Steel-Fiber–Reinforced Wet-Mix Shotcrete: Comparisons with Cast Concrete

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Abstract: As part of a larger investigation in steel-fiber–reinforced wet-mix shotcrete, companion specimens were cast using the shotcrete mixes for a direct comparison with shotcrete after hardening. Deformed steel fibers with five different geometries were investigated. Mixes were first shot on wooden forms and then cast using external vibration. Comparisons were made between shotcrete and cast concrete on the basis of compressive and flexural strengths and the flexural toughness. For a given mix, the average compressive strength of cast concrete was found to be significantly higher than that of the shotcrete. Flexural strengths, however, witnessed a reversal in the trend. In the case of flexural toughness, although the results for cast concrete were decisively different from that of shotcrete, no clear trend became apparent. The paper concludes that care should be exercised in predicting the behavior of shotcrete on the basis of the performance of cast concretes of similar proportions.

INTRODUCTION

The use of shotcrete in new construction and in the repair and rehabilitation of older and deteriorated structures has grown rapidly over the years. Shotcrete has been used in mine and tunnel linings; for rock slope stabilization; in dam construction; in swimming pools, reservoirs and ornamental rockscapes; for repair of deteriorated structures and surfaces; for fire protection coatings; in thin shell dome construction; and so on (Henager 1981; Morgan 1988, 1989; Wood 1991). Significant improvements in the properties of shotcrete due to steel-fiber reinforcement have been reported (Ramakrishnan et al. 1981; Morgan et al. 1987; Banthia et al. 1992, 1994).

Shotcrete may be produced via the dry-mix process or the wet-mix process. The mixes in the case of the wet-mix process are similar in many respects in composition and rheological characteristics to those used for cast-fiber–reinforced concrete; it is primarily the way of compaction that is different. Considerable research has taken place in the preceding 20 years in the field of steel-fiber–reinforced concrete, and it will no doubt be beneficial if that knowledge base could be extended to wet-mix fiber-reinforced shotcrete. The present paper examines the similarities and the differences between cast concrete and shotcrete produced from the same mix.

TEST PROGRAM

Full details of the test program are described in Banthia et al. (1994). Only a brief summary is presented here.

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Materials and Mixes

Five commercially available fibers, with geometries shown in Fig. 1, were investigated. Six concrete mixtures—five with fibers and one control—were mixed centrally in a ready-mix plant and transported in transit trucks to the shooting site. The as-batched mix proportions for the control mix were, cement:water:silica fume:sand:coarse aggregate of 1.0:0.405:0.067:2.24:1.33. In the fibrous mixes, the five fibers shown in Fig. 1 were added at a dosage rate of 60 kg/m^3. With the control mix designated as M0, the mixes with fibers were designated as MF1, MF2, and so on, depending on the fiber type (Fig. 1). Silica fume was added to all mixes to improve their shootability and performance (Morgan et al. 1987).

Tests were performed on fresh concrete before shooting to determine their air contents, slump values and the VeBe times. These quantities are given in Table 1.

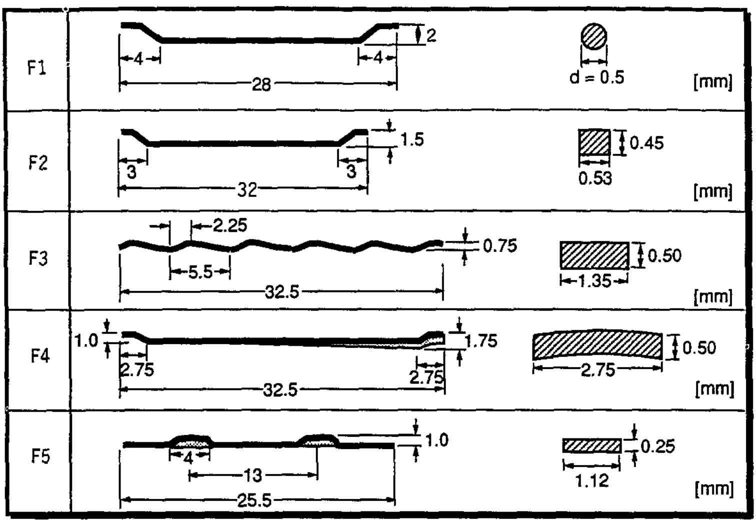

FIG. 1. Fibers Investigated

TABLE 1. Properties of Fresh Concrete

Mix (1)	Slump (mm) (2)	Air[a] (percent) (3)	VeBe Initial slump (mm) (4)	VeBe Time (s) (5)
M0	130	2.5	105	2.3
MF1	130	7.0	110	2.0
MF2	110	3.0	60	3.4
MF3	130	3.3	110	2.8
MF4	90	3.1	83	3.0
MF5	90	3.2	63	3.8

[a]Before shooting or casting.

Shotcreting

Fresh concrete from the ready-mix truck was shot on wooden forms 600 mm × 600 mm × 200 mm resting at a small angle with respect to the vertical support. The overall rebound of shotcrete, and that of fibers, was measured using a rebound chamber as described in Banthia et al. (1994). The rebound data are reported in Table 2.

Three days after shooting, the forms were stripped and each panel was sawed and cored to obtain three beam specimens (100 mm × 100 mm × 350 mm) for flexural toughness tests and two cylinders (75 mm × 150 mm) for compressive strength determination. All specimens were further moist cured until tested at the age of 7 days for strengths and toughness.

Cast Specimens

From the shotcrete mixes, three beams (100 mm × 100 mm × 350 mm) and four cylinders (75 mm × 150 mm) were cast using external vibration. Three days after casting, the specimens were demoulded and further moist cured until tested at the age of 7 days.

Testing

Strengths

Compression tests were conducted on cast and cored cylinders and compressive strengths were determined. Flexural strengths were determined

TABLE 2. Rebound Data

Mix (1)	Total rebound (percent) (2)	Fiber rebound (percent) (3)
M0	9.4	—
MF1	8.8	18.3
MF2	8.9	11.5
MF3	12.5	12.5
MF4	14.8	17.0
MF5	11.3	11.8

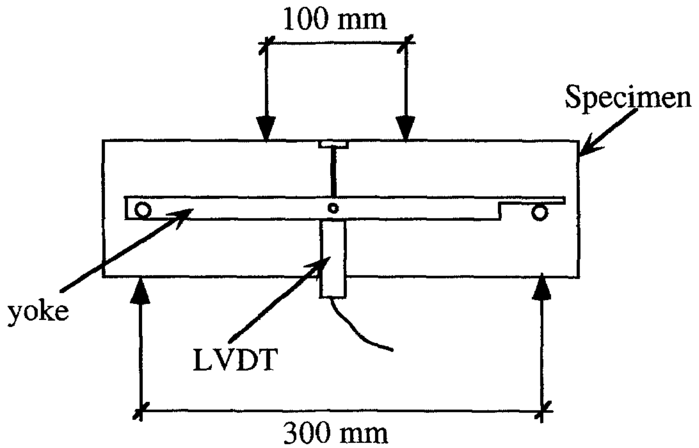

FIG. 2. Toughness Test Setup Showing Yoke

from the peak loads recorded in flexural toughness tests described later herein.

Flexural Toughness

Cast and shot specimens were tested under four-point flexure on a span of 300 mm using a 150 kN Instron. The extraneous system deformations (Banthia and Trottier 1994) were eliminated by reading the beam displacements from a "yoke" installed around the specimen as shown in Fig. 2. The applied load and deflection data were electronically acquired at a 10 Hz acquisition frequency. Additional details of the test setup may be found in Trottier and Banthia (1994). The data were analyzed using both ASTM C-1018 (*Standard* 1990) and JSCE-SF-4 ("Method" 1984) techniques.

Results

Strengths

Compressive and flexural strengths for the various mixes are plotted in Fig. 3. Notice that the compressive strengths for the cast specimens were

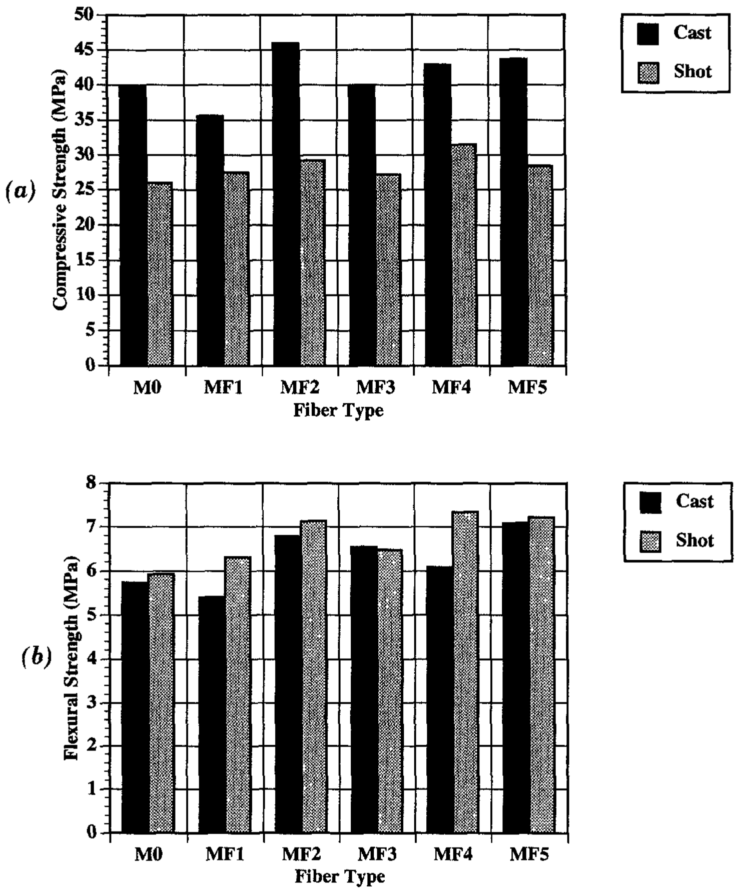

FIG. 3. 7-Day Strengths for Plain and Fibrous Mixes: (*a*) Compressive; (*b*) Flexural

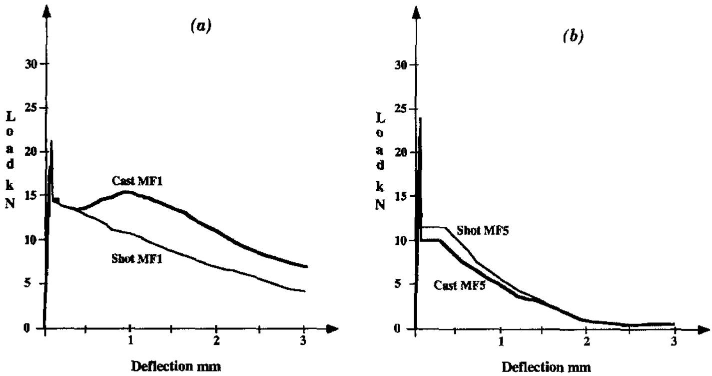

FIG. 4. Typical Flexural Load versus Deflection Plots: (*a*) for Cast and Shot Mixes with Fiber F1; (*b*) for Cast and Shot Mixes with Fiber F5

TABLE 3. Flexural Data

Mix		Peak load (kN)	First crack deflection (mm)	First crack energy (N·m)
Type (1)	Application (2)	(3)	(4)	(5)
M0	Cast	19.43	0.064	0.711
M0	Shot	19.76	0.049	0.572
MF1	Cast	18.04	0.053	0.540
MF1	Shot	21.02	0.058	0.750
MF2	Cast	23.31	0.060	0.821
MF2	Shot	23.80	0.059	0.834
MF3	Cast	21.87	0.056	0.704
MF3	Shot	21.59	0.056	0.745
MF4	Cast	20.60	0.068	0.771
MF4	Shot	24.46	0.060	0.867
MF5	Cast	23.68	0.057	0.787
MF5	Shot	24.06	0.059	0.804

consistently higher than those for the shot specimens. The trend in the case of the flexural strength, however, appears to have been reversed; most shot specimens were stronger in flexure. The effect of fibers was noticeable, in general, in improved compressive and flexural strengths compared to the plain control mix.

The improved compressive strength of cast concrete is apparently the result of a better compaction achieved through external vibration in cast concrete as compared to that through pneumatic compaction in shotcrete. In this regard, note that the actual air contents in-place shotcrete or cast concrete were not measured in this investigation; the air contents reported in Table 1 are those before the process of shooting or casting. The possible reason for the improved flexural strength of shotcrete over cast concrete is the preferential alignment of fibers in shotcrete perpendicular to the direction of shooting (Ramakrishnan et al. 1981).

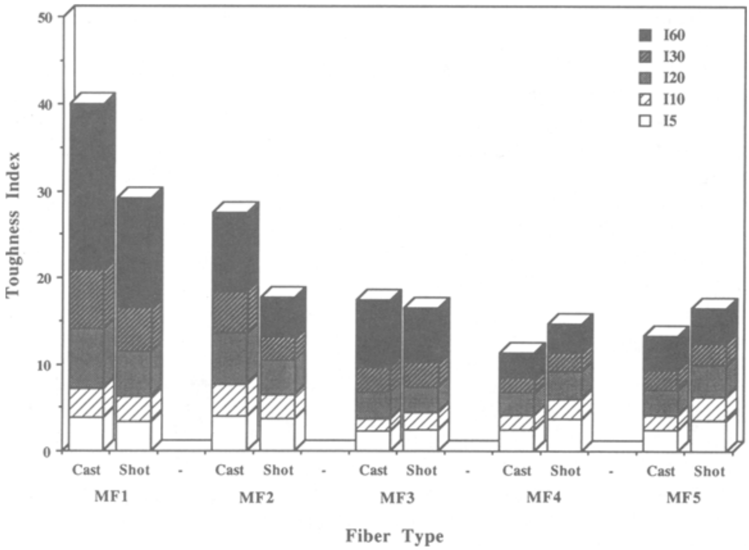

FIG. 5. Toughness Indices for Cast and Shot Specimens

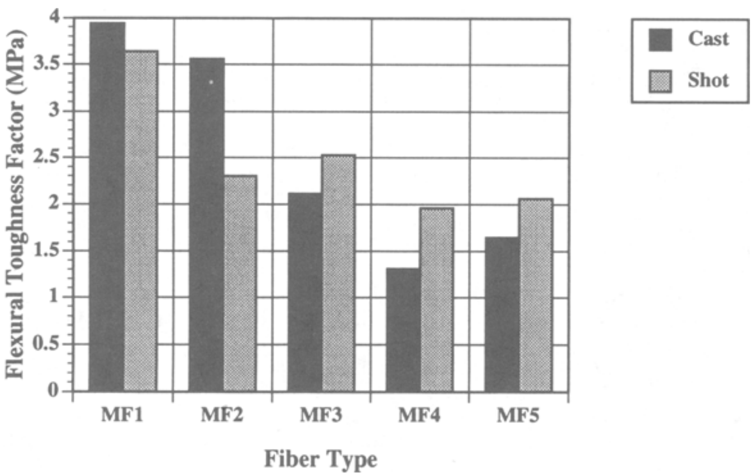

FIG. 6. Flexural Toughness Factors

Flexural Toughness

Typical flexural load versus deflection curves are shown in Fig. 4. Note the significant enhancement in the toughness due to fiber reinforcement. In general, cast specimens were found to have better post-crack toughness for Fibers F1 and F2, comparable toughness for Fiber F3, and an inferior toughness for Fibers F4 and F5. Average peak loads, first-crack deflections [measured at a point of significant nonlinearity in the curve; (Banthia and Trottier 1994)] and first-crack energy values are given in Table 3. Note that the first-crack energy values in the presence of fibers are consistently higher in the case of shot specimens than those for cast specimens.

The "toughness indices" (ASTM: "Standard" 1990) and "flexural toughness factors" (JSCE: "Method" 1984) are plotted in Figs. 5 and 6, respectively. Based on the two chosen toughness parameters, cast specimens demonstrated a better energy absorption capability over shotcreted specimens for the end-deformed Fibers F1 and F2. For the other fibers, however, a reversal in the trend occurred.

It must also be recognized that shotcreted specimens had lower volume fractions of fibers than cast specimens due to fiber rebound that occurred during shooting. Despite this reduction in the fiber content, shotcrete specimens demonstrated better flexural strengths for all mixes and better toughness for mixes with end-deformed fibers.

CONCLUSIONS

The compressive strength of shotcrete is significantly lower than its cast counterpart. The flexural strength, however, can be expected to be higher, due probably to the preferential alignment of fibers.

The correlation between the flexural toughness of shotcrete and its cast counterpart appears to be dependent on the fiber geometry.

There are differences in the physical properties of specimens cast or shot from the same concrete mixture. Thus, care should be exercised while attempting to predict shotcrete behavior on the basis of the performance of cast concretes of similar proportions.

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