A Comparative Evaluation of Plain, Polypropylene Fiber, Steel Fiber, and Wire Mesh Reinforced Shotcretes

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Since the early 1970s, steel fiber reinforced shotcrete has been increasingly used for such applications as support in tunnels, mines, excavations, and rock slopes. Previous studies have shown that steel fiber reinforced shotcrete, at fiber addition rates now commonly used, can provide equivalent or even superior performance than that provided by standard wire mesh reinforcement, when properties such as residual load-carrying capacity after first crack are compared. This paper presents the results of recent studies comparing the performance of common wire mesh reinforced shotcretes with that of shotcretes reinforced with high-volume concentrations of a collated fibrillated polypropylene (CFP) fiber. The tests were conducted using wet-mix shotcrete applied to large panels, which were anchored and loaded to destruction with continuous monitoring of the crack formation and load vs. deflection characteristics of the panels. The panels were tested in the same manner as tests previously conducted on plain, wire mesh, and steel fiber reinforced shotcretes. Thus, the performance characteristics of the various shotcrete mixtures can be compared. It is shown that at certain addition rates of CFP fiber, similar residual load-carrying capacity after first crack can be obtained compared with shotcrete reinforced with wire mesh and shotcrete reinforced with steel fiber. Testing of standard flexural test beams to ASTM C1018 provided further verification of the equivalence of performance between shotcretes with these levels of addition of steel and CFP fiber with respect to parameters such as toughness index. The incorporation of high-volume concentrations of CFP fiber in wet-mix shotcrete presents opportunities for a wide range of applications where a tough, ductile, corrosion-resistant material is required.

Shotcrete has proven useful over the years for a wide variety of applications (*1*). These include

- Linings for support of underground openings in mines, tunnels, and other excavations;
- Soil and rock slope stabilization;
- Remedial works on deteriorated concrete and masonry structures;
- Construction of a wide variety of structures, including domes, culverts, canals, bulkheads, swimming pools, and water tanks; and
- Sealing surfaces of tailings and waste rock piles and toxic waste disposal sites.

Plain shotcrete has been used in some of the above applications. In most applications, however, various degrees of reinforcing are necessary to overcome the inherently low tensile strength and lack of ductility of portland cement concrete mixtures; conventional reinforcing steel or welded wire mesh fabric have long been used. More recently, steel fiber reinforcement has been found to be equivalent or even superior to traditional welded wire mesh reinforcement (*2*). Steel fiber reinforced shotcrete has enjoyed increasing use in a wide variety of shotcrete applications since the early 1970s (*3–6*).

Previous tests conducted on 1525 mm × 1525 mm × approximately 75 mm (5 ft × 5 ft × approximately 3 in) dry-mix shotcrete test panels (*2*) have established the equivalence, and even superior performance, of steel fiber reinforcement to certain wire mesh reinforcement. ASTM C1018 tests previously conducted on polypropylene fiber reinforced shotcrete (PFRS) by the authors provided a basis for the comparison of PFRS and steel fiber reinforced shotcrete. The following question, however, still arose:

> How does the performance of PFRS compare with that of mesh reinforced shotcrete in conditions of loading that might be experienced in such applications as support of rock slopes or underground openings?

This paper describes the program of testing that was undertaken to address this issue.

SHOTCRETE MIX DESIGN, PRODUCTION, AND APPLICATION

A wet-mix shotcrete mix design typical of mixes commonly used in the construction industry in the Vancouver area was selected for study. The mix proportions are given in Table 1. The shotcrete contained 400 kg/m^3 (675 lb/yd^3) of cement and a combined aggregate gradation that conformed to the requirements of ACI 506.2–77, Table 2.2.1. Gradation No. 2 (i.e., a 10 mm (3/8 in.) maximum size aggregate).

The shotcrete was supplied in 1.0 m^3 (1.3 yd^3) loads in a transit mixer. The slump, air content, and temperature were checked when the transit mixer arrived at the test site. Additional water was added to the fiber reinforced shotcrete mixes, prior to fiber addition, to produce the required slump for shooting. All shotcretes were applied at slumps in the range of 25 to 50 mm (1 to 2 in.). (If compressive strength or minimization of drying shrinkage capacity of the shotcrete are of concern, superplasticizers can be used instead of water to provide the necessary slump after fiber addition. Superplas-

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TABLE 1 BASE SHOTCRETE MIX DESIGN

Material	lb/cu. yd.	kg/m^3
Type I Cement	674	400
10 mm Coarse Aggregate	725	430
Concrete Sand (SSD)	2166	1285
Water	320	190
Water Reducing Admixture	8 fl. oz./100 lb Cement	500 ml/100 kg Cement
Air Content	5 ± 1 %	5 ± 1 %

TABLE 2 PROPERTIES OF FRESH CFP FIBER REINFORCED WET-MIX SHOTCRETE

Mix No.	Slump	Air (%)	Mix Temperature (°C)	Comments
1	30	5.5	11	Plain
2	50	4.8	11	Plain
3	200	4.8	8	Before fibres added
	45	N/A	8	6 kg/m^3 fibres added
4	100	5.2	7	Before fibres added
	40	N/A	7	4 kg/m^3 fibres added

Notes: 1) Ambient Temperature = +4°C

2) Fibre length = 38 mm (1-1/2 in.)

3) 1 kg/m^3 = 1.6856 lb/cu. yd.

ticizers were not used in this particular study.) Results of the tests on plastic shotcrete are given in Table 2.

The plain shotcrete was brought to the point of discharge by reversing the transit mixer drum. Then, the 38 mm (1½ in.) long Forta CR CFP fiber was dumped on the shotcrete, and the mixer drum was rotated at full mixing speed for approximately 5 min. This procedure provided excellent dispersion of the fibers throughout the mix. (Note: this same procedure has been used with equal success in 10 m^3 (13 yd^3) truck loads on recent construction projects; however, longer mixing times, usually about 6 to 8 min, are required with the larger load sizes.)

On completion of mixing, the shotcrete was discharged into a wet-mix shotcrete pump. It was then applied through a 50 mm (2 in.) I.D. hose. A 5600 L^3/min (200 ft^3/min) compressor was used for a supply of compressed air at the nozzle. A standard rubber-tipped wet-mix shotcrete nozzle was used. Both the plain and fiber reinforced shotcretes were readily pumped and pneumatically placed with no excess line pressures or blockages.

MANUFACTURE OF TEST PANELS

Small Test Panels

Standard 600 mm × 600 mm × 125 mm (24 in. × 24 in. × 5 in.) test panels were fabricated for each of the following shotcretes:

- Panel No. 2—Plain shotcrete,
- Panel No. 3—Shotcrete with 6 kg/m^3 (10.1 lb/yd^3) of 38 mm (1½ in.) long collated fibrillated polypropylene (CFP) fiber, and
- Panel No. 4—Shotcrete with 4 kg/m^3 (6.7 lb/yd^3) of 38 mm (1½ in.) long CFP fiber.

The panels were oriented at an angle of about 30° from vertical at the time of the shotcrete application. Immediately after fabrication, they were covered with a plastic sheet and allowed to cure in the field for 28 days. The reason for field curing, rather than standard moist curing in the laboratory, was to subject the shotcrete to the same curing conditions as the large, field-cured test panels.

Large Test Panels

A series of eight 1525 mm × 1525 mm × approximately 75 mm (5 ft × 5 ft × approximately 3 in.) test panels were fabricated in this test program. Two of each of the following types of panels were shot:

- Panel No. 1—Plain shotcrete reinforced with 102 × 102 MW 13.3 × MW 13.3 (4 × 4 8/8) wire mesh,
- Panel No. 2—Plain shotcrete reinforced with 152 × 152 MW 18.7 × MW 18.7 (6 × 6 6/6) wire mesh,
- Panel No. 3—Shotcrete reinforced with 6 kg/m³ (10.1 lb/yd³) of 38 mm (1½ in.) long CFP fiber, and
- Panel No. 4—Shotcrete reinforced with 4 kg/m³ (6.7 lb/yd³) of 38 mm (1½ in.) long CFP fiber.

The panel forms were placed in a horizontal orientation. Wire mesh was chaired at a nominal height of 28 mm (1.1 in.) off the base form, using metal chairs in the mesh reinforced test panels. The actual concrete cover to the mesh, measured from the bottom of the panel, is shown in Table 3. Shotcrete was applied vertically downward to a nominal thickness of 75 mm (3 in.). Screeding was performed to remove high spots and improve control of the shotcrete thickness but was kept to a minimum to prevent disturbance of the freshly placed shotcrete. Average shotcrete thicknesses for the various test panels varied between 71.0 and 87.9 mm (2.8 and 3.5 in.). Actual thickness was determined on fracture faces of the different panels after completion of testing. Detailed thickness measurements are given in Table 4.

TABLE 3 CONCRETE COVER TO WIRE MESH IN 5 ft × 5 ft PANELS

PANEL	TEST METHOD	CONCRETE COVER MEASUREMENTS (mm)	AVERAGE (mm)
1	Restrained	25, 30, 30, 30, 28, 28, 27, 28	28.3
2	Restrained	23, 25, 30, 28, 28, 30, 25, 28, 27	27.1
1	Unrestrained	25, 33, 30, 30, 30, 23, 23	27.7
2	Unrestrained	15, 28, 30, 30, 28, 23, 20	24.9

NOTES: 1) Concrete cover is the distance between the wire mesh and the bottom of the panel.

2) 1 mm = 0.03937 in.

TABLE 4 THICKNESS MEASUREMENTS IN 5 ft × 5 ft TEST PANELS

PANEL	TEST METHOD	THICKNESS MEASUREMENTS (mm)	AVERAGE (mm)
1	Restrained	78, 78, 78, 73, 70, 74, 74	75.4
2	Restrained	70, 70, 73, 75, 73, 75, 80, 76, 80	74.6
3	Restrained	77, 80, 80, 80, 78, 78, 72, 74, 72	76.7
4	Restrained	88, 85, 83, 82, 89, 90, 90, 90, 90	87.4
1	Unrestrained	75, 74, 75, 77, 77, 70, 70	74.0
2	Unrestrained	72, 70, 70, 70, 70, 71, 74	71.0
3	Unrestrained	75, 80, 79, 81, 81, 81, 83, 82, 80	80.2
4	Unrestrained	88, 85, 85, 85, 88, 90, 90, 90, 90	87.9

NOTES: 1) Measurements taken along the fractured face of test panels.

2) 1 mm = 0.03937 in.

TEST PROCEDURES AND RESULTS

Standard Tests

At age 28 days, three 75 mm (3 in.) concrete cores were extracted, by diamond core drilling, from standard test panels 2, 3, and 4. The cores were trimmed, sulphur capped, and compression tested in accordance with ASTM C42. Test results are given in Table 5. Reported core compressive strengths have been corrected to equivalent 2:1 length/diameter ratios using the correction factors prescribed in ASTM C42.

An additional three 75 mm (3 in.) diameter cores were extracted at age 28 days from these same test panels to determine absorption, after immersion and boiling, and the volume of permeable voids in accordance with ASTM C642. Test results are given in Table 5.

Three 75 mm × 75 mm × 355 mm (3 in. × 3 in. × 14 in.) prisms were diamond saw cut at age 28 days from panels 2, 3, and 4. These prisms were tested in accordance with ASTM C1018 for

- First crack and ultimate flexural strength;
- I_5, I_{10}, and I_{20} toughness index; and
- $I_{5,10}$ and $I_{10,20}$ residual strength.

Test results are given in Table 5. These ASTM C1018 tests were performed on an MTS servo-controlled universal testing machine. Load vs. deformation data was recorded on an autographic X-Y plotter for fiber reinforced test specimens from test panels 3 and 4.

Tests on Large Shotcrete Panels

These tests were undertaken to simulate different loading conditions that could be imposed on an anchored shotcrete

TABLE 5 PHYSICAL PROPERTIES OF HARDENED POLYPROPYLENE FIBER REINFORCED WET-MIX SHOTCRETE AT 28 DAYS

PANEL NO./PROPERTY	2		3		4	
Fibre Dosage, kg/m^3	0	AVG.	6	AVG.	4	AVG.
Compressive Strength, MPa	47.4 47.3	47.4	38.5 40.2 40.2	39.6	42.8 41.4 41.4	41.9
First Crack Flexural Strength, MPa	5.9 5.1 5.3	5.4	4.9 5.2 3.6	4.6	4.9 4.2 4.9	4.7
Ultimate Flexural Strength, MPa	5.9 5.1 5.3	5.4	4.9 5.2 3.6	4.6	4.9 4.2 4.9	4.7
Toughness Index, I_5	-		3.5 2.8 3.6	3.3	2.3 2.5 2.8	2.5
Toughness Index, I_{10}	-		6.8 5.3 7.4	6.5	3.9 4.6 5.2	4.6
Toughness Index, I_{20}	-		10.7 8.0 11.9	10.2	5.4 6.6 7.6	6.5
Residual Strength, $20 (I_{10} - I_5)$, %	-		66 50 76	64	32 42 48	41
Residual Strength, $10 (I_{20} - I_{10})$, %	-		39 27 45	37	15 20 24	20
Boiled Absorption, %	6.8 6.6 7.2	6.8	8.7 8.9 8.9	8.8	7.8 7.8 8.2	7.9
Permeable Voids, %	14.7 14.4 15.5	14.9	18.4 18.7 18.7	18.6	16.6 16.6 17.4	16.9

NOTES: 1) 1 mm = 0.03937 in.

2) 1 MPa = 145 psi

lining applied to surfaces such as a rock, soil, or concrete face. Two test configurations were investigated: (a) a restrained test assemblage, and (b) an unrestrained test assemblage. Details of these two test assemblages are displayed in Figures 1 and 2, respectively.

The 1525 × 1525 mm (5 ft × 5 ft) test panels were anchored at their corners at 1220 × 1220 mm (4 ft × 4 ft) centers. The restrained test assemblage used 100 mm (4 in.) diameter steel tube sections and 100 mm (4 in.) square anchor plates, but used chain links instead of steel tubes to provide an unrestrained, pin-ended loading condition.

The large test panels were tested at 28 days using central point loading. The load was applied to a 100 mm (4 in.) diameter steel plate using a calibrated hydraulic jack. The load was applied steadily in approximately 2 kN (225 lb) increments until center point deflections of approximately 50 mm (2 in.) had been reached in the restrained tests and until complete fracture and loss of load-carrying capacity had been reached in the unrestrained tests. Complete failure in the unrestrained test panels occurred at deflections in excess of 40 mm (1½ in.). Deflections were monitored with an independently supported dial gauge mounted centrally in the test panel, which could be read to an accuracy of 0.01 mm (0.0004 in.).

Complete load vs. deflection plots are shown in Figure 3 for the four restrained test panels and in Figure 4 for the four unrestrained test panels.

A record was kept of the mode of cracking and the loads at which different cracks occured in each of the test panels. All of the panels first fractured by development of a central transverse hinge. Crack widths versus load were recorded for the first primary cracks that developed. A number of the panels developed additional secondary cracks; however, the widths were not recorded.

On completion of load testing, the test panels were removed from the testing bed and broken into two halves along the prime fracture face. Panel thickness along this fracture face was measured at between 7 and 9 points along the panel, and an average thickness was calculated (see Table 4). The depth of concrete cover from the base of the test panel to the reinforcing mesh was also recorded at between 7 and 9 locations for mesh reinforced panels 1 and 2, and an average cover thickness was calculated (see Table 3).

DISCUSSION

Standard Tests

The compressive strength test results in Table 5 show that the fiber reinforced shotcrete panels have lower 28-day compressive strengths than the plain shotcrete. This is to be expected since the fiber reinforced shotcrete mixes were retempered with water to provide the necessary slump for shooting.

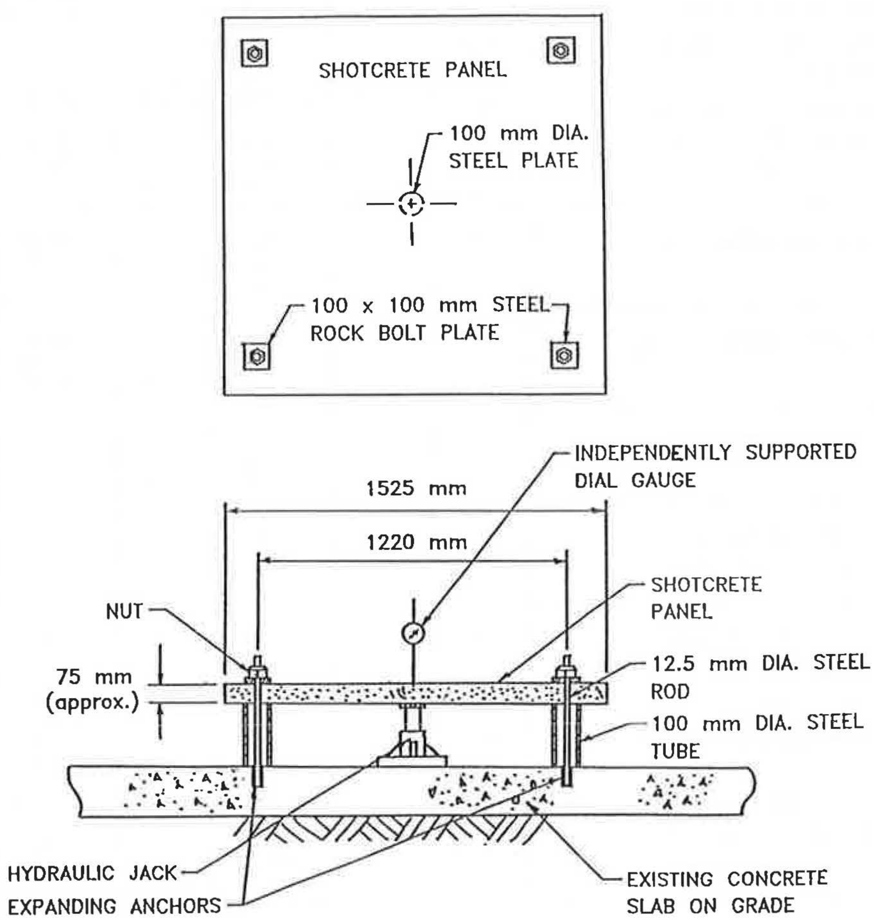

FIGURE 1 Details of restrained test assembly.

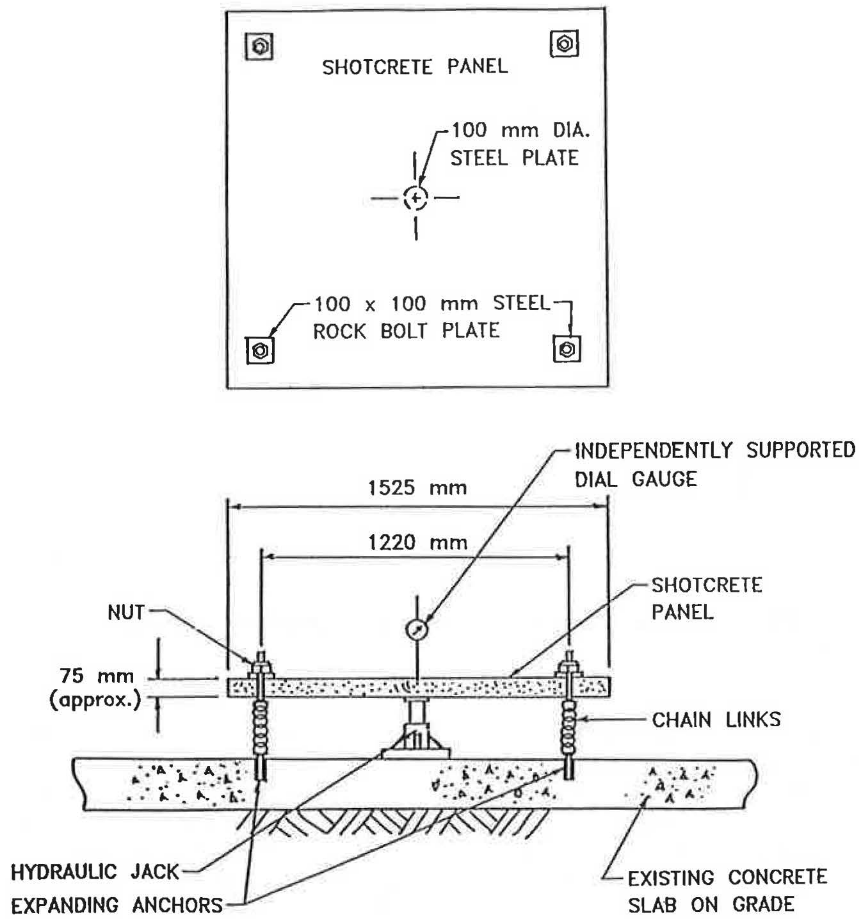

FIGURE 2 Details of unrestrained test assembly.

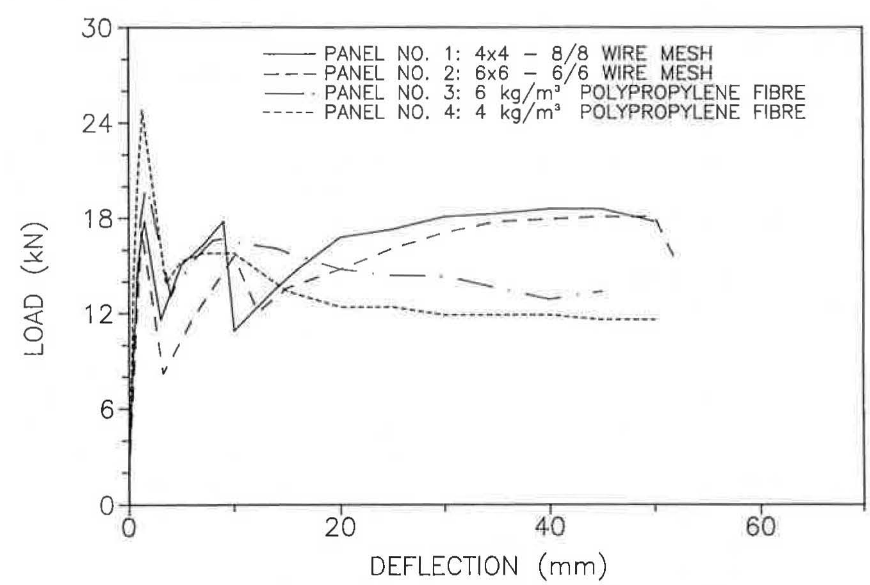

FIGURE 3 Load versus deformation (restrained) of polypropylene fiber versus wire mesh.

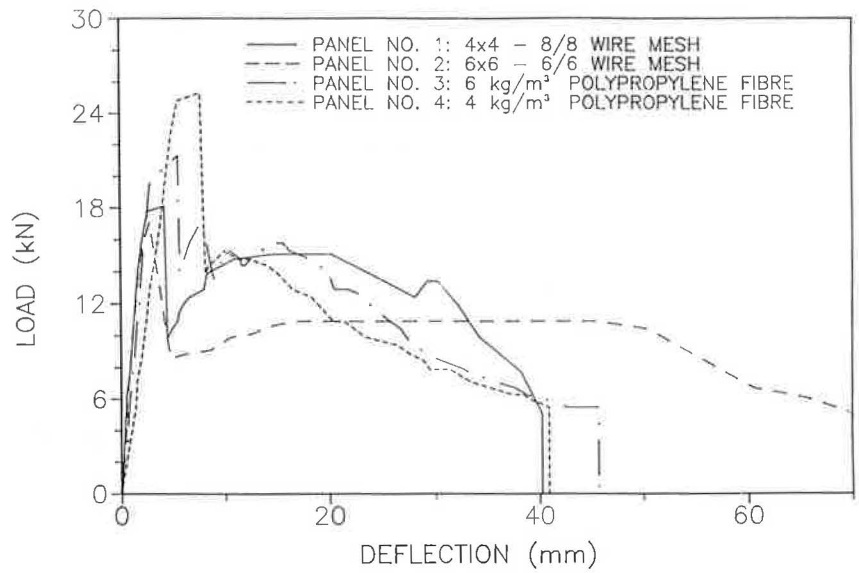

FIGURE 4 Load versus deformation (unrestrained) of polypropylene fiber versus wire mesh.

Nevertheless, the compressive strengths were quite adequate for most shotcrete applications at around 40 MPa (5,800 psi). [If concrete strength, or other factors related to increased water demand, are of concern (e.g. drying shrinkage) then the shotcrete could be retempered with superplasticizer to provide the necessary slump, without any increase in water demand.]

Similarly, the addition of water produced a reduction in flexural strength in fiber reinforced mixes (panels 3 and 4) compared with the plain shotcrete mix (panel 2), as shown in Table 5. Again, this is as expected. The recorded values of first crack and ultimate flexural strength were the same in each individual test, which reflects the fact that the load on the cracked shotcrete beams did not increase beyond the first crack load. This is as expected for the volume concentrations of fiber used in this study.

Of particular interest is the toughness index and residual strength data. The addition of 4 and 6 kg/m³ (6.7 and 10.1 lb/yd³) of 38 mm (1½ in.) long CFP fiber produced average 28-day I_5 toughness index values of 2.5 and 3.3, respectively, and I_{10} toughness index values of 4.6 and 6.5, respectively. The I_5 and I_{10} toughness index values for 4 kg/m³ (6.7 lb/yd³) of CFP fiber compare favorably with the performance of certain commercially used, lower aspect ratio steel fibers added at a rate of 60 kg/m³ (101 lb/yd³). The I_5 and I_{10} toughness index values for 6 kg/m³ (10.7 lb/yd³) of CFP fiber approach the performance of certain higher aspect ratio steel fibers commercially used at a dosage of 60 kg/m³ (101 lb/yd³) (7).

In terms of the descriptors suggested by Morgan (7) for ASTM C1018 toughness index values for steel fiber reinforced shotcretes, the mix with 6 kg/m³ (10.7 lb/yd³) CFP fiber could be given a "fair" to "good" rating. The volume concentration of 6 kg/m³ (10.7 lb/yd³) of CFP fiber in wet-mix shotcrete is 0.67 percent, and the volume concentration of 60 kg/m³ (101 lb/yd³) of steel fiber is 0.75 percent. This partially explains the good performance of the CFP fiber in shotcrete, in spite of the large difference in fiber mass compared with the mass of steel fibers used at typical dosage rates in wet-mix shotcrete. Probably of more significance, however, is the much larger number of CFP fibers, compared with steel, that span a fracture face at the above fiber addition rates. The fractured face of a PFRS specimen has an almost brush-like appearance.

The boiled absorption and volume of permeable voids in the fiber reinforced shotcrete mixes are higher than in the plain shotcrete mix, as shown in Table 5. This is attributed primarily to the effect of water addition in the fiber reinforced mixes. Retempering with superplasticizer would be expected to negate this effect. In terms of the indicators of shotcrete quality suggested by Morgan (7), the plain shotcrete mix (panel 2) and the mix with 4 kg/m³ (6.7 lb/yd³) CFP fiber (panel 4) would be rated as good and the mix with 6 kg/m³ (10.7 lb/yd³) CFP fiber (panel 3) would be rated as fair.

Tests on Large Shotcrete Panels

Two different loading configurations were evaluated: a restrained and an unrestrained test assemblage. The restrained test assemblage was designed to simulate the following conditions:

- Shotcrete has been applied to a substrate such as rock, soil, or concrete.
- The shotcrete is effectively anchored to the substrate with anchors spaced at 1.22 m (4 ft) on center.
- There is no effective bond to the substrate that can be relied on for resistance to applied loads (e.g., such conditions might exist for shotcrete applied to rock that is fractured in behind the bond interface; shotcrete applied to unconsolidated soil; or shotcrete applied to concrete that has continued to deteriorate behind the shotcrete layer, as can occur with alkali-aggregate reactivity).

The unrestrained test assemblage simulates the same conditions as the restrained test assemblage previously described, except that the restraint offered by the anchorage system has been lost. Such a condition might prevail where anchors have

TABLE 6 FIRST CRACK WIDTHS AND DEFLECTION AT TERMINATION OF LOAD TEST

PANEL NO.	TEST METHOD	AT TERMINATION OF TEST	
		CRACK WIDTH (mm)	DEFLECTION (mm)
1	Restrained	5	50
2	Restrained	10	52
3	Restrained	10	45
4	Restrained	10	50
1	Unrestrained	9	40
2	Unrestrained	17	70
3	Unrestrained	7	46
4	Unrestrained	10	41

NOTES:
1) Only first crack width at termination of test recorded.
2) For unrestrained test panels test terminated at complete failure of panel in load test.
3) 1 mm = 0.03937 in.

slipped in a weak substrate material. This presents an extremely pessimistic loading scenario, but it is useful for differentiating between the relative influences of different mesh and fiber reinforcing systems without the superimposed influences of anchor fixity.

In most loading situations, shotcrete would be subjected to uniformly distributed loading, as might be imposed by displaced soil or rock masses or hydraulic pressures. In this study, a central point load was applied for ease of load application. This presents a more severe loading condition and thus provides a lower bound statement of the load-carrying capacity of the shotcrete panels.

The results of the load vs. deflection tests on the large test panels are plotted in Figures 3 and 4 for the restrained and unrestrained tests, respectively. In comparing test results for the different panels, the variations in average panel thickness must be recognized (see Table 4). For example, restrained test panels 1, 2, and 3 are all close to 75 mm (3 in.) thick, but panel 4 is somewhat thicker. In the unrestrained tests, panel 2 is slightly thinner than 75 mm (3 in.), and panels 3 and 4 are somewhat thicker. This variation in panel thickness is reflected in the reported ultimate loads. If all panels were of identical thickness, the ultimate loads would likely be similar.

Of more interest than the ultimate load is the post-first-crack residual load-carrying capacity of the various panels. In the restrained tests, at deflections up to about 15 mm (0.6 in.), the residual load-carrying capacity of mesh reinforced panels 1 and 2 was fairly similar to fiber reinforced panels 3 and 4. At larger deflections up to the termination of the test at about 50 mm (2 in.) deflection, the mesh reinforced panels displayed a somewhat higher residual load-carrying capacity. The superior load-carrying capacity of the 6 kg/m^3 (10.7 lb/yd^3) fiber reinforced panel vs. the 4 kg/m^3 (6.7 lb/yd^3) panel with increasing deflection is well illustrated.

In the unrestrained tests, the smaller gauge mesh panel (panel 1) and fiber reinforced panels 3 and 4 displayed similar residual load-carrying capacity at deflections all the way up to failure, which occurred at deflections in excess of 40 mm (1.6 in.). The heavier gauge mesh panel (panel 2) displayed a generally lower load-carrying capacity up to 20 mm (0.75 in.) deflection and superior load-carrying capacity after about 30 mm (1.2 in.) deflection until failure at 70 mm (2.8 in.). The generally superior load-carrying capacity of the 6 kg/m^3 (10.1 lb/yd^3) fiber reinforced panel vs. the 4 kg/m^3 (6.7 lb/yd^3) with increasing deflection is also evident (particularly when the differences in panel thickness are taken into consideration).

The first crack widths increased approximately linearly with increasing deflection in most of the panels. Crack widths at termination of the load test (for restrained panels) and at ultimate failure (for the unrestrained panels) are summarized in Table 6.

The crack width at termination of the test for the restrained test panels was 10 mm (0.4 in.), except for panel 1, where multiple cracking developed and the first crack width at termination of the test was only 5 mm (0.2 in.). For the unrestrained test panels, the first crack width at failure was in the range of 7 to 10 mm (0.3 to 0.4 in), except for test panel 2, in which the first crack width was 17 mm (0.7 in.) wide when ultimate failure occurred at a deflection of 70 mm (2.8 in.).

The panels were severely deformed at deflections of 50 mm (2 in.). From a practical perspective, the portion of the load-deflection curve at deformations of up to about 15 mm (0.6 in.) is of most interest. At this deflection, first crack widths are still generally less than 3 mm (0.1 in.), and the serviceability of the shotcrete may not yet have been compromised in many applications. Figures 3 and 4 show that the CFP fiber reinforced shotcrete test panels compare favorably with the wire mesh reinforced test panels at deflections of up to 15 mm (0.6 in.), both with respect to residual load-carrying capacity and crack widths. This indicates that the addition of high-volume CFP fiber reinforcement can provide a viable alternative to traditional wire mesh or steel fiber reinforcement in wet-mix shotcrete.

COMPARISON OF STEEL AND POLYPROPYLENE FIBER REINFORCED SHOTCRETES

Previous studies (*2*) comparing plain, mesh, and steel fiber reinforced shotcrete (SFRS) were conducted on dry-mix shotcretes. Nevertheless, it is interesting to compare the performance of these shotcretes with the wet-mix, mesh, and PFRS shotcretes described previously in this paper. The shotcretes from the two different studies were tested in essentially the same way in the large test panel study. For ease of comparison, the data from the previous study (*2*) has been graphed in Figures 5 and 6, using the same scale as used in Figures 3 and 4. While direct comparisons must be made with discretion because of variations in panel thickness and shotcrete strength, certain trends are evident.

The load vs. deflection curves for restrained test panels shown in Figures 3 and 5 demonstrate that the performance of PFRS with 6 kg/m^3 (10.1 lb/yd^3) of CFP fiber approaches the performance of SFRS with 59 kg/m^3 (100 lb/yd^3) of hooked-end steel fiber. The load vs. deflection curves for the unrestrained test panels shown in Figures 4 and 6 reveal similar performance between the PFRS mix with 6 kg/m^3 (10.1 lb/yd^3) of CFP fiber and 59 kg/m^3 (100 lb/yd^3) of hooked-end steel fiber.

In short, the observations of relative performance between PFRS and SFRS in the 75 mm × 75 mm × 355 mm (3 in. × 3 in. × 14 in.) beams tested according to ASTM C1018

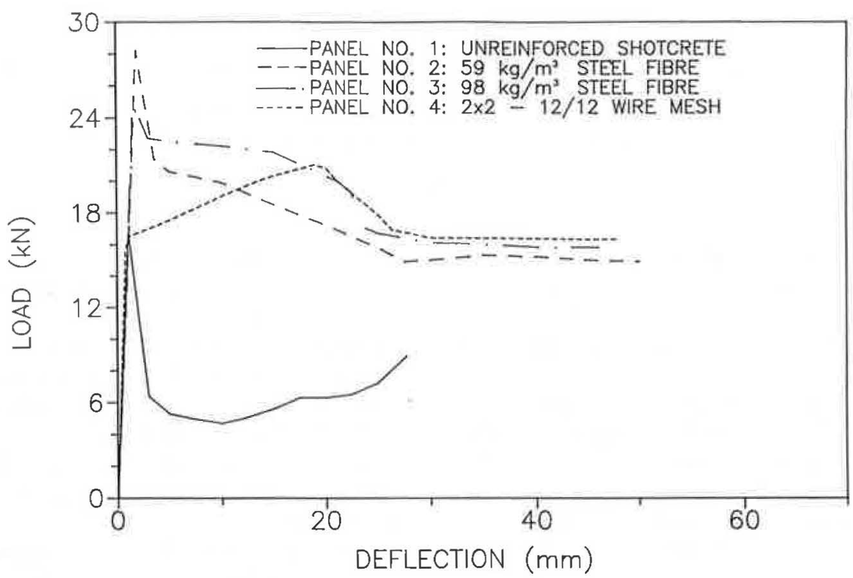

FIGURE 5 Load versus deformation (restrained) of steel fiber versus wire mesh.

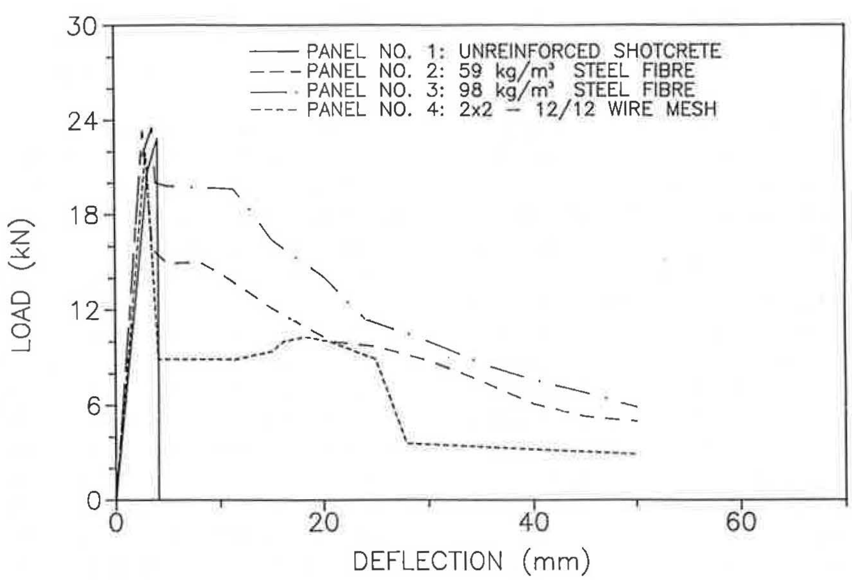

FIGURE 6 Load versus deformation (unrestrained) of steel fiber versus wire mesh.

appear to be reproduced in the large panel tests. This means designers can use the smaller scale ASTM C1018 tests and consider the statement of relative performance, as measured by toughness index values, to be representative of the behavior of shotcrete in the larger scale.

CONCLUSIONS

• The 38 mm (1½ in.) long CFP fiber evaluated in this study can be easily added to wet-mix shotcrete in a ready-mix concrete truck on site at rates of 4 and 6 kg/m³ (6.7 and 10.1 lb/yd³) and be thoroughly mixed, dispersed, and applied by the wet-mix shotcrete process, using a common shotcrete pump. No modifications to the shotcrete pump, equipment, or application procedures are required.

• The addition of CFP fiber at rates of 4 and 6 kg/m³ (6.7 and 10.1 lb/yd³) reduces the apparent workability of the mix as measured by the slump test. In this study, water was added to provide the necessary slump of 25 to 50 mm (1 to 2 in.) required for shooting. As expected, this caused some reduction in the compressive and flexural strength of the fiber reinforced shotcrete compared with the plain shotcrete. In applications where retempering with water is not desirable (for example, where high strength and minimizing the volume change potential of the shotcrete are important), then the required workability can be attained through the addition of superplasticizers in conjunction with fiber addition.

• The addition of 4 kg/m³ (6.7 lb/yd³) of CFP fiber produced ASTM C1018 I_5 and I_{10} toughness index values of 2.5 and 4.6, respectively, at 28 days. These values compare favorably with the performance of certain lower aspect ratio steel fibers added at a rate of 60 kg/m³ (101 lb/yd³) to wet-mix shotcrete.

• The addition of 6 kg/m³ (10.1 lb/yd³) of CFP fiber produced ASTM C1018 I_5 and I_{10} toughness index values of 3.3 and 6.5, respectively, at 28 days. These values are in the same range as the performance of certain higher aspect ratio steel fibers added at a rate of 60 kg/m³ (101 lb/yd³) to wet-mix shotcrete.

• The addition of CFP fiber at the rate of 4 kg/m³ (6.7 lb/yd³) and 6 kg/m³ (10.1 lb/yd³) did not result in an increase in the load-carrying capacity of either the ASTM C1018 flexural test prisms or the large test panels, after first crack. There was, however, a substantial change in post-first-crack residual load-carrying capacity. Plain shotcrete, without mesh or fiber reinforcement, would have no residual load-carrying capacity after first crack in either the ASTM C1018 toughness index test or the unrestrained large panel tests; the shotcrete would simply break into two pieces. Plain shotcrete in a restrained large test panel would continue to carry some load because of aggregate interlock and anchor restraint effects. By contrast the PFRS would continue to carry a significant portion of the ultimate load after first crack for substantial deflections.

• In the restrained large test panels, at deflections of up to about 15 mm (0.6 in.), the PFRS and the shotcrete reinforced with 102 × 102 MW 13.3 × MW 13.3 (4 × 4 8/8) and 152 × 152 MW 18.7 × MW 18.7 (6 × 6 6/6) welded wire reinforcing mesh displayed similar load-carrying capacity after cracking. At larger deflections, up to termination of the test at about 50 mm (2 in.), the mesh reinforced panels displayed somewhat higher residual load-carrying capacity. From a practical perspective, the performance of the shotcretes at deflections of about 15 mm (0.6 in.) or less is of most interest since, at deflections significantly larger than this, the width of crack opening is generally greater than 3 mm (0.1 in.); hence, the serviceability of the shotcrete would likely be compromised in most applications.

• In the unrestrained large test panels, the PFRS and the shotcrete reinforced with 102 mm × 102 MW, 13.3 mm × MW 13.3 (4 in. × 4 8/8 in.) wire mesh displayed similar residual load-carrying capacity after first crack at deflections all the way up to failure, which occurred at deflections in excess of 40 mm (1.6 in.). The panel reinforced with the heavier 152 mm × 152 MW 18.7 × MW 18.7 (6 in. × 6 6/6 in.) wire mesh displayed lower load-carrying capacity after first crack at deflections up to 20 mm (0.75 in.) and superior residual load-carrying capacity at deflections from about 30 mm (1.2 in.) to failure at 70 mm (2.8 in.).

• A comparison of load vs. deflection test results for previously tested SFRS in large restrained test panels indicated that the PFRS with 6 kg/m³ (10.1 lb/yd³) of 38 mm (1½ in.) long CFP fiber reinforcement approached the performance of SFRS with 59 kg/m³ (100 lb/yd³) of hooked-end steel fiber.

• A comparison of load vs. deflection test results for previously tested SFRS in large unrestrained test panels indicated that the PFRS with 6 kg/m³ (10.1 lb/yd³) of 38 mm (1½ in) long CFP fiber reinforcement had a similar performance to the SFRS with 59 kg/m³ (100 lb/yd³) of hooked-end steel fiber.

• The addition of high-volume concentrations of up to 6 kg/m³ (10.7 lb/yd³) of 38 mm (1½ in.) long CFP fiber can provide a viable alternative to traditional mesh or steel fiber reinforcement of wet-mix shotcretes for many applications.

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