	3.77 (0.25)
	28d	10.38 (1.01)	5.28 (0.35)	10.16 (0.61)	22.50 (3.35)	4.76 (0.19)
F-1.5	3d	3.78 (0.54)	5.12 (0.56)	9.87 (1.18)	28.77 (4.08)	2.63 (0.19)
	7d	8.53 (1.01)	5.26 (0.31)	10.10 (0.23)	24.82 (0.11)	3.68 (0.27)
	14d	8.96 (1.11)	5.37 (0.31)	10.63 (1.14)	25.77 (3.46)	4.99 (0.40)
	28d	13.14 (2.20)	5.00 (0.35)	9.1 (0.90)	20.46 (2.63)	5.65 (0.51)

*Number in parenthesis are standard deviations

significant effect on both autogenous and drying shrinkages for the concretes tested. Both autogenous and drying shrinkages linearly decreased with increasing fiber content (Fig. 9) and they approximately reduced at a rate of 170×10^{-6} per percent steel fibers added. This is probably because self-compacting SFRC used in this study contain more paste, and are therefore more sensitive to fiber content, than ordinary SFRC mentioned in References 4 and 17.

Figure 8 also compares the measured drying shrinkage of the plain concrete F-0 with that predicted by the model of the ACI committee 209 (1992). This model predicts well the drying shrinkage after a long drying period, whereas it underestimates the shrinkage of the concrete after a short drying period.

5. Creep

Compressive creep tests were performed for the concretes *F*-0 and *F*-1.0 according to the specifications of ASTM C-512. For each concrete, two 100× 300 mm cylinders were prepared and cured in the same manner as those for drying shrinkage, and the same type of strain gage was used to measure the length change.

Creep coefficients as defined by ACI Committee 209 (1992) were calculated for each concrete (*F*-0 and *F*-1.0) and are presented in Fig. 10. Adding

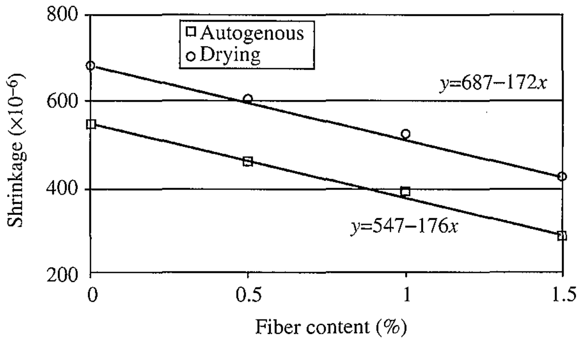

Fig. 9 Shrinkage versus fiber content of concrete

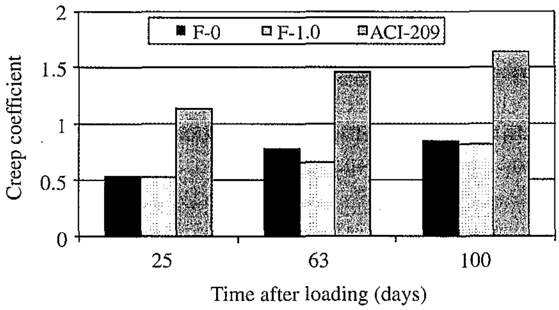

Fig. 10 Creep coefficient of concrete

steel fibers into the self-compacting SFRCs did not significantly reduce its creep coefficient. This is consistent with the low volume fraction of fibers when compared with an aggregate volume of approximately 65 percent.

Figure 10 also indicates that the model of ACI Committee 209 (1992) overestimates the creep coefficient of the plain concrete F-0 by 100% for all three ages reported. The major factor having contributed to this overestimation would be the correction factor for slump (Eqs. (2)-(23) of ACI, 1992) which may not be suitable for self-compacting concrete.

VI. CONCLUSIONS

The following conclusions can be drawn based on the findings obtained from this investigation for the concrete mixes and procedures used:

1. Self-compacting SFRC with high workability and good slump retention can be obtained for a fiber content up to 1% for the fiber tested.
2. Adding steel fibers increased the entrapped air content in self-compacting SFRC for the fiber tested. This increase was well fitted by a power function.
3. The addition of steel fibers improved (by up to 20%) the compressive strength of the self-compacting SFRC at early ages (3 and 7 days). However, the plain to fibrous concrete strength ratio decreased as concrete age increased.
4. Adding steel fibers significantly improved the flexural strength of the self-compacting SFRC.
5. The Japanese flexural toughness factors (JCI SF-4) were less variable and more sensitive both to concrete age and to fiber content than the ASTM toughness indices I_5, I_{10} and I_{30} for the concretes studied. They increased as concrete age or fiber content increase.
6. Both the autogenous and drying shrinkage of self-compacting SFRC depend on the fiber content. They linearly decreased at a rate of 170×10^{-6} for each percent of steel fibers added.
7. Steel fibers had little effect on the compressive creep of the concretes studied.
8. The ACI model (Committee 209) accurately predicted the long-term drying shrinkage of the plain concrete F-0, but it underestimated its short-term drying shrinkage and overestimated its compressive creep for the test periods reported.

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