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EFFECTS OF MANUFACTURING TECHNIQUES ON THE FLEXURAL BEHAVIOR OF STEEL FIBER-REINFORCED CONCRETE

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ABSTRACT

This paper presents experimental research investigating the effects of manufacturing techniques on the mechanical properties of steel fiber-reinforced concrete. Both the effects of curing environments and that of testing direction relative to casting direction on the mechanical properties of fiber-reinforced concrete are reported. Specimens were cured in three different environmental conditions: steam, moisture, and air. Results show that steam curing, as compared to moisture curing, does not enhance the flexural strength of steel fibrous concrete but does reduce flexural toughness. As expected, air curing shows detrimental effects on all aspects of the test results, as compared to steam and moisture curing.

The flexural behavior of steel fiber-reinforced concrete is strongly affected by testing direction. When testing direction is perpendicular to casting direction, specimens exhibit reductions in both flexural strength and toughness compared to the case when testing and casting directions are parallel. The effect of testing direction relative to casting direction on flexural strength and toughness increases with increasing the flowability (workability) of the fibrous mixture, which encourages fiber settlement during placement. *© 1998 Elsevier Science Ltd*

Introduction

Prevention of moisture loss and immediate water-curing are directly related to the mechanical properties and durability of concrete. Research shows air curing is not a reliable curing procedure because it greatly influences the durability and strength (1–4). Steam curing is recommended in concrete that contains mineral additives, such as silica fume and slag, to improve the strength and durability (5).

Fly ash can be an important ingredient to be added to the fibrous concrete mixtures. The addition of fly ash to the fiber concrete mixture increases the volume of paste content and thus facilitates the accommodation of the fibers, minimizing fiber settlement (6). Furthermore, fly

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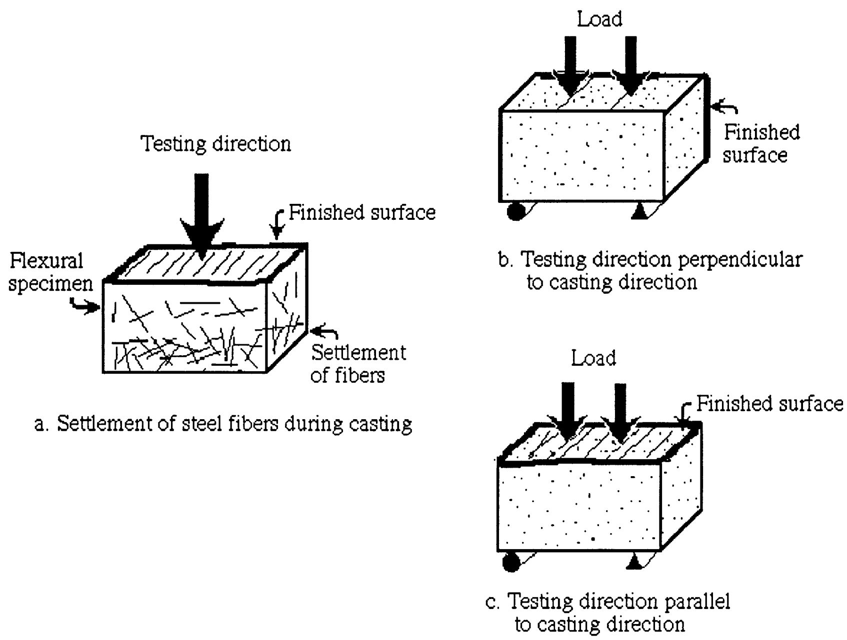

FIG. 1.
Fiber settlement and testing direction compared to casting (placement) direction.

ash improves the workability and pumpability of fiber-reinforced concrete (7). Results show that a number of mechanical properties of fiber-reinforced concrete are positively affected by the curing procedure (2), matrix composition and fiber size (9), fiber content (10,11), fiber spacing and arrangement (12), fiber direction vs. testing direction (12,13), and addition of fly ash (8).

Upon placement and compaction of steel fibrous concrete, the fibers tend to settle towards the bottom part of the beam. During flexural testing, depending on the relative location of testing direction compared to casting (placement) direction, fiber settlement may affect test results (Fig. 1a). Depending on the flowability of the fibrous mixture, fiber settlement may be extensive, moderate or mild, and test results are affected accordingly. ASTM C 1018, which describes flexural test methods utilized on fiber-reinforced concrete (using beam with third-point loading) (14), specifies that testing direction be perpendicular to casting direction for thick specimens (Figs. 1b and c). This eliminates the effect of fiber settlement, which may lead to nonuniform fiber dispersion (more fibers in the lower half of the beam). This fiber settlement effect can be utilized to enhance the flexural behavior of steel fiber concrete in application fields such as slabs on grade, floor systems, tensile skin in beams, etc. This utilization mandates assessment of the fiber settlement effect on flexural behavior.

This paper focuses on two topics: first, the investigation of the effect of curing methods on the flexural and compressive strength of fiber-reinforced concrete; and second, the investigation of the effect of the direction of testing with respect to fiber direction on the flexural strength of steel fiber-reinforced concrete.

Experimental Program

Materials

All of the steel fiber-reinforced concrete specimens included in the experimental program related to curing procedure had a water-to-binder (cement + fly ash) ratio of 0.4, fly ash-to-binder ratio of 1.0, and superplasticizer-to-binder ratio of 1.5%. ASTM Type F fly ash was used, with a silica (SiO_2) content of 47% (14). The average particle size of the fly ash was 18 mm. The superplasticizer was a naphthalene formaldehyde sulfonate manufactured by W.R. Grace, Daracem 100,® with 41% solid contents and a relative density of 1.21. ASTM Type I Portland cement was used. The aggregates were natural river sand and gravel, with a maximum coarse aggregate size of 19 mm (0.75 in). Steel fibers were straight-round with a length of 51 mm (2 in) and a diameter of 0.8 mm (0.035 in), resulting in an aspect ratio of 57.

For the experimental program that studied the effects of testing direction, all specimens had a water-to-binder ratio of 0.41, fly ash-to-binder ratio of 0.3, superplasticizer-to-binder ratio of 1%, and a maximum size aggregate of 19 mm (0.75 in). Two types of steel fibers were used: straight-round (Type A) and crimped-rectangular (Type B). Both steel fiber types had the same dimensions, length 51 mm (2 in) and diameter 0.8 mm (0.035 in), resulting in an aspect ratio of 57.

Specimen Preparation

A rotary drum mixer was used for making the concrete mixtures. The mixing procedure was as follows:

1) Charge the mixer with all the sand and gravel.
2) Start the mixer and add 1/3 of the water-superplasticizer mixture.
3) Add half to 70% of the cementitious materials (cement + fly ash) together with another 1/3 of the water-superplasticizer mixture over a 4-min period.
4) Add fibers to the mix (preferably through a wire mesh basket with an opening measuring 38 × 38 mm (1.5 × 1.5 in) in a gradual manner such that piling up of fibers on the mix is prevented. The addition of fibers usually takes about 3 min.
5) Add the remainder of the water-superplasticizer mixture and cementitious materials over a 2-min period.
6) Continue mixing for 3 min until a homogeneous mix is achieved, then stop the mixer for 3 min, followed by a 2-min mixing period.

Following mixing, the workability of the fresh mix was measured by the inverted slump cone testing procedure (ASTM C 995) (14). Compaction of fresh fibrous mixtures was performed externally, using a vibrating table. Each specimen was vibrated in two layers, with each layer composing half of the thickness. Each layer was vibrated for 15 to 20 s or until a thin film of bleed water appeared on the surface.

For investigating the effect of curing procedure, three steel fibrous concrete mixtures were prepared. Three different curing procedures were used: 1) moisture curing, 2) steam curing, and 3) air curing. The first step of curing was identical for all three curing procedures and

TABLE 1
Mix design program for investigating the effects of testing direction.

Flowability Rate	Mix	V_f (%)	FT	AG/B	BC (kg/m^3)	G/S
high flowability	1M	1	A	4.0	504.7	1.0
	2M	2	A	3.5	546.8	1.0
moderate flowability	3M	2	A	4.0	504.7	1.0
	4M	2	B	4.0	504.7	1.0
low flowability	5M	2	A	4.5	462.6	1.0

Notes: V_f, fiber volume fraction; FT, fiber type where type A is straight-round and type B is crimped-rectangular; AG/B, aggregate/binder; BC, binder content; G/S, gravel/sand

consisted of keeping the specimens in their molds covered with polyethylene sheets for 24 h. The specimens were then removed from their molds. The second step of curing was as follows:

For moisture curing, the specimens were kept at 22°C (72°F) and approximately 100% relative humidity until the age of 7 days. Thereafter, the specimens were kept at a constant room temperature (laboratory environment).

For steam curing, the second step consisted of exposing the specimens to steam with a temperature of 80°C (175°F) and approximately 100% relative humidity for 4 days. Thereafter, the specimens were left at constant room temperature (laboratory environment).

For air curing, the specimens were placed in a regular laboratory environment after removal from their molds.

All specimens were tested at an age of 28 days. Two cylindrical compression test specimens measuring 150 mm (6 in) in diameter and 300 mm (12 in) in height, and three flexural specimens measuring 150 × 150 × 500 mm (6 × 6 × 20 in) were made from each mix of the experimental program on curing. The compressive stress-strain behavior was obtained using a compressometer as described by ASTM C 469 (14). Two displacement transducers were used to monitor the displacements at the load points in flexural tests, which were conducted by loading at 1/3 points on a span of 450 mm (18 in) with testing direction parallel to casting direction.

For investigating the effects of testing direction, six flexural specimens were made. Three specimens were tested with testing direction parallel to casting direction and three were tested with testing direction perpendicular to casting direction (see Fig. 1). The specimen dimensions and testing technique were identical to those described earlier for the experimental program of curing procedure. As noted in Table 1, the steel fiber concrete mixtures were divided into three groups. Group 1 consisted of two mixtures with relatively high flowability, which might result in fiber settlement during vibration. Group 2 was composed of two mixtures with typically moderate flowability, and Group 3 included a mixture with relatively low workability, which might discourage fiber settlement. The purpose of this division was to assess the effects of mix flowability on steel fiber settlement during casting/vibration, through investigating the flexural behavior of the mix with testing direction parallel to casting direction as compared to its behavior with testing direction perpendicular to casting direction.

TABLE 2
Test results from the effects of curing procedure.

Curing	First-Crack Flexural Strength MPa (psi)	Ultimate Flexural Strength MPa (psi)	Flexural Toughness $I_{5.5}$	Compressive Strength MPa (psi)	Compressive Toughness $IC_{5.5}$
Air	5.5 (796)	8.1 (1173)	12.4	35.4 (5130)	5.8
Moisture	9.9 (1432)	11.6 (1681)	13.5	41.9 (6080)	5.1
Steam	9.6 (1395)	11.6 (1675)	6.45	51.2 (7430)	4.3

Results

Curing Procedure

Results on the effect of curing on the mechanical properties of steel fiber-reinforced concrete are summarized in Table 2. In Table 2, the flexural toughness ($I_{5.5}$) is the energy absorbed (area under load-deflection curve, Fig. 2) up to 5.5 times the first-crack deflection divided by the precracking energy absorption (area under load-deflection curve up to first-crack deflection). The compressive toughness ($IC_{5.5}$) is defined similar to the flexural toughness, which uses the strain at peak compressive strength, as in the compressive stress-strain diagrams of

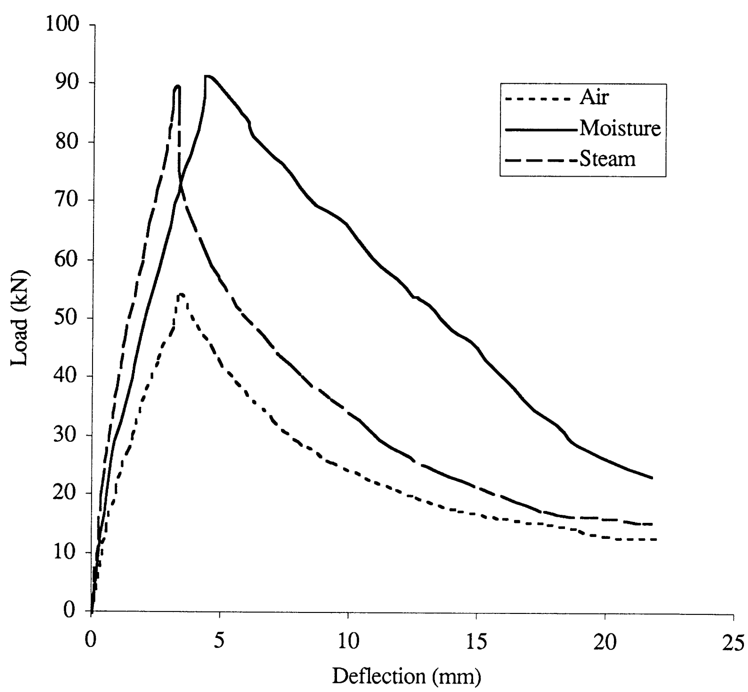

FIG. 2.
Effect of curing procedure on the flexural behavior of steel fiber-reinforced concrete.

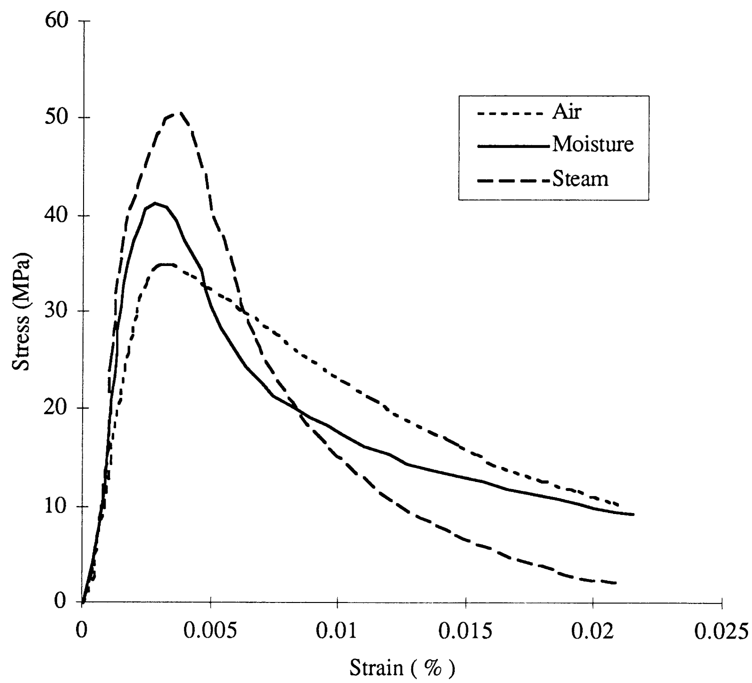

FIG. 3.
Effect of curing procedure on the compressive behavior of steel fiber-reinforced concrete.

Fig. 3, rather than the deflection at flexural first-crack strength and the flexural load-deflection curves shown in Fig. 2. The inverted slump cone time of the fresh steel fiber concrete mixture, for mixtures investigating the effect of curing procedure, was measured to be 21 s, which can be considered typical.

In comparison with moisture curing, steam curing has no significant effect on first-crack

TABLE 3
Test results pertaining to the effect of testing direction on flexural behavior.

Flowability Rate	Mix	Testing Direction/ Casting Direction	First-Crack Strength MPa (psi)	Ultimate Strength MPa (psi)	Toughness Index $I_{5.5}$
high	1M	0°	5.0 (725)	7.3 (1058)	11.6
	1M	90°	4.0 (585)	6.1 (879)	8.2
	2M	0°	8.1 (1172)	11.8 (1725)	11.2
	2M	90°	7.3 (1052)	8.6 (1249)	7.8
moderate	3M	0°	9.9 (1432)	11.6 (1681)	13.5
	3M	90°	9.1 (1320)	11.2 (1622)	11.8
	4M	0°	6.3 (920)	10.1 (1460)	13.8
	4M	90°	6.1 (880)	10.2 (1475)	10.3
low	5M	0°	7.8 (1125)	10.6 (1542)	10.1
	5M	90°	6.7 (971)	9.9 (1435)	8.7

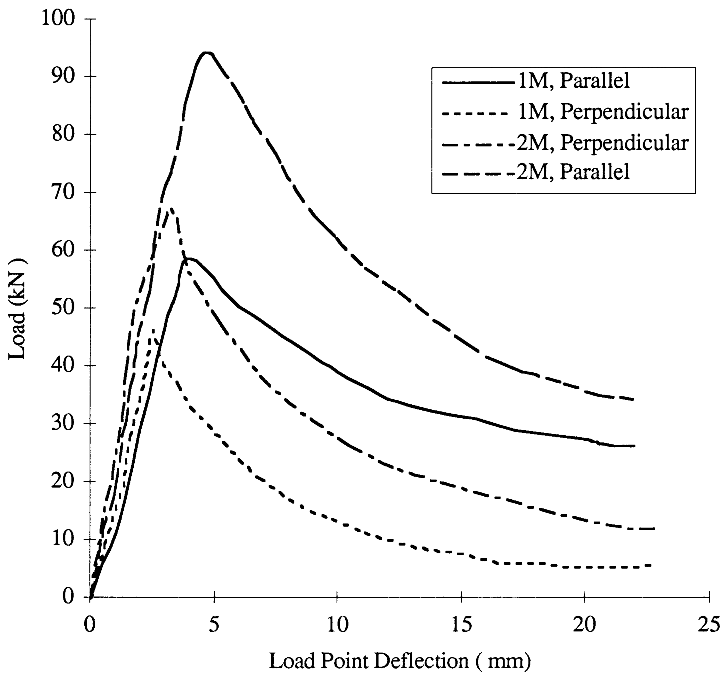

FIG. 4.
Effect of testing direction on the flexural behavior of steel fiber-reinforced concrete mixtures with high flowability (mixes 1M and 2M).

or ultimate flexural load (stress); air curing, however, reduces first-crack and ultimate flexural strength of steel fiber-reinforced concrete significantly. On the other hand, steam curing significantly reduces flexural toughness (which indicates damage to post-cracking behavior), whereas air curing has a slight adverse effect on flexural toughness compared to moisture curing. This indicates that high intensity curing tends to cause the fiber-matrix bond to become brittle. Air curing also seems to result in a reduction in the effectiveness of fibers in enhancing the flexural toughness of steel fiber concrete.

As far as compressive behavior is concerned (Fig. 3), high intensity curing (steam curing) seems to increase compressive strength and decrease compressive toughness as compared to moisture curing. Air curing, however, is seen to decrease compressive strength and enhance the compressive toughness of steel fiber-reinforced concrete when compared to moisture curing. The effect of curing on the compressive behavior of steel fiber-reinforced concrete seems to result mainly from the effect of curing on conventional concrete (15). This is explained by the fact that the compressive behavior of steel fiber concrete is strongly influenced by the plain concrete matrix.

Testing Direction Relative to Casting Direction

Table 3 presents a summary of the effect of testing direction relative to casting direction on the flexural behavior of steel fiber-reinforced concrete.

Figure 4 shows the effects of testing direction for mixes 1M and 2M, representing mixes

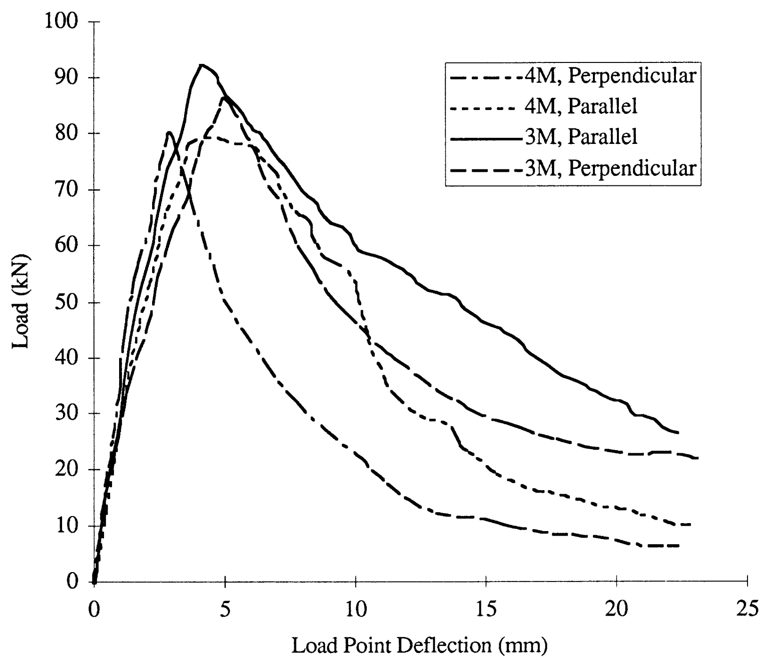

FIG. 5.
Effect of testing direction on the flexural behavior of steel fiber-reinforced concrete mixtures with moderate flowability (mixes 3M and 4M).

with relatively high flowability (inverted slump cone times were measured to be 11 and 14 s for mixes 1M and 2M, respectively). As can be seen in Fig. 4, for relatively fluid fibrous mixtures, testing direction has a significant effect on test results. Specimens tested in the direction perpendicular to casting direction possess a less favorable flexural behavior, evident by the reduction of first-crack strength (average of 14%), ultimate strength (average of 22%), and flexural toughness, $I_{5.5}$, (average of 30%) as compared to specimens tested in the direction parallel to the casting direction.

Figure 5 shows the effect of testing direction on flexural behavior of moderate flowability mixtures (mixes 3M and 4M, with inverted slump cone times of 21 and 17 s, respectively). Testing direction has no significant effect on first-crack and ultimate flexural strength, whereas it does have an effect on flexural toughness. Specimens exhibited a reduction in flexural toughness by as much as 20% when they were tested in the direction perpendicular to casting direction, as compared to those were tested in the direction parallel to casting direction.

Figure 6 shows the effect of testing direction on flexural behavior of low flowability mixture (inverted slump cone time of 50 s of mix 5M). Specimens tested in the direction perpendicular to the casting direction exhibited reductions of 14% in flexural toughness and about 10% in first-crack and ultimate strength as compared to the specimens that tested in the direction paralleled to casting direction.

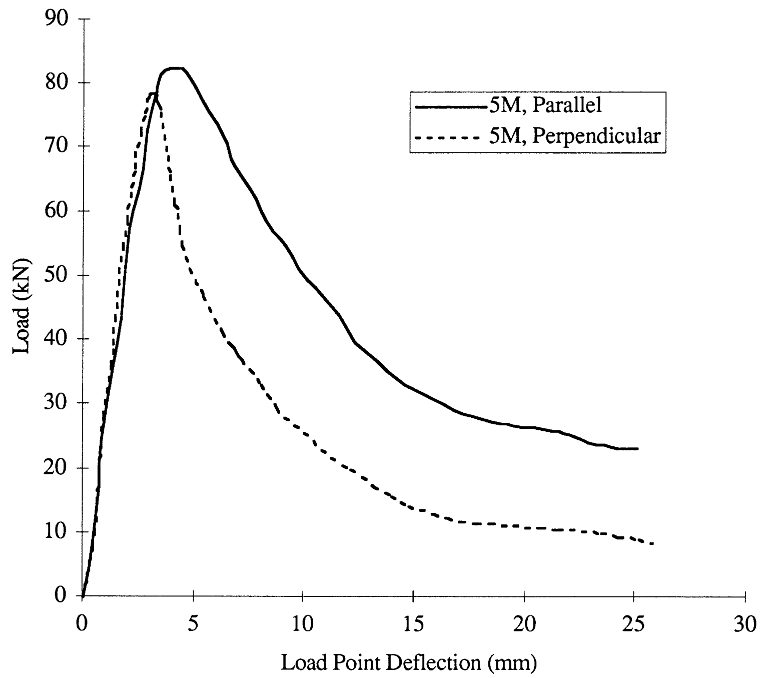

FIG. 6.
Effect of testing direction on the flexural behavior of steel fiber-reinforced concrete mixtures with low flowability (mix 5M).

Conclusions

An experimental research was conducted to study the effects of manufacturing techniques on the flexural and compressive behaviors of steel fiber-reinforced concrete. Both the effects of curing and of the testing direction relative to casting direction on the mechanical properties of fiber-reinforced concrete were studied. The following conclusions can be drawn from this study:

1) In comparison to moist curing, steam curing did not seem to increase first-crack or ultimate flexural strength of steel fiber concrete. However, steam curing was found to increase the compressive strength and to reduce compressive and flexural toughness indices. Air curing, on the other hand, was noted to reduce first-crack and ultimate flexural strength significantly and to reduce flexural toughness slightly. This seemed to indicate that steam curing causes bonds between steel fibers and concrete to become brittle, and air curing is less effective in enhancing flexural behavior.
2) Steel fiber concrete specimens with relatively high flowability (workability), tested in the direction perpendicular to casting direction, exhibited reductions in flexural first-crack strength, flexural ultimate strength, and flexural toughness of 14%, 22%, and 30%, respectively, as compared to specimens tested in the direction parallel to casting direction.
3) Steel fiber concrete specimens with relatively moderate and low flowability, tested in the direction perpendicular to casting direction, exhibited insignificant reductions in flexural

first-crack and ultimate strength (for certain cases less than 10%), compared to those tested in the direction parallel to casting direction. However, significant reductions of 20% and 14% in flexural toughness were noted for mixtures with moderate and low flowability, respectively.

Acknowledgments

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References

1. P.-C. Aitcin, B. Miao, W.D. Cook, and D. Mitchell, ACI Mater. J. 91, 349 (1994).
2. A.M Paillere, M. Buil, and J.J. Serrano, ACI Mater. J. 86, 139 (1989).
3. A. Bilodeau, G.G. Carette, V.M. Malhotra, and W.S. Langley, Influence of Curing and Drying on Salt Scaling Resistance of Fly Ash Concrete. ACI SP-126, Proceedings, Second International Conference on Durability of Concrete, Montreal, Canada, V.M. Malhotra (ed.), p. 201, American Concrete Institute, Detroit, MI, 1991.
4. Y. Ballim, Mater. Struct. 26, 238 (1993).
5. G.M. Campbell and R.J. Detwiler, Concr. Int. 15, 37 (1993).
6. C.D. Johnston and R.W. Zemp, ACI Mater. J. 88, 374 (1991).
7. R. Keck and K. Casey, Concr. Int. 13, 23 (1991).
8. H. Nakagawa, S. Akihama, and T. Suenaga, Mechanical Properties of Various Types of Fiber Reinforced Concretes. Proceedings, International Conference on Fiber Reinforced Cements and Concretes: Recent Developments, University of Wales College of Cardiff, UK, R.N. Swamy and B. Barr (eds.), p. 523, Elsevier Applied Science, London, 1989.
9. V. Ramakrishnan, G.Y. Wu, and G. Hosalli, Trans. Res. Record 1226, 69 (1989).
10. M.A. Taylor, Cracking Behavior Comparisons between Normal and Fiber-Concretes. Structural Materials, Proceedings of the Sessions at the ASCE Structures Congress, San Francisco, CA, J.F. Orofino (ed.), p. 12, ASCE, New York, 1989.
11. P. Soroushian and C-D Lee, ACI Mater. J. 87, 541 (1990).
12. N.F. Dow and B.W. Rosen, NASA CR-207 (1965).
13. Z. Bayasi and P. Soroushian, Trans. Res. Record 1226, 25 (1989).
14. ASTM Annual Book of Standards, Section 4: Construction, Vol. 4.02: Concrete and Mineral Aggregates; ASTM, Philadelphia, 1990.
15. S. Mindness and J. Young, Concrete, Prentice-Hall Inc., Englewood Cliffs, NJ, 1981.