System ductility of long fibre reinforced shotcrete

by H.A.D. Kirsten*

Synopsis

Shotcrete has become a strategic component of support in underground mines. The ductility of reinforced shotcrete makes it a safe and economic means of surface support under adverse static and dynamic loads. The ability of ductile shotcrete to sustain load at large deflections enables excavations in squeezing conditions to be stabilized and the safety in excavations subject to rock bursting, to be assured.

A Shotcrete Working Group was formed to find the configurations of fibre reinforcement that would give shotcrete the same ductility as when reinforced with mesh. Beams and panels reinforced with various types and lengths of fibre were accordingly tested. A single mix design consisting of river sand, ordinary Portland cement, fly ash, condensed silica fume and gunite dust and segregation suppressant was used. Steel and polypropylene fibre varying in length from 25 to 50 mm were used in nominal contents of 5 % and 0.5% by mass respectively.

Beams, panels and control specimens were shot into specially made formers. Suitable mixing procedures were developed for the different types of fibre. The test specimens were shot in a semi-dry mix process. The shotcrete was cured until tested 28 days after shooting. The fibre contents and uniaxial compressive and Brazilian tensile strengths of the shotcrete were determined from the control specimens. The beams and panels were tested in bending in specially manufactured test rigs. The beams were examined for simple supports and fixed ends. The panels were fixed in a manner that simulated underground conditions and were loaded statically under uniform pressure. The beams were loaded and the corresponding deflections measured up to failure. The panels were loaded up to mid-span deflections of 150 mm. The results are presented in the form of load-deflection graphs.

The peak loads and ultimate deflections for the fixed end beams were considerably larger than for the simply supported beams for the various types of fibre considered. None of the beams tested, however, were able to sustain load at relatively constant value beyond the peak load.

The panel tests showed that 40 mm and 50 mm long steel fibre and 30 mm, 40 mm and 50 mm long monofilament polypropylene fibre reinforcement gave shotcrete the same ductility as mesh.

Introduction

Shotcrete is an established component of tunnel support. It comprises a quick and convenient method of construction, is cost effective, structurally outstanding, versatile and on application ensures almost immediate safety of the working place. Shotcrete provides a unique means of support in mining tunnels in which conditions vary widely. It can be used in relatively thin applications to secure unstable rock fragments. It can also be used to support ground that is subject to extensive steady state convergence. In key access ways it is on occasion subject to impact loads that are associated with large deflections. When reinforced, laced and bolted shotcrete functions as a competent yielding support.

Considerable effort has been spent in recent years to determine whether fibre can be used instead of mesh to reinforce shotcrete. The suitability of reinforced shotcrete can be demonstrated most effectively in full scale panel tests subject to bending. Two such series of tests were reported by Kirsten[1,2], in which panel thicknesses of 50, 100 and 150 mm, a single mix design, fibre lengths of 25, 30, 35 and 50 mm, a nominal fibre content of 3% by mass and point and uniformly distributed loading were considered. The loading was applied to the central 1 m square section of a 1.6 m square panel. Mesh reinforced shotcrete panels were examined for comparative purposes. The fibre contents varied from 0.6 to 3.2% by mass due to inconsistencies in the manufacturing process.

It was found that mesh reinforcement was superior to fibre reinforcement with regard to ductility, mainly because the woven mesh could unfurl and the fibres were too short. It was proposed that longer fibres, 40 to 50 mm, at contents of about 3% by mass would provide shotcrete with the desired ductility.

The Shotcrete Working Group was accordingly formed early in 1994 to find the configuration of fibre reinforcement that would give shotcrete the desired ductility. Ductility was defined for this purpose to be the ability

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Table I

Schedule of beam tests

Test no.	Mark	Fibre type	Fibre content (%)		Strength (MPa)		End condition	Load (kN)		Deflection (mm)		
			Mix	Beam	UCS	BTS		First crack	Peak	First crack	Peak load	Ult. load
1	B3/S1	Dramix steel	3.0		27.1	3.17	Fixed ended	5.20	6.40	2.80	4.84	56.8
2	B1/S1	Ferro steel	2.89	1.95	21.6	2.53	Simply supported	3.40	3.40	0.77	0.77	7.5
3	B2/S1	Ferro steel	3.59	1.98	26.6	1.80	Simply supported	1.27	3.35	1.68	0.77	9.7
4	B2/S2	Ferro steel	3.59	1.98	26.6	1.80	Simply supported	4.27	4.27	0.77	0.77	9.7
5	B3/S1	Ferro steel	4.27	3.2	21.9	2.53	Simply supported	3.15	3.96	0.89	0.77	16.0
6	B3/S2	Ferro steel	4.27	3.2	21.9	2.53	Simply supported	3.36	3.36	0.77	0.77	12.8
7	B2/S1	Ferro steel	3.59	1.98	26.6	1.80	Fixed ended	7.84	7.84	0.82	0.82	40.4
8	B1/S1	Fibrillated PP	0.36	0.31	23.6	2.10	Simply supported	2.60	2.60	0.74	0.74	32.1
9	B1/S2	Fibrillated PP	0.36	0.31	23.6	2.10	Simply supported	2.22	2.60	0.97	0.63	20.4
10	B2/S1	Fibrillated PP	0.33	0.36	19.2	1.50	Simply supported	4.20	4.51	0.91	0.63	16.2
11	B2/S2	Fibrillated PP	0.33	0.36	19.2	1.50	Simply supported	3.50	3.70	0.86	0.63	24.2
12	B3/S1	Fibrillated PP	0.44	0.6	18.5	2.05	Simply supported	2.50	2.50	0.63	0.63	18.6
13	B3/S2	Fibrillated PP	0.44	0.6	18.5	2.05	Simply supported	2.60	2.90	0.92	0.63	17.2
14	B3/S3	Fibrillated PP	0.44	0.6	18.5	2.05	Simply supported	3.00	5.35	0.63	14.4	29.7
15	B2/S1	Fibrillated PP	0.33	0.36	19.2	1.50	Fixed ended	5.04	8.00	0.57	1.12	51.5

Notes:
1. Ult. = Ultimate
2. UCS = Uniaxial compressive strength
3. BTS = Brazilian tensile strength

of a test panel to withstand not less than 50% of the peak load at a central deflection of 150 mm. The investigation was to be carried out in terms of tests on beams and panels of shotcrete reinforced with various types and lengths of fibre. The purpose in the paper is to present the findings of the investigation.

Materials and mix design

The shotcrete materials, fibre and mix design used in the tests may be described as follows.

Shotcrete materials and mix design

The mix was designed by the Cement and Concrete Institute and comprised 78% river sand, 16.3% ordinary Portland cement, 4.3% unclassified fly ash (pozzfil), 1.3% condensed silica fume, CSF 90 and 0.5% dust suppressant and segregation preventive additive. The mix complied with the ACI and SABS Gradation No 1 type shotcrete. A high strength shotcrete was obtained for some tests by using a very fine Andesitic lava aggregate instead of river sand. The grading curves for the two types of sand are given in Figure 1. Various fibre contents were considered for the mixes for the beams and panels as given in Tables I and II. The mix was supplied in 30 kg bags at a moisture content of 5% that was increased during mixing to 10%.

Control tests were carried out to determine the effects of the dust suppressant on the strength and shrinkage of the shotcrete. The water demand and cohesion of the mortar mixes were increased simultaneously by the additive at the specified dosage rates. The compressive strengths of the mixes containing the additive were comparable at similar water:cement ratios to those of mixes not containing the additive. The use of the additive also did not significantly increase the shrinkage of the mortar.

Fibre specification

Dramix fibres are made of cold-drawn carbon wire with a minimum tensile strength of 1100 MPa. They represent thin smooth lengths of wire with kinked ends that vary between 0.5 to 1.0 mm in diameter, depending on length.

Ferro fibres are cut from sheet steel and crimped at the ends. The fibres are slightly oval in cross-section and 0.5, 0.55 and 0.78 mm in diameter on average for lengths of 25, 30 and 45 mm respectively. The aspect ratios for the three lengths considered were 50, 56 and 57 and the tensile strengths 430, 430 and 275 MPa respectively.

Harex fibres have rough textured surfaces with distinctively cranked end hooks, 2.5 mm long. Drawn wire fibre type KSF 30/015 with a tensile strength in excess of 800 MPa and an aspect ratio of 75, was used in the panel reinforced

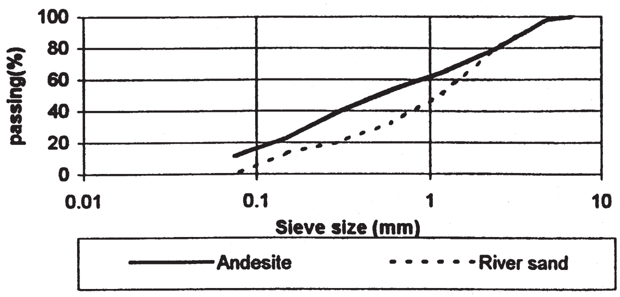

Figure 1—Grading curves for river and andesitic lava sand

Table II

Schedule of panel tests

Test no.	Mark	Fibre		Fibre content (%)		Density (kg/m³)	Strength (MPa)		Load (kN)		Deflection at (mm)	
		Length (mm)	Type	Mix	Panel		UCS	BTS	Peak	Ult	First crack	Peak load
45	B2/P3	-	Unreinforced	-	-	-	26.5	1.5	60	-	-	1.6
46	B3/P3	-	Unreinforced	-	-	2240	23.6(3)	2.43	60	-	-	1.6
43	B1/P4	-	Diamond mesh	1.4	1.4	-	-	-	90	85 (94%)	1.9	145.0
44	B2/P4	-	Diamond mesh	1.4	1.4	-	-	-	91	81 (89%)	1.9	82.0
1	B4/P3	30	Dramix steel	4.27	3.35	-	33.0	3.0	98	36 (37%)	2.2	29.0
2	B5/P2	30	Dramix steel	4.27	3.72	2148	23.3(8)	2.86	131	46 (35%)	39.0	39.0
3	B7/P1	30	Dramix steel	1.5	1.5	2305	19.9(3)	2.20	152	40 (26%)	20.0	20.0
4	B8/P1	30	Dramix steel	4.27	3.17	2303	35.1(3)	3.80	118	34 (29%)	4.4	33.0
5	B1/P1	40	Dramix steel	4.27	2.5	2311	27.0(3)	3.2	158	64 (41%)	20.0	20.0
6	B2/P1	40	Dramix steel	4.27	2.48	2218	20.5(3)	1.9	153	74 (48%)	43.0	43.0
7	B3/P1	40	Dramix steel	4.27	3.1	2218	20.5(3)	1.9	129	77 (60%)	24.0	24.0
10	B9/P1	50	Dramix steel	4.27	-	2531	31.9(3)	2.83	105	68 (65%)	4.0	34.0
11	B10/P1	50	Dramix steel	4.27	-	2531	31.9(3)	2.83	87	59 (68%)	4.0	22.0
55	B15/P1	40	Dramix steel	4.27	3.3	2534	84.9(2)	14.8	222	106 (48%)	35.0	35.0
56	B15/P2	40	Dramix steel	4.27	3.3	2534	84.9(2)	14.8	216	106 (49%)	6.0	32.0
57	B15/P3	40	Dramix steel	4.27	3.3	2534	84.9(2)	14.8	176	102 (58%)	12.0	52.0
14	B5/P3	25	Ferro steel	4.27	2.54	-	-	-	77	26 (34%)	1.2	1.2
15	B6/P3	25	Ferro steel	4.27	2.1	2207	33.0(4)	3.63	67	30 (45%)	1.1	2.2
16	B4/P2	30	Ferro steel	4.27	3.6	-	23.7(3)	3.10	100	24 (24%)	6.0	6.0
17	B4/P4	32	Ferro steel	4.27	3.27	-	24.7(3)	2.7	114	35 (31%)	2.4	2.4
18	B1/P2	40	Ferro steel	4.27	4.2	2322	27.5(3)	3.1	90	17 (19%)	2.0	2.0
19	B7/P3	30	Harex steel	4.27	4.28	1950	21.7(7)	2.47	97	30 (31%)	13.0	13.0
27	B5/P1	30	Fibrillated PP - fine	0.45	0.59	2130	18.3(8)	2.10	73	27 (37%)	1.1	1.1
28	B6/P1	30	Fibrillated PP - fine	0.45	0.90	2136	19.4(4)	2.43	65	35 (54%)	3.7	3.7
29	B1/P3	40	Fibrillated PP - fine	0.45	0.4	2136	23.8(4)	2.13	79	27 (34%)	2.4	18.0
30	B2/P2	40	Fibrillated PP - fine	0.45	0.33	2150	19.3(4)	2.45	74	36 (49%)	2.3	2.3
31	B3/P2	40	Fibrillated PP - coarse	0.45	0.46	2166	22.7(3)	2.40	96	15 (16%)	2.8	20.0
32	B3/P4	40	Fibrillated PP - coarse	0.45	0.56	-	21.5(3)	3.00	79	22 (28%)	2.9	24.0
35	B6/P2	30	Monofilament PP	0.45	0.35	2153	24.7(4)	2.70	65	37 (57%)	5.0	13.0
36	B7/P4	30	Monofilament PP	0.45	0.38	2134	23.8(4)	2.13	71	44 (62%)	3.9	3.9
37	B5/P4	40	Monofilament PP	0.45	0.21	2084	22.4(3)	2.23	52	18 (35%)	1.5	1.5
38	B6/P4	40	Monofilament PP	0.45	0.49	2136	16.1(4)	1.73	70	44 (63%)	1.7	4.0
40	B9/P4	40	Monofilament PP	0.45	0.36	2208	31.6(3)	3.30	55	42 (76%)	0.5	0.5
48	B13/P1	40	Monofilament PP	0.45	-	2243	31.2(3)	2.58	62	43 (69%)	2.1	38.0
49	B13/P2	40	Monofilament PP	0.45	-	2226	31.0(2)	1.95	53	37 (70)%	5.0	32.0
41	B10/P4	50	Monofilament PP	0.45	0.35	2289	37.6(3)	3.06	61	50 (82%)	0.5	2.9
42	B11/P4	50	Monofilament PP	0.45	0.34	2207	23.1(3)	2.13	68	44 (65%)	0.5	0.5
50	B13/P3	50	Monofilament PP	0.45	0.34	2238	31.4	3.52	69	42 (61%)	2.3	11.0
52	B14/P1	50	Monofilament FPP	0.45	0.35	2241	28.5(3)	2.17	73	45 (62%)	7.0	16.0
53	B14/P2	50	Monofilament FPP	0.45	0.34	2241	28.5(3)	2.17	66	40 (61%)	2.4	2.4
54	B14/P3	50	Monofilament FPP	0.45	0.34	2241	28.5(3)	2.17	63	47 (75%)	7.0	16.0

Notes:

1. *Mark: Batch No./Panel No.*
2. *Fibre content by mass*
3. *Number in brackets next to UCS represents number of tests*
4. *Number in brackets next to ultimate load represents proportion of peak load*
5. *UCS: Uniaxial compressive strength*
6. *BTS: Brazilian tensile strength*
7. *Ult.: Load at target deflection of 150 mm*
8. *PP: Polypropylene*
9. *FPP: Fluorinated polypropylene*
10. *Diamond mesh: aperture = 100 mm, diameter = 3.2 mm*

with Harex fibre. Only 30 mm long Harex fibre was used in the test panels as greater lengths were not available. The results from this test are not conclusive, but are included for the sake of completeness.

A Contra-K type fibrillated polypropylene fibre that mixes readily with shotcrete was used. The material was a 100% low denier polypropylene with a specific gravity of 0.9, a melt point of 165°, high acid and salt resistance, a water immersion time of less than 90 seconds, a breaking strength of 37 MPa and an elongation at yield of 18%. The monofilament polypropylene fibres consisted of single strands of the same material as the fibrillated polypropylene fibres.

Formers and manufacturing procedures

The formers for the beams and panels and the mixing, application and curing procedures adopted may be described as follows.

Formers

The beams were shot into wooden formers 1.6 m long x 200 mm wide x 75 mm deep. Four 1600 mm square x 75 mm deep formers were initially made from plate steel for the panel tests as shown in Figure 2. Four additional 2052 mm square x 75 mm deep steel formers were subsequently made

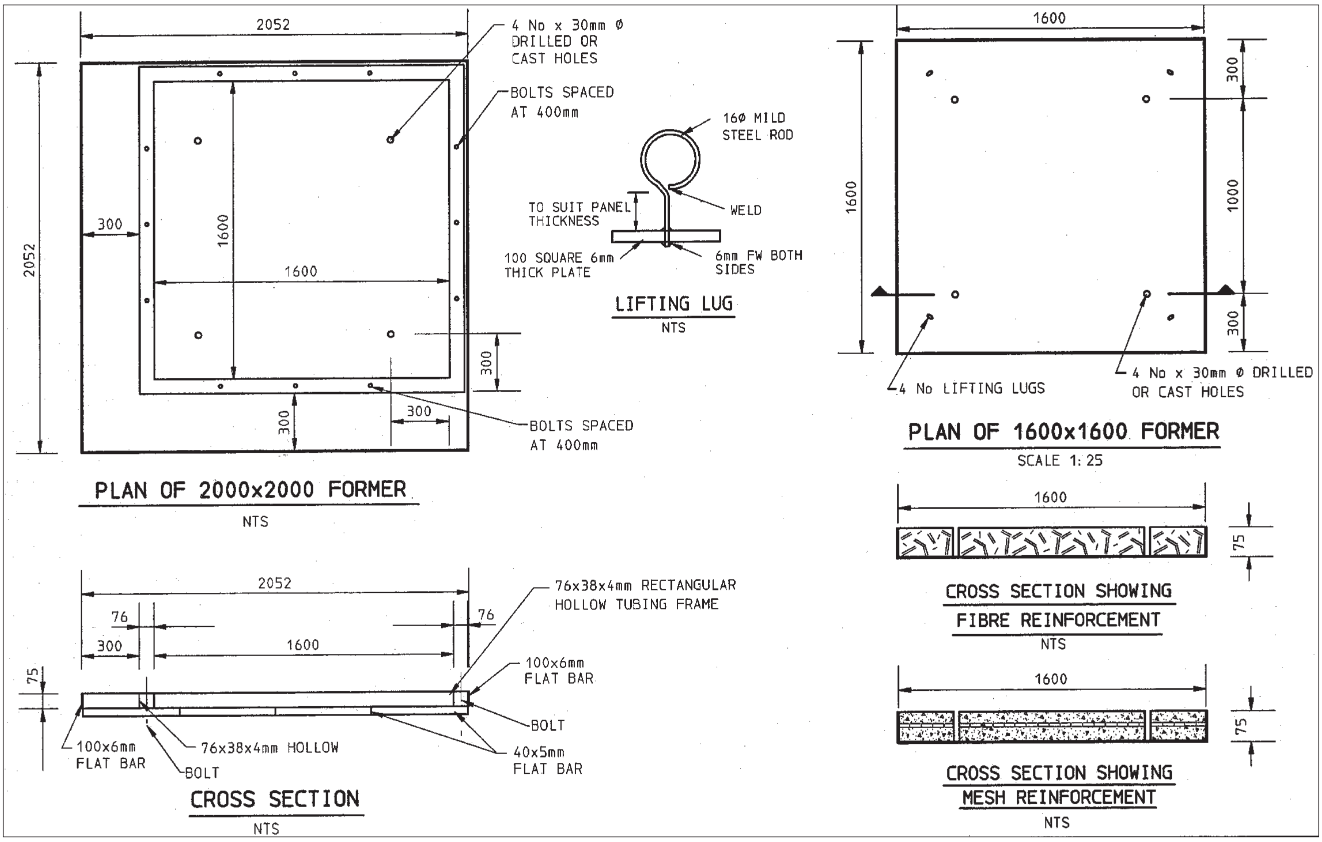

Figure 2—Panel formers

to increase the overall rate at which panels could be prepared, cured and tested. These formers were enlarged to 2052 mm square to enable beams 1600 mm long x 300 mm wide x 75 mm deep to be shot alongside the panels. Eight trapezoidal formers 180 mm deep, 500 mm x 700 mm top area and 300 mm x 500 mm bottom area were used in addition for control strength testing. The same mix was shot into these formers as that used for the test panels. Cylindrical core was drilled from the trapezoidal formers for compression and tensile strength tests. Lifting hooks were cast into the panels at positions outside the bolt holes as shown in Figure 2 to ensure that they did not cause cracks during testing.

Mixing procedures

Different mixing procedures were developed for the different types of fibre to prevent balling. For the Dramix fibres, one quarter of the sand and water for the mix was mixed with the fibres in the drum mixer for 2 minutes to dissolve the glue on the fibres after which the remainder of the sand and the dust suppressant were added. The cementitious material was added when the sand had pelletized. The total mixing period was about 6 minutes.

For the Ferro and Harex fibre, the sand, water and dust suppressant were placed in the drum mixer. The cementitious material and fibres were added in that order when the sand had pelletized and mixing allowed to continue for a total time of 4 minutes.

One-quarter of the sand, the water and the polypropylene fibres were placed in the drum mixer and mixing started. Early wetting of the fibres prevented segregation from the mix. The remainder of the sand, dust suppressant and cementitious material were added in that order when the fibres were dispersed and discoloured and mixing continued for a total period of 6 minutes.

Shooting and curing procedures

The nozzle was held at right angles to and 0.6 to 1.5 m away from the former placed in a nearly upright position. The material was shot into the former in 300 mm wide bands from the bottom upwards. The nozzle was rotated in small circular movements whilst gradually moved across the width of the former. The panels were continuously spray cured for three days after shooting and subsequently moist-air cured under a tarpaulin for 25 days until tested.

Fibre content was determined from samples taken from the trapezoidal formers. It was expressed as the proportion of the dry weight of the fibres to the total weight of the sample. Rebound was not measured.

Shotcreting system

A dry mix shotcreting system was used to shoot the panels. The key components of the machine comprise a rotor drum assembly, mixer feed screw, electrical motor, switching panel and delivery hose. The mixer feed screw provides the rotor drum with a gravity feed, since it cannot be choke fed with a mix that contains extra long fibres. The rubber liner in the delivery hose is of sufficient hardness to effectively obviate drag on the fibres and aggregate.

The material is supplied to the system in bagged form.

The bagged material comprises the aggregate, fibre, if used, and chemical additives and is premixed in a rotary drum mixer at a moisture content of 5% to prevent segregation during transportation and balling of the fibre during mixing and shooting

Test programme

The test programme included compressive and tensile strength tests and bending tests on beams and panels. The testing arrangements and procedures followed and the tests completed may be described as follows.

Compressive and tensile strength tests

Cores were drilled from the control panels for each batch of test panels. Cylinder compression and Brazilian tensile strength tests were carried out on these cores as recorded in Table II. The number of tests carried out in each instance are shown in brackets next to the uniaxial compressive strength. The cores were 90 mm in diameter and length for the compressive strength tests except for tests 1, 16 and 17 in which instance the dimensions were 150 mm. The discs for the Brazilian strength tests were 90 mm in diameter and in thickness. The cores for compression testing were capped with sulphur mortar in terms of SABS Specification 865. All the strengths were determined 28 days after placing the shotcrete.

Beam testing arrangement and procedures

The test rig for the beams is shown in Figure 3. It comprises a two-point loading system with measurement of the deflections by three dial gauges at the centre and at opposite edges on the centre line of the beam. The loads were applied by cylindrical rollers 300 mm apart. The supports were 1 m apart and consisted of cylindrical rollers for the simply supported tests. The ends of the beams were secured for the fixed-ended tests by bolting 300 mm long sections onto the bed of the test rig at each end.

Panel testing arrangement and procedures

The test rig for the panels is shown in Figure 4. It caters for a 1.6 m square panel which is held down by 4 bolts over a 1 m square area in the centre. The load is applied by means of a water filled reinforced rubber bag 1 m square. A system of valves permitted air to be bled and the pressure in the bag to be regulated.

The pressures in the bag were measured with an in-line pressure transducer connected to a Ringwood analogue-digital converter. The converter was calibrated against an in-line 1000 kPa dial type pressure gauge.

The calibration was carried out at 50 kPa intervals over the range of pressures expected. The calibrating adjustments were continued until the readings correlated consistently over two to three cycles of rising and falling pressures over the full range of test pressures, to within 1 kPa at the zero point, and to within 3 to 4 kPa at an applied pressure of 150 kPa.

Deflections were measured at the centre of the panel with 50 mm or 100 mm travel dial gauges, resting on a small aluminium plate attached to the centre point.

Beam tests completed

The system ductility of shotcrete derives from the two-way

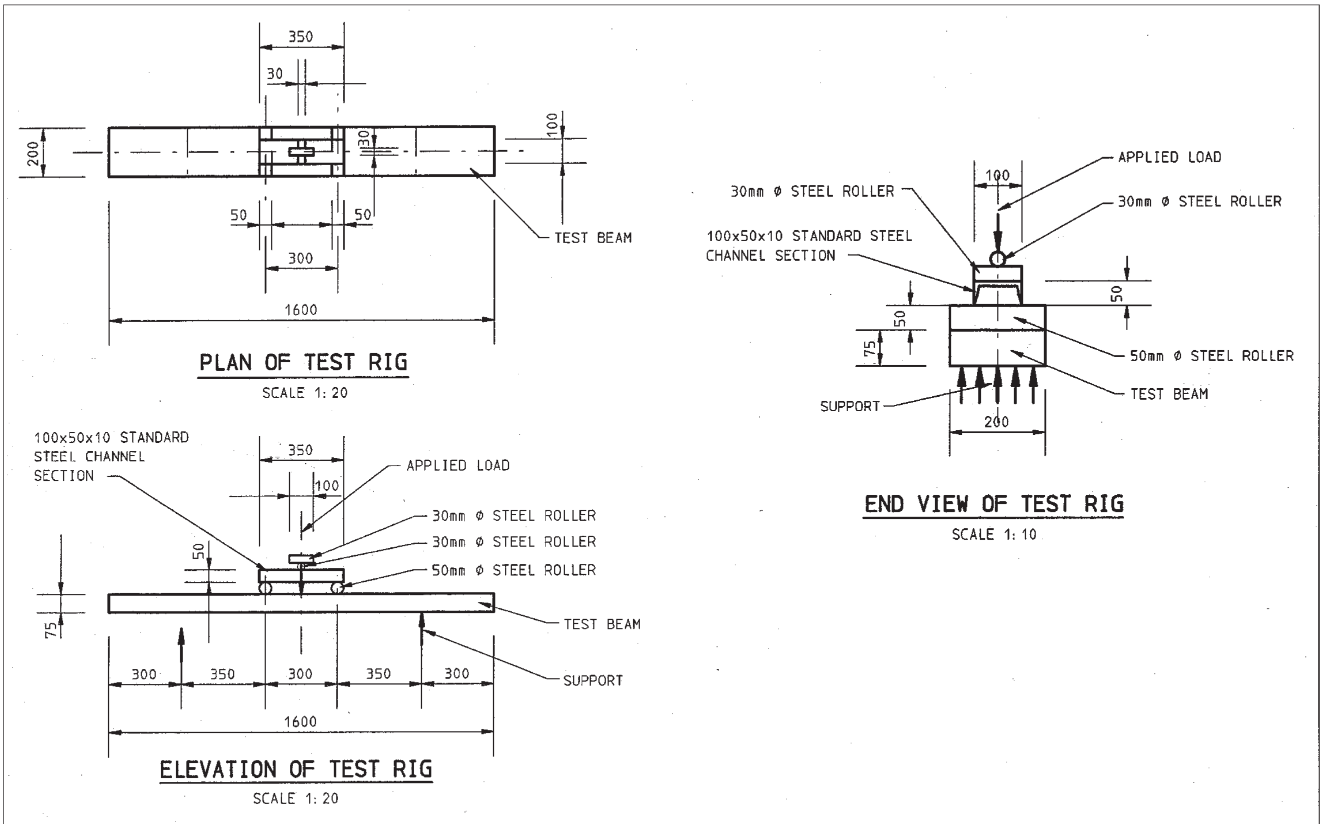

Figure 3—Test rig for beams

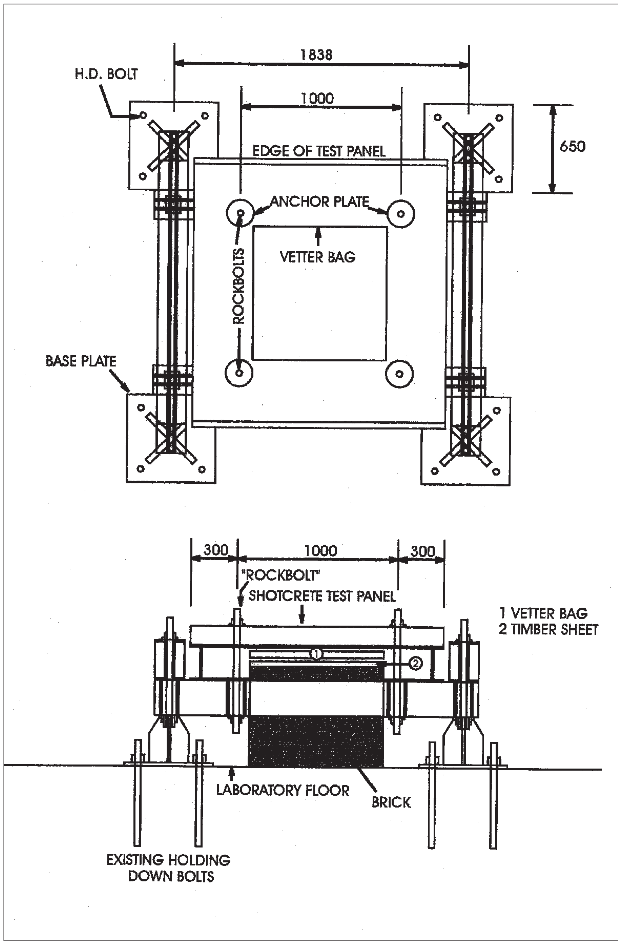

Figure 4—Test rig for panels

spanning nature of shotcrete and from the continuity of the shotcrete across the lines of support provided by the rock bolts. The purpose of the beam tests was to examine to what extent one-way spanning represented the system ductility of shotcrete.

Fifteen beam tests were accordingly carried out as scheduled in Table I. The beams were shot into wooden formers 1.6 m long x 200 mm wide x 75 mm deep. The beams were reinforced with Dramix steel, Ferro steel and fibrillated polypropylene fibre, all of 45 mm length. All the beams were tested 28 days after placing the shotcrete.

Panel tests completed

The purpose of the panel tests was to determine the ductility of shotcrete under conditions similar to actual applications. The 41 tests were carried out on panels 75 mm thick. These were alternatively reinforced with Dramix (12), Ferro (5) and Harex (1) steel fibre, fibrillated (6) and monofilament (13), polypropylene fibre and woven wire mesh (2). The number of tests completed are given in brackets. Two additional panels were not reinforced at all. The Dramix steel fibres comprised lengths of 30, 40 and 50 mm, the Ferro steel fibres, lengths of 25, 30 and 40 mm, the Harex steel fibres, a length of 30 mm, the fibrillated polypropylene fibres, lengths of 30 and 40 mm and the monofilament polypropylene fibres, lengths of 30, 40 and 50 mm. The diamond mesh was made of 3.1 mm diameter strand with an aperture of 100 mm square.

Nominal fibre contents of 5% and 0.5% by mass were respectively aimed at for the steel and polypropylene fibre reinforced panels. It was attempted to reinforce a number of panels with 1.5% by mass of steel fibre to represent general practice in industry. This could, however, not be achieved with sufficient accuracy as submitted above. A fine fibrillated polypropylene fibre was used in 4 panels and a coarse fibre in the remaining 2, reinforced with 40 mm long fibres. The monofilament polypropylene fibres in 3 of the panels were fluorinated, but in the other panels were not treated. A common mix design was employed except in the case of 3 of the panels reinforced with 40 mm long Dramix fibres, which were made of high strength shotcrete. An inventory of the tests completed is given in Table II, from which it can be seen that the actual fibre content varied to some extent. All the panels were tested 28 days after placing the shotcrete.

Test results

The results of the tests may be presented as follows in terms of fibre content, crack patterns, strengths and load-deflection graphs.

Fibre content in beams and panels

The steel fibre contents in the beams were on average 36% less than in the corresponding mixes as evident in Table I. The measured contents of fibrillated polypropylene fibre in the beams, were generally more than in the corresponding mixes. This anomaly arose due to difficulties in removing all the aggregate fines from the fibre and from drying it completely.

The Dramix, Ferro and monofilament polypropylene fibre contents in the panels were on average 27%, 26% and 23% less than in the corresponding mixes in terms of the measurements given in Table II. The difficulties that were encountered in measuring the fibrillated polypropylene fibre contents in the beams were also encountered in respect of the panels.

Crack patterns in beams and panels

The beams developed tension cracks at small deflection under either or both loading points. The cracks opened up as the test proceeded until the system became unstable. The loads and deflections at first crack are given in Table I.

A tension crack developed at small deflection in the top surface across the middle and parallel to the edges of the panels in all instances. A second, similar tension crack developed shortly thereafter at right-angles to the first crack. Tension cracks developed in the bottom surface diagonally across the bolt holes as the test proceeded. Diagonal compression cracks soon followed in the top surface inside the bolt supports. In some instances the two main tension cracks in the top surface were followed by smaller parallel cracks, in which case the widths of the main cracks were limited. The loads and deflections at first crack are given in Table II. A typical pattern for the main cracks is shown in Figure 5.

Compressive and tensile strengths

The uniaxial compressive and Brazilian tensile strengths were determined for the panels as given in Table II. The compressive strength for the ordinary shotcrete varied from

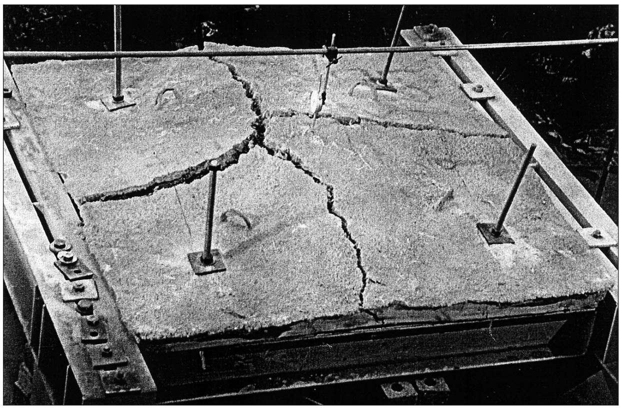

Figure 5—Typical cracks in panel

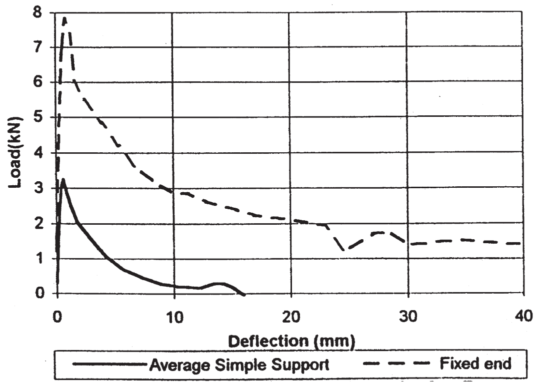

Figure 8—Average load-deflection graphs for Ferro fibre reinforced beams of different end conditions

16.1 to 37.5 MPa with an average of 25.9 MPa and the tensile strength from 1.5 to 3.8 MPa with an average of 2.6 MPa. The ratio of compressive to tensile strength varied from 7.7 to 17.7 with an average of 10.3. The compressive strength for the Andesitic lava shotcrete was 84.9 MPa on average and the tensile strength 14.8 MPa on average. The corresponding ratio of compressive to tensile strength amounted to 5.7.

Load-deflection graphs for beam tests

Deflection of the beams was recorded with three dial gauges. The deflections referred to here represent the averages of the three readings.

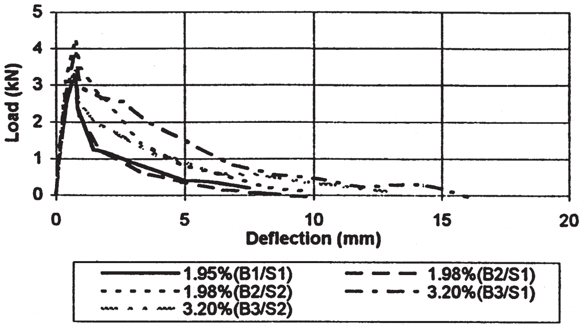

Figure 6—Load-deflection graphs for simply supported Ferro fibre reinforced shotcrete beams

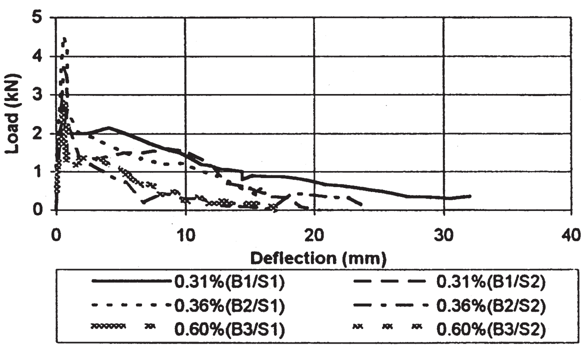

Figure 7—Load-deflection graphs for simply supported fibrillated polypropylene fibre reinforced shotcrete beams

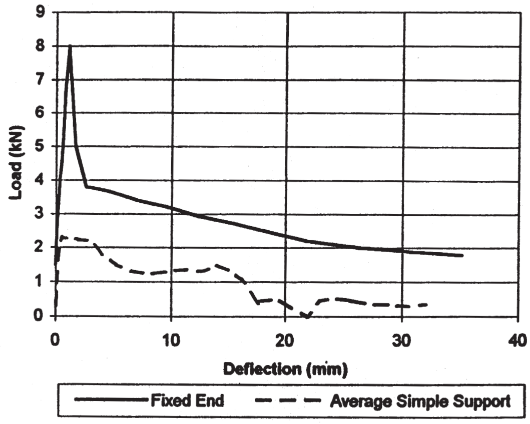

Figure 9—Average load-deflection graphs for fibrillated polypropylene fibre reinforced shotcrete beams of different end conditions

The load-deflection graphs for the 5 simply supported Ferro fibre reinforced shotcrete beams are given in Figure 6. The graphs rise within a deflection of 1 mm to a peak and then rapidly fall to zero within 9 to 16 mm of deflection.

The load-deflection graphs for the 7 simply supported fibrillated polypropylene fibre reinforced shotcrete beams are given in Figure 7. The graphs rise to a peak load within 1 mm, drop as rapidly to half the peak load and then gradually reduce to zero load within 17 to 30 mm of deflection.

The average load-deflection graphs for the Ferro fibre reinforced shotcrete beams simply supported and fixed ended are shown in Figure 8. The graphs are similar in shape in that a peak is reached within 1 mm, after which the load drops off gradually to zero. The peak loads amount to 3.2 kN and 7.8 kN and the ultimate deflections to 16 mm and 40 mm respectively.

The average load-deflection graphs for the fibrillated polypropylene fibre reinforced shotcrete beams simply supported and fixed ended are shown in Figure 9. The graph for the simple support does not represent the shape of the underlying graphs. It rises to a peak load of about 2.3 kN and then reduces to zero at about 30 mm deflection. The graph for the fixed end support rises to a peak load of 8 kN, drops to half the peak load and then gradually reduces to zero at a deflection of about 50 mm.

The average load-deflection graphs for simply supported Ferro and fibrillated polypropylene fibre reinforced shotcrete beams are shown in Figure 10. The graph for the Ferro fibre does not represent the underlying graphs. It rises to a peak load of about 3.1 kN and then gradually reduces to zero at a deflection of about 16 mm. The graph for the fibrillated polypropylene fibre rises to a peak of about 2.2 kN and then reduces gradually to zero at a deflection of about 22 mm.

The average load-deflection graphs for fixed ended Dramix, Ferro and fibrillated polypropylene fibre reinforced shotcrete beams are shown in Figure 11. The graphs are different in shape. The graph for the Dramix fibre reinforced beam rises to a peak of 6.3 kN, maintains the peak for about 5 mm deflection and then gradually reduces to zero at an ultimate deflection of about 55 mm. The graph for the Ferro fibre reinforced beam rises very rapidly to a peak of 7.8 kN and then drops to zero at a gradually reducing rate to an ultimate deflection of 40 mm. The graph for the polypropylene fibre reinforced shotcrete beam rises to a peak at 8 kN, falls as rapidly to about half the peak and then very slowly falls to an ultimate deflection of 50 mm.

Load-deflection graphs for panel tests

The load-deflection graphs for the two unreinforced panel tests are given in Figure 12. The graphs are very similar and rise to an identical peak value of 60 kN at a deflection of 1.6 mm. The load thereafter rapidly fell to zero as the panels became completely unstable on the development of major cracks.

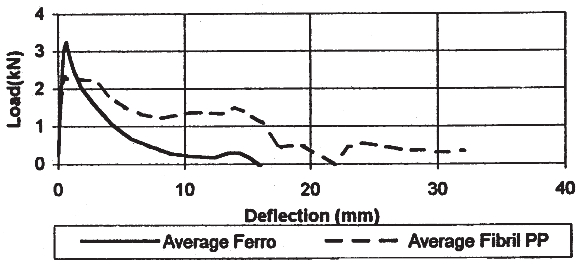

Figure 10—Load-deflection graphs for simply supported shotcrete beams reinforced with various types of fibre

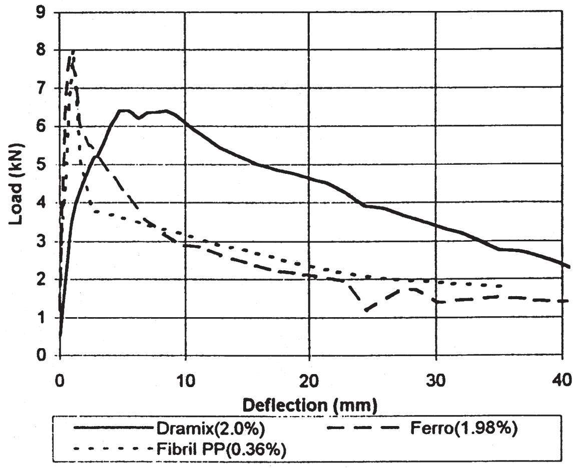

Figure 11—Load-deflection graphs for fixed ended shotcrete beams reinforced with various types of fibre

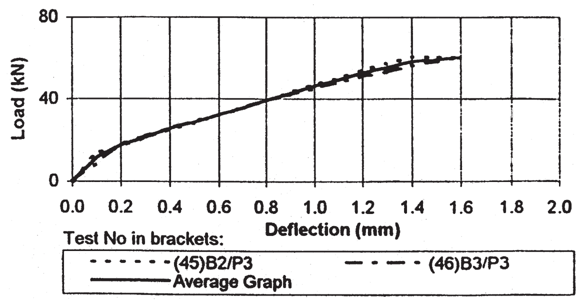

Figure 12—Load-deflection graphs for unreinforced shotcrete panels

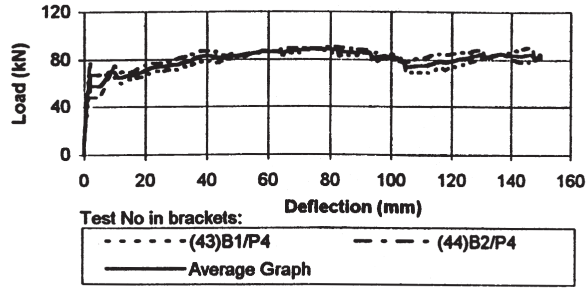

Figure 13—Load-deflection graphs for 100 mm aperture diamond mesh reinforced shotcrete panels

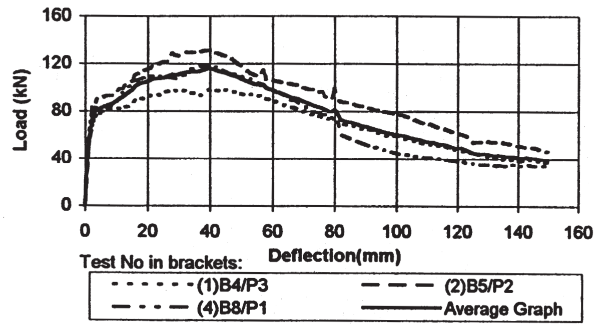

Figure 14—Load-deflection graphs for 30 mm long Dramix fibre reinforced shotcrete panels

The graphs in Figure 13 for the two diamond mesh reinforced panels are scattered from the average by ±5%. After an initial spike the load drops slightly and then rises steadily to a maximum of about 90 kN, after which it drops to an average of about 80 kN that is maintained up to the target deflection of 150 mm.

The load-deflection graphs for the three 30 mm long Dramix fibre reinforced panels are given in Figure 14. The graphs rapidly rise to a yield load of 80 kN on average, then increase gradually to an average peak load of about 115 kN, after which they drop off steadily to an ultimate load of 40 kN at the target deflection of 150 mm. These graphs are typical of the other tests on Dramix fibre reinforced panels. The scatter about the average for all the Dramix fibre reinforced panel tests is on average 11% at the peak load and 9% at the ultimate load.

The load-deflection graphs for the two 30 mm long Ferro fibre reinforced panels are given in Figure 15. The graphs

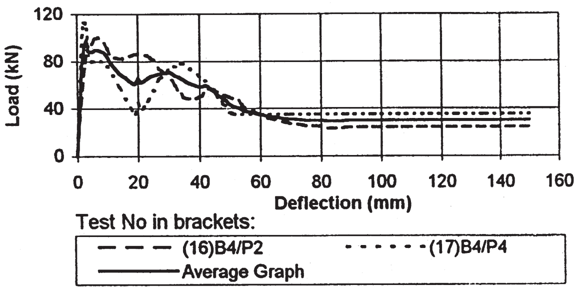

Figure 15—Load-deflection graphs for 30 mm long Ferro fibre reinforced shotcrete panels

rapidly rise to a yield load of about 97 kN on average, then steadily fall to a load of 30 kN at about 60 mm deflection which is maintained to the target deflection of 150 mm. These graphs are typical of the other tests on Ferro fibre reinforced panels. The scatter about the average for all the Ferro fibre reinforced panel tests is of the order of 20% shortly after the peak load and on average about 17% at the ultimate load.

The load-deflection graphs for the two 30 mm long fibrillated polypropylene fibre reinforced panels are given in Figure 16. After an initial spike the load first drops and then recovers to a peak value of about 60 kN which is maintained constant up to a deflection of about 40 mm after which it drops steadily to an ultimate load of 30 kN at the target deflection of 150 mm. These graphs are typical of the other tests on fibrillated polypropylene fibre reinforced panels. The scatter about the average for all the fibrillated polypropylene fibre reinforced panel tests is on average 23% at the peak load and 15% at the ultimate load.

The load-deflection graphs for the two 30 mm long monofilament polypropylene fibre reinforced panels are given in Figure 17. After an initial spike, the load first drops and then recovers to a peak value of about 60 kN after which it

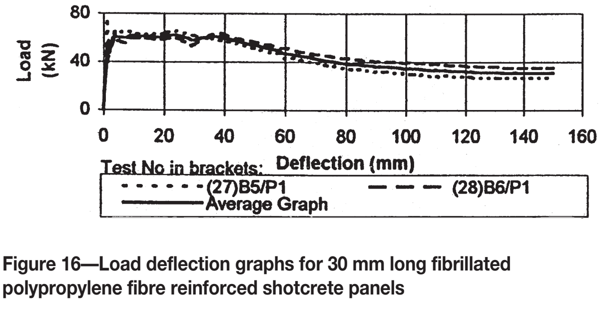

Figure 16—Load deflection graphs for 30 mm long fibrillated polypropylene fibre reinforced shotcrete panels

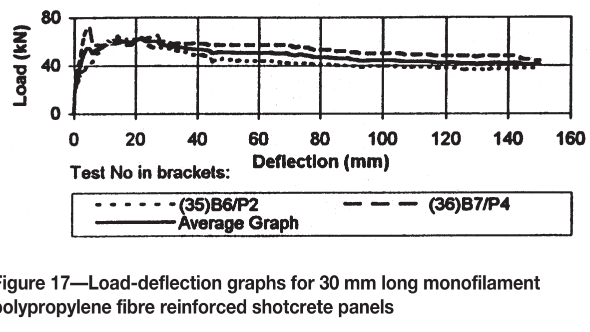

Figure 17—Load-deflection graphs for 30 mm long monofilament polypropylene fibre reinforced shotcrete panels

reduces very gradually to an ultimate load of about 40 kN at the target deflection of 150 mm. These graphs are typical of the other tests on monofilament polypropylene fibre reinforced panels. The scatter about the average for all the monofilament polypropylene fibre reinforced panel tests is on average 12% at the peak load and 16% at the ultimate load.

The load-deflection graph for the Harex fibre reinforced panel is shown in Figure 18. The graph rises to an initial peak, drops and rises again to a slightly higher peak at about 97 kN. It then drops within a deflection of 30 mm to a plateau at about 30 kN which extends to the target deflection of 150 mm.

Findings from beam tests

The peak loads for the different Ferro fibre reinforced beams are not affected by differences in fibre content as evident from Figure 6. However, the ultimate deflections of the beams containing a fibre content at 3.2% were larger than those of the beams with a content of 1.98% by mass.

It is shown in Figure 7 that neither the peak loads nor the ultimate deflections for the beams reinforced with fibrillated polypropylene fibre, are affected by differences in fibre content.

It is evident from Figure 8 that the end condition increases the peak load and ultimate deflection of beams reinforced with Ferro fibre. The peak load is more than doubled and the ultimate deflection, more than trebled by a fixed end than by a simply supported condition.

The end condition more than trebles the peak load and more than doubles the ultimate deflection of fibrillated polypropylene fibre reinforced shotcrete beams as shown in Figure 9.

Fibrillated polypropylene fibre doubled the ultimate deflection of the simply supported beam compared to Ferro fibre as shown in Figure 10. It can be seen from Figure 11 that the Dramix fibre reinforced beams carried considerably higher loads beyond the peak than either the Ferro or polypropylene fibre reinforced beams.

These observations confirm that the ability of shotcrete to sustain load at extended deflection is determined, in addition to the properties of the material, by the characteristics of the structural system as represented by the support conditions. However, the reduction in load beyond the peak confirms that the beam test does not enable the ability of shotcrete to sustain load for extended deflections at a significant proportion of the peak load, to be determined.

Findings from panel tests

The findings from the fibre reinforced panel tests may be presented as follows with regard to equivalence in ductility to mesh reinforced panels and with regard to satisfying the criterion of the ultimate load not being less than 50% of the peak load at a deflection of 150 mm.

No reinforcement and mesh reinforcement

It is evident from Figure 12 that unreinforced shotcrete possesses no ductility and from Figure 13 that mesh reinforced shotcrete is ideally plastic. In the first instance the panel collapses at a deflection of 1.6 mm and in the second, the panel continues to carry load to a deflection of at least 150 mm.

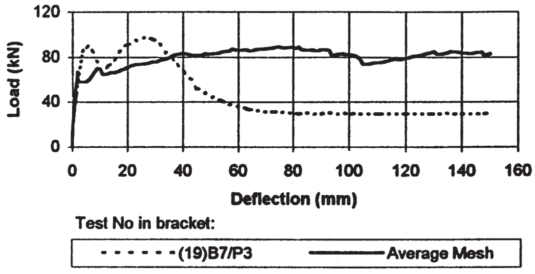

Figure 18—Load-deflection graph for 30 mm long Harex fibre reinforced shotcrete panel

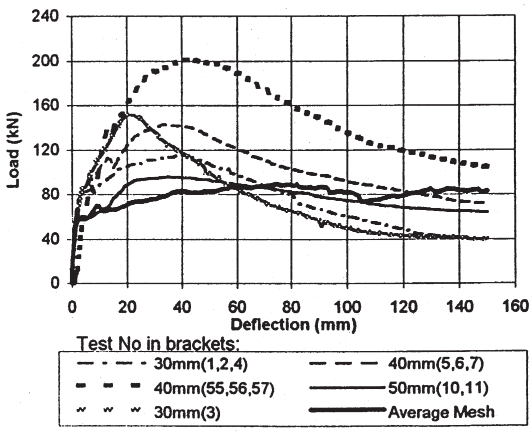

Figure 19—Average load-deflection graphs for Dramix fibre reinforced shotcrete panels

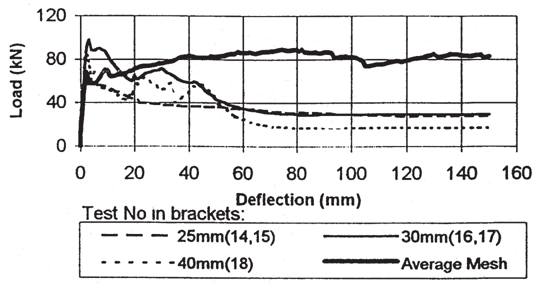

Figure 20—Average load-deflection graphs for ferro fibre reinforced shotcrete panels

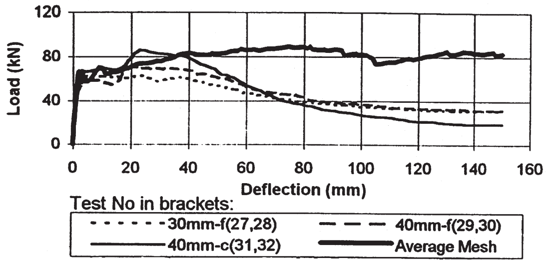

Figure 21—Average load-deflection graphs for fibrillated polypropylene fibre reinforced shotcrete panels

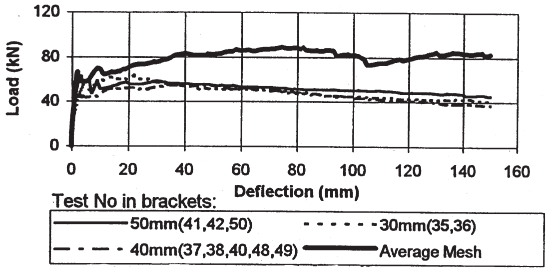

Figure 22—Average load-deflection graphs for monofilament polypropylene reinforced shotcrete panels

Dramix fibre reinforcement

The average load-deflection graphs for the Dramix fibre reinforced panels are shown in Figure 19. The peak loads are not progressed in sequence of fibre length. The peak load for the panel reinforced with 30 mm long fibre at about half the fibre content compared to the others, test 3, is completely out of sequence. The ultimate loads for the panels reinforced with 40 mm and 50 mm long fibres are not in sequence, but are distinctly higher than those for the panels reinforced with 30 mm long fibres. The ratios of ultimate to peak load are strictly in order of fibre length and content at 27%, 34%, 51% and 68% for 30 mm, 30 mm, 40 mm and 50 mm long fibre, the first of these results represents a fibre content of 1.5% and the remaining three, a fibre content of just over 3%. The panels reinforced with 40 mm and 50 mm long fibre closely resemble the ductility of the mesh reinforced panels and are the only ones that give an ultimate load approximating that of the mesh reinforced panels.

The topmost graph in Figure 19 represents an average shotcrete strength of 84.9 MPa compared to 25.9 MPa for the other tests. The higher strength of the shotcrete evidently increases both the peak and ultimate loads very greatly. The ratio between ultimate and peak load is 53% which is similar to that for the lower strength material reinforced with fibres of the same length, 40 mm.

Ferro fibre reinforcement

The average load-deflection graphs for the Ferro fibre reinforced panels are shown in Figure 20. The peak and ultimate loads for the 25 mm and 30 mm long fibre reinforced panels are sequenced in order of fibre length. Those for the 40 mm long fibre are not. The ratios of ultimate to peak load are 40%, 31% and 20% for 25 mm, 30 mm and 40 mm long fibres. The ductility of panels reinforced with this fibre does not resemble that of panels reinforced with mesh.

Harex fibre reinforcement

The load-deflection graph for the Harex fibre reinforced panel is shown in Figure 18. The ratio of ultimate to peak load is 31%. The ductility of the panel does not resemble that of the mesh reinforced panels. No conclusion can, however, be drawn in this regard from the single test carried out.

Fibrillated polypropylene fibre reinforcement

The average load-deflection graphs for the fibrillated polypropylene fibre reinforced panels are shown in Figure 21. The peak loads are in sequence of fibre length and the ultimate loads not. The sequences of the graphs for the coarse and fine 40 mm long fibre are reversed at peak and ultimate load. The ratios of ultimate to peak load are 50%, 44% and 22% for 30 mm, 40 mm and 40 mm fibre lengths respectively. The ductility of panels reinforced with this fibre does not sufficiently resemble that of panels reinforced with mesh.

Monofilament polypropylene fibre reinforcement

The average load-deflection graphs for the monofilament polypropylene fibre reinforced panels are shown in Figure 22.

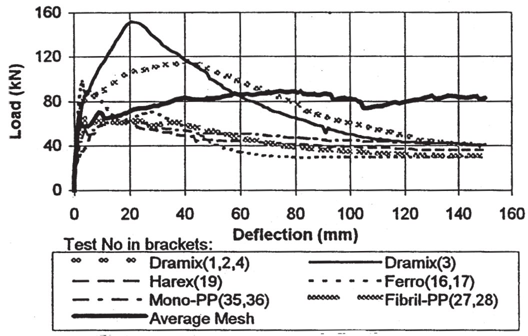

Figure 23—Average load-deflection graphs for various types of 30 mm long fibre reinforced shotcrete panels

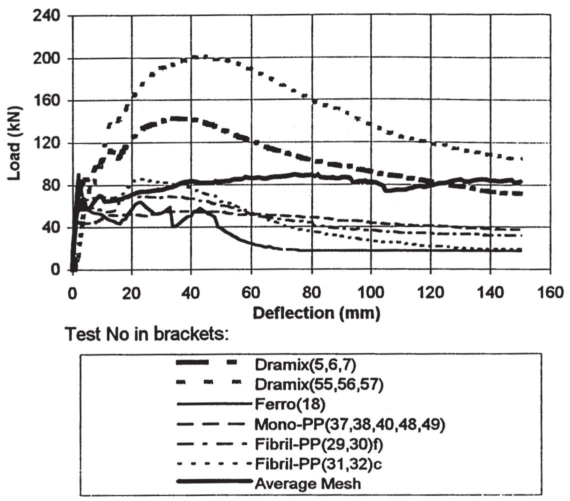

Figure 24—Average load-deflection graphs for various types of 40 mm long fibre reinforced shotcrete panels

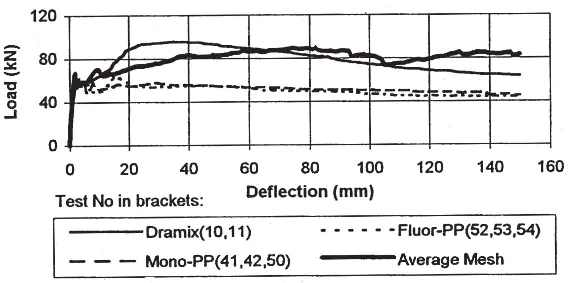

Figure 25—Average load-deflection graphs for various types of 50 mm long fibre reinforced shotcrete panels

The graphs are very similar at all deflections and are not in sequence of fibre length. The graphs representing the behaviour of the 50 mm long untreated and fluorinated polypropylene fibre are, practically speaking, identical. The ratios of ultimate to peak load are 65%, 64%, 75% and 73% for fibre lengths of 30 mm, 40 mm, 40 mm and 50 mm respectively. The ductility of panels reinforced with this fibre closely resembles that of panels reinforced with mesh.

30 mm long fibre reinforcement

The average load-deflection graphs for panels reinforced with Dramix, Ferro, Harex and fibrillated and monofilament polypropylene fibre of 30 mm long fibre are shown in Figure 23. The two graphs for 30 mm long Dramix fibre represent contents of 1.5% and 3.4% respectively. The peak loads for all the steel fibre reinforced panels are considerably higher than those for the polypropylene fibre reinforced panels and yet the ultimate loads are very similar for all the fibre types. The ratios of ultimate to peak load in sequence of the types referred to, are 27%, 34%, 31%, 31%, 50% and 65%. Only the 30 mm long polypropylene fibre reinforced panels are equivalent to the mesh reinforced panels and satisfy the ductility design criterion.

40 mm long fibre reinforcement

The average load-deflection graphs for panels reinforced with Dramix, Ferro and fibrillated and monofilament polypropylene fibre of 40 mm long fibre are shown in Figure 24. The two graphs for 40 mm long Dramix fibre reinforced panels represent high and ordinary strength shotcrete respectively. The peak and ultimate loads for all the Dramix fibre reinforced panels are considerably higher than those for the other panels. The ratios of ultimate to peak load for the Dramix (high strength shotcrete), Dramix (standard strength shotcrete), Ferro, fibrillated polypropylene and monofilament polypropylene fibre, are 53%, 51%, 20%, 22% and 70%. Only the 40 mm long Dramix and monofilament polypropylene fibre reinforced panels are equivalent in ductility to the mesh reinforced panels and satisfy the ductility design criterion.

50 mm long fibre reinforcement

The average load-deflection graphs for panels reinforced with Dramix and monofilament polypropylene fibre of 50 mm in length are shown in Figure 25. The peak and ultimate loads for the Dramix fibre are considerably higher than those for the monofilament polypropylene fibre reinforced panels. The ratios of ultimate to peak load are 68% and 73% for the two types of fibre respectively. Both types of 50 mm long fibre are equivalent in ductility to the mesh reinforced panels and satisfy the ductility design criterion.

Overall conclusions

Within the test series only 40 mm and 50 mm long Dramix fibre and 30 mm, 40 mm and 50 mm long monofilament polypropylene fibre reinforcement are equivalent in ductility to mesh reinforcement and satisfy the ductility criterion that the ultimate load should be at least 50% of the peak load at 150 mm deflection. Unreinforced shotcrete possesses no ductility. Fibre lengths of 30 mm generally do not accord shotcrete the ductility that mesh does.

Recommended further testing

Fibre type and length were examined mainly in the investigation under static loading conditions. In addition other parameters need to be investigated for static loading as motivated below.

Mix design

Numerous mix designs are used in the mining industry which include dry mixes with rapid hardening characteristics, wet mixes based on crusher sand and mixes in which pretreated extruded perlite is used as aggregate. This mix, which does not absorb water, has a unit weight of about one-third of that of ordinary shotcrete and provides very good thermal insulation. The performance of these mixes should be examined in representative tests.

Bolt spacing

Bolt spacing varies to a considerable extent in practice due to the unevenness of the rock surface and the associated difficulties in accurately collaring the drill holes. The continuity of the shotcrete across the lines of support between bolts which directly affects the ductility of the shotcrete as a system, will be affected most by a variation in bolt spacing. A spacing of 1 m has been considered in the tests completed to date. Spacings of 1.25 m and 1.5 m should, in addition, be examined.

Panel thickness

All panels tested to date were 75 mm thick. At least two further thicknesses, 50 mm and 100 mm, should be examined to ensure that the conclusions derived from the tests on the 75 mm thick panels, apply to the various thicknesses used in practice.

Wire rope lacing

Diagonal wire rope lacing across the bolts reduces the span of the shotcrete and thereby ensures the ductility of the system. The extent to which rope lacing affects the ductility of the system depends on the bolt spacing which should therefore be examined in conjunction with different patterns of rope lacing in a sufficient number of tests.

Fibre content and length

Fibre length only was varied in the study. An overall economically and structurally optimum relationship is expected to exist between fibre content and length. The existence of such a relationship should be investigated by comparing the ductility of panels reinforced with higher concentrations of shorter fibres with that of panels reinforced with lower concentrations of longer fibres.

Mesh position

The mesh was placed in the middle of the shotcrete panels tested. In practical applications the position of the mesh varies considerably within the thickness of the shotcrete due to undulations in the rock surface. At the bolts the mesh is against the rock and between the bolts, it can be either in the back or in the front of the shotcrete. Due to the random undulation of the rock surface, the mesh is as a result not likely to contribute to the flexural strength of the shotcrete in more than about half of the area that it covers. This drawback does not apply to fibre reinforcement that is evenly distributed throughout the thickness of the shotcrete. The overall efficiency of mesh reinforcement is adversely affected by the random variation in position within the shotcrete and should be examined in representative tests.

Weld mesh profile

Weld mesh is frequently preferred in practical applications over diamond mesh. Straight and profile stranded mesh should be evaluated with regard to panel ductility in representative panel tests. The straight stranded mesh is not expected to impart the same degree of ductility to the shotcrete as diamond mesh does. The unfurling profile of woven diamond mesh is largely responsible for the basketing ability of shotcrete reinforced therewith. The application advantages of weld mesh can be combined with the structural excellence of diamond mesh by considering kinked or profiled weld mesh. Straightening of the kinks will ensure that the strands in weld mesh do not fail prematurely under tension and thus model the behaviour of diamond mesh.

Bolt yielding

Yielding of the bolts affects the continuity of the shotcrete across the lines of support between the bolts and therefore the ductility of the system. Bolt yielding is, however, associated with impact loading and should be considered in conjunction with rockbursting.

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