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Correlations in the behaviour of fibre reinforced shotcrete beam and panel specimens

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ABSTRACT

Satisfactory structural performance of Fibre Reinforced Shotcrete (FRS) in applications such as tunnel linings is dependent on an ability to support load after cracking. At present, both beam and panel specimens are used to measure the post-crack flexural capacity of this material. Although these tests have been widely used to develop improved fibres and FRS mix designs, the relationship between performance data produced in beam and panel tests is unclear. This investigation was therefore undertaken to examine possible correlations in behaviour between beam and panel specimens and determine which was the most appropriate type of test for a given FRS application.

RÉSUMÉ

La performance structurale du béton projeté renforcé de fibres (BPRF) pour des utilisations telles que le support et le renforcement de tunnels dépend de l'aptitude du matériau à supporter les charges après fissuration. À l'heure actuelle, des échantillons de poutre ou de petites dalles sont utilisées pour mesurer la résistance en flexion après fissuration du BPRF. Même si de nombreux essais ont été réalisés pour développer de meilleures fibres et améliorer la composition des mélanges de BPRF, la correspondance entre les résultats obtenus par l'essai sur poutre et ceux sur dalle est ambiguë. La présente étude a donc été réalisée afin d'examiner les relations possibles entre les résultats des essais sur dalle et ceux sur poutre pour déterminer la configuration d'essai la plus appropriée pour une utilisation donnée de BPRF.

1. INTRODUCTION

The ability of Fibre Reinforced Shotcrete (FRS) to support load in the cracked state is the basis for its use in many construction applications. The most common application to date has been in the production of linings for civil tunnels and mine drives [1]. Its popularity has increased over the last 25 years as a result of improvements in both economic competitiveness and structural performance, to the point where it is used for at least a part of almost every tunnel recently constructed [2].

Improvements in the structural performance of FRS have occurred as a result of experimentation with mix designs and research into the mechanical behaviour of fibres in a hardened concrete matrix. This experimentation is partly the result of a move away from prescriptive specifications for shotcrete design to performance-based specifications. In the early history of FRS use, it was generally believed that all fibres exhibited similar performance in the post-crack range and that the principal determinant of post-crack performance was fibre dosage [3]. Experience has since revealed these premises to be false. Structural specifications for FRS are now based on performance, primarily in the cracked state, using either beam or panel specimens. Commonly used tests include the ASTM C-1018 test for beams [4] and the EFNARC panel test [5].

Fibre reinforcement produces a concrete lining exhibiting quite different characteristics to mesh reinforced concrete. The principal difference is that most commercially viable FRS mix designs exhibit post-crack strain softening in flexure, whilst mesh reinforced concrete is often plastic (at least up to moderate crack widths). The degree of strain softening exhibited depends on many factors, particularly fibre type and dosage, and varies greatly between concretes used for different projects. The complexity of post-crack material behaviour has confounded attempts to develop a rational method of lining design using FRS, with the result that arbitrary measures of performance have been adopted. In this confused situation, it is not surprising that considerable debate exists as to which type of test results in the most suitable measure of performance to distinguish between competing FRS mixes.

In seeking a solution to this problem, a series of beam and panel specimens were produced using commercially viable FRS and tested to examine relationships between the performance of specimens [6-8]. This has also helped to indicate which type of test is the most appropriate for a given application.

2. EXPERIMENTAL PROCEDURES

2.1 Production of specimens

The investigation consisted of an experimental assessment of post-crack performance in 62 sets of FRS specimens. Each set of specimens was produced using a different type or dosage of fibre for reinforcement. One plain concrete set and two sets of mesh reinforced shotcrete specimens were also included. The tests undertaken on the specimens were the EFNARC third-point loaded beam test [5], a centrally loaded beam test [9], the EFNARC panel test [5], and a Round Determinate Panel test [6, 10]. Three specimens were examined for each test method for each set of specimens resulting in over 700 specimens in total.

All of the specimen sets were made using one of five mix designs. The majority were made using a mix conforming with that described in column 3 of Table 1. Two sets were made using a mix in which a precipitated silica was used as a substitute for silica fume (column 4 of Table 1). For another two sets a high strength shotcrete was required, so the mix design was altered significantly to achieve this (column 5, Table 1). Details of the materials used to produce these mixes are described by Bernard [6-8].

The specimens were produced by inclining plywood forms at approximately 45° against a supporting frame and manually spraying the shotcrete in a circular fashion around the form until it was full. A crew of four men then moved each specimen to level ground after which it was screeded to achieve uniform thickness and a smooth surface. About 30-60 minutes after spraying, a polythene sheet was placed over the surface of each specimen to limit evaporation. The specimens were then left to harden and cure overnight, and were cut to size using a concrete saw the following day.

Commercially produced concrete was used for the investigation, primarily because of the large quantity required (2 m^3 per set), but also because of a desire to assess the variability of specimens sprayed using shotcrete from a commercial plant rather than 'labcrete'. This decision resulted in some loss of control over the consistency of the concrete used in the study. In the early stages of the investigation, attempts were made to maintain the water content of the concrete at 200 L/m^3, but this was impossible. For the majority of specimen sets a consistent amount of superplasticiser was therefore added to each batch and water was then used to regulate the rheology to obtain a target slump of 60-70 mm. Following difficulties encountered in obtaining a pumpable mix in the early part of the investigation, fire clay was added to every batch in the latter part of the investigation to aid pumpability.

In the following sections, particulars of each test procedure undertaken on the hardened specimens are provided.

2.2 Third-point testing of beams

The third-point loaded EFNARC beam test [5] is a well established procedure used for FRS performance assessment in many parts of the world. The specimen measures 75 × 125 × 550 mm (tested over a span of 450 mm), cut from a much larger beam or panel in such a way that the upper face of the beam corresponds to the plane of the sprayed surface.

The EFNARC specification states that a beam specimen must be tested in a manner that excludes extraneous deformation from the central deflection record, but is vague in describing how this is to be achieved. The procedure for deflection measurement described in ASTM C1018 [4] has therefore been adopted in the present investigation because this is meticulous in describing how extraneous deflections are to be excluded. Dual side-mounted LVDT's were used to measure the deflection of the central upper surface of the beam relative to the mid-plane of the supported ends.

The Modulus of Rupture (MOR) was calculated using elastic engineering bending theory, the peak load reached immediately prior to cracking, the span of the test apparatus, and the section modulus at the position of the crack. Toughness was quantified in terms

Table 1 – Mix design for concrete

Ingredient	Mix 1 Sets 1-5 (kg/m^3)	Mix 2 Sets 6-34 (kg/m^3)	Mix 3 Sets 39-40 (kg/m^3)	Mix 4 Sets 50, 51 (kg/m^3)	Mix 5 All others sets (kg/m^3)
Coarse agg. (7/10 mm)	620	500	500	550	500
Coarse sand (0.3-4.75 mm)	615	775	850	900	850
Fine sand (0.15-2.36 mm)	410	415	225	100	225
Cement (GP)	380	360	500	500	360
Fly ash	40	-	-	20	-
Silica Fume	40	40	-	30	40
Precipitated Silica	-	-	8	-	-
Fire Clay	-	-	5	5	5
Water reducer	1900 mL	1900 mL	1900 mL	1900 mL	1900 mL
Target Slump*	60-70 mm	60-70 mm	60-70 mm	60-70 mm	60-70 mm

* *Water content not measured but adjusted to regulate slump.*

of residual strengths, toughness indices in accordance with ASTM C1018, and energy absorption in accordance with JSCE SF4 [11]. The residual strengths were determined using the section modulus at the point of cracking, and the residual load capacity of the beam at central deflections of 0.50 mm (span/900) and 3.00 mm (span/150). The ASTM Toughness Indices I_{10} to I_{50} were determined by the normal procedure, regardless of the fact that the beams did not conform to the conventional ASTM dimensions. The Japanese measures of toughness T_{JSCE} and F_{JSCE} (energy under the load-deflection curve up to 3.0 mm deflection and equivalent residual flexural strength) were also determined by the normal method using the dimensions of the EFNARC beam.

2.3 Centrally loaded beam tests

A problem inherent in third-point loaded beam tests is the lack of control over the position of the crack [12]. The result can be widely differing angles of rotation at the crack for a given central deflection. Since the tensile load capacity of the majority of fibres decreases as crack width increases, this feature of third-point loaded beams is believed to be a cause of significant variability.

In an effort to overcome some of the limitations of third-point beam testing, an alternative beam test involving a central point load was recently suggested by Bernard [6]. Although the position of the crack remains uncontrolled in this test, the fact that a central load is imposed results in a sharp peak in flexural stress (calculated using engineering bending theory) around the centre of the beam typically resulting in failure very close to the point of load application. The result is a more consistent crack rotation for a given central deflection. The behaviour of the uncracked portion of the beam is discounted from the rotation at the crack, thereby focussing attention on the part of the specimen undergoing deformation. The moment-crack rotation relationship derived from this test is also of direct structural relevance to lining behaviour and is unaffected by any geometric characteristic of the beam other than thickness. Centrally loaded beams have been tested in this investigation using the apparatus shown in Figs. 1 and 2. The size of the specimen used in this test is the same as that used in the EFNARC third-point loaded beam test (75 × 125 × 550 mm, on a 450 mm span with the upper face corresponding to the plane of the sprayed surface).

The performance of the Centrally Loaded Beam has been reported in terms of the Modulus of Rupture and post-crack moment capacity expressed as a function of crack rotation. The moment-crack rotation relationship was also integrated to obtain an estimate of the energy absorbed by the beam between the point of cracking and 0.05 radians of crack rotation. The method used to derive the moment-crack rotation relation is described by Bernard *et al.* [9].

2.4 EFNARC panel tests

An alternative to beam-based toughness testing is panel testing. Since sprayed concrete linings are often required to resist point loads, it is rational in some situations to quantify the performance of competing mix designs through the application of a point load to a panel that represents a portion of a continuous lining. The EFNARC square panel test [5] is possibly the most widely known panel-based assessment procedure. This test involves the application of a central point load to a 100 × 600 × 600 mm square panel simply supported on a 500 × 500 mm flat square base.

Performance in EFNARC panels is assessed by two means: measurement of the peak load sustained, and energy absorbed up to a central deflection of 25 mm. The first parameter is not a particularly useful characteristic of these panels because it is strongly influenced by distortions in the base of the specimen that is produced off the form during spraying. It is also determined by the strength of the matrix and bears little relation to the performance of the fibres, at least for mixes with normal levels of energy absorption. In contrast, the energy absorbed up to a deflection of 25 mm is strongly influenced by the performance of the fibres. This parameter is calculated by integrating the area under the load-displacement curve so that the result is measured in units of energy known as Joules, which are equivalent to Newton-metres. The higher the energy absorption, the more capable a mix is of supporting a load in the cracked state. This property is commonly referred to as 'toughness'.

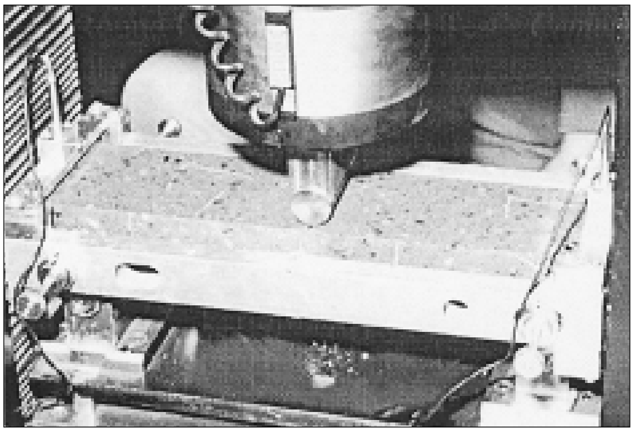

Fig 1. – Centrally loaded beam test.

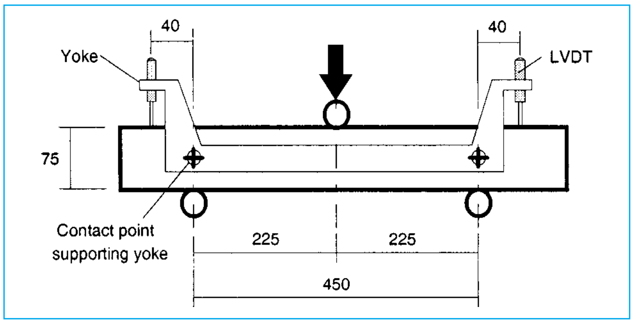

Fig. 2 – Centrally loaded beam test configuration.

Although this test has been widely accepted in Europe and elsewhere, it suffers a number of shortcomings. The most significant is the difficulty entailed in trying to produce a specimen with a flat base. The base of the specimen is only truly simply supported if it is flat and evenly supported around the perimeter of the test fixture. A specimen that is flat will typically produce a load-displacement record with a single peak and maximum possible performance, quantified in terms of energy absorption between the start of loading and 25 mm total central deflection. A specimen that is not flat will deform in an unpredictable manner, will often display multiple peaks in load capacity as stress is re-distributed around the progressively failing panel, and will display overall performance that is compromised [13].

2.5 Round determinate panel tests

An alternative to the EFNARC panel is the Round Determinate Panel (RDP) test, recently developed by Bernard [6] and Bernard and Pircher [10]. This test addresses each of the shortcomings evident in the EFNARC panel test. A central point load is imposed on a round specimen measuring 75 × Ø800 mm, supported on three radial points located on a 750 mm diameter (Fig. 3). The use of three pivoted supports ensures that load distribution at the start of testing is always determinate in the specimen, regardless of tolerances on base flatness. The fact that the specimens are sprayed on a round form to the final size removes the need for expensive concrete cutting, and the 75 mm thickness reflects the thickness of linings commonly used in mining applications and some civil infra-structure tunnels.

Performance in Round Determinate Panels has been measured by two means: load capacity, and energy absorption up to selected values of central deflection. Geometric correction factors are available to scale the performance of specimens not conforming with the standard dimensions of 75 × Ø800 mm [10].

The energy absorbed by the specimen up to a central displacement of 5 or 40 mm is found by integrating the load-deflection curve up to these points. These quantities are a direct reflection of the post-crack performance of the fibres (although they include energy absorption prior to cracking) and are measured in Joules. A displacement of 5 mm is used to indicate performance at low levels of deformation as may be required for civil applications in which crack control is important. A displacement of 40 mm is used to assess performance at high levels of deformation typical of applications such as mines where large cracks can be tolerated.

3. RESULTS

The magnitude and variability in performance parameters for the 62 sets of specimens tested in this investigation are summarised in Tables 2 and 3. Each result represents the mean for three nominally identical specimens. Load-displacement, moment-crack rotation, and energy absorption curves for the specimens are described in references 6 to 8. Performance has been summarised using a number of parameters, especially for the third-point loaded beams, as a consequence of the many existing methods of quantifying performance. The fact that each parameter has been calculated for the same specimens, or beams and panels produced from the same mix, permits a comparison between the alternative performance parameters.

3.1 Correlations in matrix performance parameters

A plot of the mean Modulus of Rupture for the concrete matrix as derived from both the third-point and centrally loaded beam tests (Fig. 4) reveals that the two tests produced almost the same result. However, the MOR derived from the centrally loaded beam test is slightly higher in magnitude, possibly because failure in this test is forced to occur near the point of loading whilst it is free to occur anywhere in the central third of the specimen in the third-point loaded beam. This would allow failure at the 'weakest point' in the central uniformly stressed region for the latter type of beam.

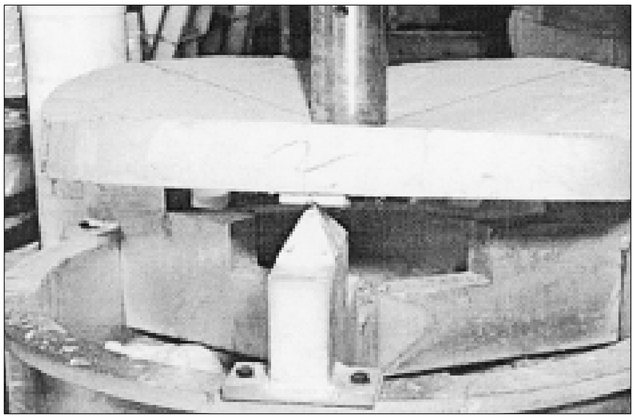

Fig. 3 – Round Determinate Panel test.

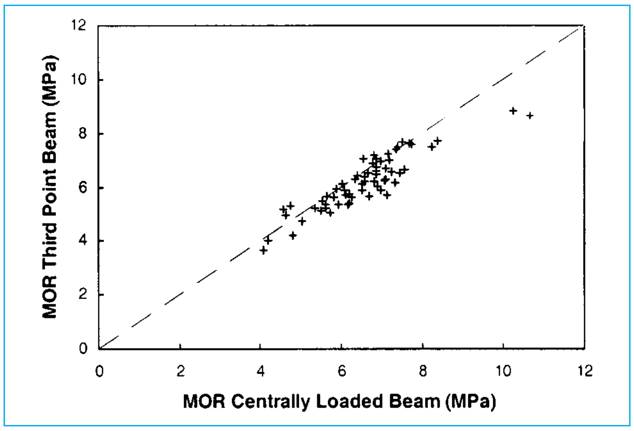

Fig. 4 – Modulus of rupture derived from both beam tests.

Table 2 – Performance results for panel specimens

Set	Fibre*	EFNARC Panel Peak Load (N)	EFNARC Panel Energy (25 mm) (J)	Round Panels (Corrected for Geometry) Thick. (mm)	Dia. (mm)	Peak Load (N)	Cracking Load (N)	Cracking Energy (J)	5 mm Load (N)	5 mm Energy (J)	10 mm Load (N)	10 mm Energy (J)	40 mm Load (N)	40 mm Energy (J)
1	18x0.6 mm EE SSS	71910	356	76.4	799.4	35029	35832	18.7	5383	69.5	1805	84.9	10	104
2	18x0.6 mm EE SSS	93468	661	77.7	799.5	37996	37366	23.2	15270	120.7	6349	169.4	412	230
3	30x0.5 mm HE SW Type A	63322	765	75.4	799.8	30501	30501	14.6	11577	64.8	8579	115.1	2318	254
4	30x0.5 mm HE SW Type A	70528	1026	78.0	799.1	32247	32247	15.3	20210	101.8	14558	188.2	3625	415
5	30x0.7 mm FE SW	85104	1096	77.6	800.7	38223	38222	20.8	25057	126.9	15124	227.1	1285	380
6	50 mm DPP	41127	629	76.8	798.3	24761	24761	13.8	8589	51.9	8849	96.7	1663	225
7	50 mm DPP	61669	944	75.4	800.0	24457	24457	13.9	12835	63.3	13819	132.9	2532	329
8	50 mm DPP	80172	1171	74.9	800.6	27784	27784	15.8	17189	79.1	19164	173.5	3595	455
9	50 mm DPP	83778	1459	75.8	798.9	25762	25739	14.6	22179	93.1	21149	206.1	4301	506
10	30 mm DPP Type A	58177	724	78.6	800.0	27399	27399	14.2	10518	54.9	8921	104.6	1081	204
11	30 mm DPP Type A	56432	737	76.3	800.0	26577	26241	13.3	12746	62.0	12291	126.0	1827	319
12	50 mm DPP/30x0.7 mm FE	68532	926	76.7	797.2	29715	29715	15.9	19428	96.5	16502	187.7	2577	395
13	50 mm DPP/30x0.7 mm FE	78356	1124	76.6	796.7	26156	26095	17.5	19282	92.3	17281	183.9	3445	429
14	Plain concrete	51155	76	78.6	799.2	29411	29410	11.9	37	20.5	0	20.6	0	21
15	52 mm SCP	53445	788	77.5	797.2	27566	27566	12.6	6999	43.8	6657	77.8	3353	228
16	52 mm SCP	58335	1060	75.9	800.6	31670	31670	16.5	13743	72.3	12982	138.8	5976	416
17	52 mm SCP	64818	1223	75.6	798.9	29600	29599	18.1	16168	78.2	15646	157.0	7672	501
18	52 mm SCP	70841	1352	75.7	798.9	23709	23709	18.7	16973	72.9	17719	159.9	8955	550
19	35x0.6 mm HE SW	63620	852	78.8	807.2	29679	29679	13.9	17886	97.4	10854	166.4	1804	306
20	35x0.6 mm HE SW	78684	767	81.0	799.5	31187	30051	13.0	17250	121.6	7024	177.3	850	257
21	35x0.6 mm HE SW	66587	772	82.5	806.1	35601	32142	17.0	16551	123.6	6178	175.4	485	239
22	35x0.77 HE SW	73299	1199	78.3	803.9	33933	33932	18.9	23889	117.0	17929	219.7	4500	502
23	35x0.54 mm HE SW Type A	91712	1471	77.4	800.9	30574	30001	15.1	24096	120.1	17092	222.1	4685	498
24	35x0.54 mm HE SW Type A	89914	1628	78.2	804.4	31353	29609	18.1	30718	135.1	24981	273.6	7759	701
25	30x0.7 mm FE SW	80567	1017	77.3	802.6	27196	27195	13.2	15986	90.0	11571	158.2	1470	310
26	30x0.7 mm FE SW	81447	1030	77.0	802.6	31034	30952	14.2	20272	107.1	15449	196.9	2783	416
27	30x0.7 mm FE SW	88224	1311	78.4	797.4	31463	31081	20.8	24881	117.6	19538	228.3	3277	513
28	4x50 mm mesh	87025	1151	76.1	800.0	33576	22373	8.5	29251	112.0	33357	270.9	10094	966
29	35x0.6 mm HE SW	50790	547	77.6	797.2	25865	25718	13.0	13028	86.9	6956	133.8	1763	241
30	35x0.6 mm HE SW	53212	756	75.2	799.8	27851	27381	16.4	20061	108.8	10913	180.8	2574	340
31	35x0.6 mm HE SW	69749	841	76.4	798.9	31138	30525	17.5	22743	124.2	11843	206.8	2828	377
32	30x0.7 mm HE SW Type A	50977	724	76.8	800.9	25056	24738	12.3	13243	76.8	9693	133.2	1664	269
33	30x0.7 mm HE SW Type A	46090	769	77.2	797.1	26834	26186	14.9	16232	93.0	11154	160.0	1823	310
34	30x0.7 mm HE SW Type A	61534	975	76.4	800.6	29856	29711	17.4	17630	100.5	12735	175.2	1894	347
35	30 mm DPP Type B	50462	914	76.5	800.6	23285	23285	11.2	13330	64.1	13705	130.8	3907	373
36	42 mm DPP	57752	948	75.5	799.9	21908	21902	10.2	10666	53.1	13045	112.0	4115	347
37	50 mm DPP/30x0.7 mm FE	68921	1046	76.5	799.0	30066	29430	18.3	27399	126.8	20822	246.4	3110	505
38	50 mm DPP/30x0.7 mm FE	84889	1263	77.4	797.9	32223	32002	20.4	30196	137.3	23468	271.6	4522	587
39	50 mm DPP/30x0.7 mm FE	67514	1126	74.1	800.6	23250	23146	11.8	20536	92.3	20119	193.5	4812	512
40	50 mm DPP/30x0.7 mm FE	69144	1273	76.3	804.0	23499	23298	12.5	19902	90.3	19813	189.3	4909	507
41	25x0.9 DSW	53527	549	86.5	798.3	23948	23948	10.8	10975	65.6	7138	109.7	558	195
42	30x0.7 mm HE SW Type B	69443	1111	75.7	799.6	27172	26844	14.3	19709	100.4	15045	187.2	4078	442
43	30x0.7 mm HE SW Type B	77860	1271	79.5	796.5	28410	28366	17.6	22022	103.9	17140	201.3	4795	494
44	20 mm CSAW	47699	223	77.4	797.2	33670	32734	24.9	5177	74.8	1551	88.9	0	99
45	20 mm CSAW	70092	294	77.2	799.1	42201	41676	33.8	7097	100.9	1985	120.0	0	132
46	F41 mesh	74243	935	79.4	802.0	25953	25899	11.5	20574	82.3	21065	187.8	3628	469
47	30x0.6 mm HE SW Type A	64335	765	75.8	799.6	29639	29619	15.1	19253	97.8	10656	170.0	1415	297
48	30x0.6 mm HE SW Type B	60935	805	75.1	803.4	27154	27154	15.0	15199	77.6	10313	140.0	1466	274
49	30x0.7 mm HE SS	48564	394	75.7	801.7	30368	30354	15.7	9449	74.0	4589	106.2	312	159
50	35x0.44 mm HE SW	100085	1340	78.5	803.3	42782	42727	19.5	39694	169.6	20634	313.6	4748	588
51	35x0.44 mm HE SW	144404	1997	74.5	800.2	48923	41484	18.9	46752	197.3	28024	379.6	7413	811
52	50 mm CP	63267	1055	78.4	804.0	25410	25377	14.5	20821	87.8	18773	189.7	4169	457
53	37x0.56 mm HE SW	77505	1044	78.1	800.9	29863	29815	18.8	21724	102.0	16008	195.2	2624	418
54	37x0.56 mm HE SW	109158	1591	77.6	803.2	38640	33755	21.8	38131	156.9	29662	329.1	6234	761
55	30 mm SPP	27228	353	79.1	801.0	19583	19527	15.3	4802	42.2	4042	63.7	1081	137
56	30 mm SPP	47354	658	78.6	804.7	24525	24463	14.0	9184	54.5	7526	94.7	1844	222
57	30 mm SPP	57477	948	77.4	802.0	21790	21657	17.5	16296	79.3	12984	150.0	3206	371
58	35x0.54 mm HE SW Type B	77505	1044	78.1	800.9	29863	29815	18.8	21724	102.0	16008	195.2	2624	418
59	35x0.54 mm HE SW Type B	52973	752	79.1	802.7	24721	24721	13.4	15032	77.7	8919	135.0	2545	277
60	35x0.54 mm HE SW Type B	55595	491	78.1	807.1	29413	29412	15.8	10752	82.0	5173	119.3	685	182
61	35x0.54 mm HE SW Type C	54425	896	78.1	798.6	24319	24302	13.8	17413	82.3	12433	156.4	3839	367
62	35x0.54 mm HE SW Type C	65219	631	77.9	802.2	29020	28906	17.0	15499	91.3	8479	147.6	1805	265
	Overall Mean	68959				29728								
	Mean within-set COV (%)	10.0	8.8	1.6	0.37	4.6	4.6	12.5	8.4	6.3	8.4	6.5	23.7	6.5

* EE = Enlarged End; SS = Slit Sheet; HE = Hooked End; SW = Steel Wire; FE = Flattened End; DPP = Deformed PolyPropylene;
SCP = Straight Co-Polymer; CP = Co-Polymer; DSW = Deformed Steel Wire; CSAW = Chromium Steel Alloy Whisker; SPP = Straight PolyPropylene

Table 3 – Performance results for beam specimens

Set	Dosage[a] (kg/m³)	Mix	UCS[b] (MPa)	Third-point Loaded EFNARC Beams: MOR (MPa)	Residual Strength 0.5 mm (MPa)	Residual Strength 3.0 mm (MPa)	ASTM Toughness I_{10}	ASTM Toughness I_{20}	ASTM Toughness I_{30}	ASTM Toughness I_{50}	JSCE T (Nm)	JSCE F (MPa)	Fibre Count (/face)	Centrally Loaded Beam: MOR (MPa)	Energy (0.05 rad) (J)*	Fibre Count (/face)
1	25	1	-	7.17	2.26	0.35	4.79	6.77	8.76	9.88	6.39	1.25	26.8	6.83	9.71	37.5
2	50	1	-	7.66	6.45	1.66	6.39	10.39	12.60	15.29	16.07	3.34	92.2	7.51	15.87	71.2
3	25	1	-	7.62	3.23	1.70	5.10	8.42	11.18	15.70	12.04	2.58	28.3	7.70	8.60	38.7
4	50	1	-	7.22	3.38	2.53	5.20	10.05	14.14	21.25	15.36	3.26	38.3	7.16	15.58	33.0
5	50	1	-	7.57	4.54	4.55	6.33	12.15	17.95	29.12	21.94	4.70	39.5	7.74	21.26	39.0
6	5	2	53.3	6.42	0.86	1.13	3.24	4.41	5.74	8.83	5.93	1.21	21.0	6.41	6.69	19.5
7	7	2	61.8	6.87	1.09	1.44	3.29	4.70	6.29	9.95	6.81	1.46	26.5	6.78	9.48	28.2
8	9	2	59.8	7.50	1.49	2.60	3.70	5.84	8.30	14.06	10.46	2.24	38.3	8.25	11.97	32.0
9	13.5	2	58.5	6.70	1.79	2.91	3.88	6.87	10.26	17.98	11.20	2.53	49.5	7.12	13.55	47.3
10	7	2	56.7	7.04	0.86	1.04	3.02	4.16	5.44	8.18	5.69	1.22	27.0	6.56	9.68	31.2
11	9	2	55.0	6.95	1.43	2.15	3.48	5.55	7.93	13.49	9.28	1.94	43.2	6.99	10.30	37.3
12	4/20	2	51.5	7.03	2.72	2.37	4.76	8.43	12.02	18.45	13.10	2.75	30.8	6.89	12.17	35.2
13	5/25	2	53.0	6.73	2.31	2.27	4.53	7.53	10.60	17.11	10.98	2.41	33.5	6.88	17.08	39.7
14	25	2	55.2	7.41										7.36		
15	4.6	2	46.8	6.38	1.19	1.12	3.25	4.74	6.22	9.40	6.34	1.34	45.3	6.59	5.98	44.3
16	6.9	2	56.2	6.52	1.33	1.37	3.39	5.14	6.95	10.66	6.90	1.52	67.3	7.45	8.73	66.5
17	9.2	2	46.8	5.89	1.72	1.67	4.05	6.70	9.36	14.60	8.95	1.85	98.5	6.53	10.01	85.3
18	11.5	2	46.8	4.20	2.15	2.57	5.56	10.30	15.23	25.71	10.92	2.41	120.7	4.82	14.91	105.2
19	30	2	50.9	7.00	2.55	1.86	4.43	7.87	11.05	16.13	12.14	2.54	20.0	7.18	10.88	31.3
20	40	2	52.3	5.35	3.22	1.35	6.17	11.46	16.13	22.30	12.14	2.58	23.2	6.18	11.19	27.8
21	50	2	48.0	7.73	4.89	1.64	6.42	11.77	15.09	19.54	15.08	3.34	28.8	8.38	14.33	32.5
22	35	2	50.8	7.48	3.78	3.15	5.50	10.03	14.41	22.29	17.07	3.68	22.2	7.39	11.59	17.2
23	40	2	52.2	6.55	3.56	2.80	5.79	10.94	15.70	24.21	17.30	3.40	34.2	7.25	22.55	43.0
24	60	2	44.8	5.63	3.67	3.54	6.47	12.97	19.58	32.04	19.49	3.84	55.7	6.26	24.93	42.7
25	40	2	46.1	6.14	2.97	1.66	5.19	9.34	12.94	18.55	12.24	2.66	26.8	7.35	15.63	22.7
26	50	2	45.5	6.51	3.51	2.95	5.88	10.71	15.50	24.35	15.43	3.45	28.2	6.68	15.74	27.3
27	60	2	46.9	5.91	3.88	2.20	6.56	11.67	16.22	24.00	15.00	3.19	32.3	6.08	16.92	33.0
28	-	2	47.4	5.95	3.49	6.18	5.72	12.97	21.44	39.13	22.19	5.00		5.89	34.06	42.3
29	30	2	55.2	6.01	3.15	1.41	5.61	9.98	13.86	19.04	11.73	2.57	21.0	6.92	8.72	21.8
30	40	2	46.4	5.67	3.21	1.57	5.92	10.75	14.86	20.53	11.12	2.55	24.2	6.70	8.91	22.8
31	50	2	47.3	6.20	4.47	2.01	6.94	13.41	18.49	25.65	16.15	3.50	29.3	6.83	11.99	27.8
32	40	2	49.4	5.37	1.86	1.33	4.34	7.19	9.80	14.52	8.06	1.74	23.8	5.95	7.35	20.0
33	50	2	42.4	5.60	2.64	1.71	5.28	9.14	12.57	18.36	10.25	2.31	27.8	5.82	10.96	23.7
34	60	2	46.2	5.37	3.30	1.82	6.24	10.78	14.72	21.05	12.16	2.61	38.0	5.62	13.07	31.3
35	9.1	5	54.5	5.71	1.29	1.74	3.50	5.78	8.33	13.81	8.04	1.71	27.5	6.12	9.92	38.0
36	9.1	5	52.4	6.10	1.05	1.33	3.19	4.85	6.63	10.44	6.17	1.41	24.5	6.02	9.59	27.5
37	7/35	5	53.4	5.68	2.74	2.27	5.27	9.45	13.36	20.62	12.34	2.62	36.3	5.65	14.73	32.2
38	9/45	5	53.9	6.26	3.82	3.04	6.11	11.72	17.20	26.42	17.15	3.70	44.0	7.06	20.96	37.2
39	7/35	3	32.7	4.01	2.51	2.14	5.88	11.25	16.42	25.91	11.58	2.47	39.0	4.18	12.00	27.5
40	9/45	3	33.4	3.66	1.78	2.08	5.72	10.05	14.63	24.17	9.24	2.00	38.8	4.09	13.19	35.5
41	30	5	53.3	6.58	1.99	1.05	3.64	6.12	8.51	11.91	7.06	1.59	20.5	6.87	10.39	21.5
42	40	5	52.3	6.45	2.80	2.26	4.87	8.99	12.74	19.66	12.20	2.62	22.0	6.86	14.48	21.5
43	50	5	53.7	6.30	3.67	2.82	6.05	11.68	16.85	25.97	15.40	3.37	24.8	7.11	15.60	22.2
44	30	5	44.0	6.19	1.28	0.12	4.02	5.05	5.64	6.18	3.89	0.88	46.7	6.58	5.98	24.3
45	30	5	51.2	6.65	2.07	0.23	4.74	5.85	6.56	7.29	5.07	1.17	40.0	7.58	7.23	34.2
46	-	5	53.5	5.70	2.16	2.66	4.21	8.69	13.72	22.87	12.42	2.70		7.13	31.95	41.2
47	37	5	47.3	5.29	2.76	1.71	5.41	10.32	15.05	22.19	12.43	2.61	33.7	4.75	14.56	27.5
48	37	5	43.8	5.47	2.11	1.74	4.31	7.59	10.78	16.40	9.50	2.12	23.5	5.54	11.34	23.8
49	37	5	48.0	5.22	2.31	0.61	5.00	7.95	10.07	12.94	7.10	1.51	16.3	6.05	6.38	12.0
50	23	4	99.3	8.66	2.32	1.36	3.94	7.10	9.48	12.52	11.35	2.47	17.0	10.67	24.12	23.2
51	43	4	99.5	8.83	5.02	4.95	6.20	12.45	18.97	29.96	27.40	5.87	41.8	10.26	29.33	26.8
52	9	5	56.5	5.05	1.98	2.33	4.72	8.62	12.81	21.14	12.39	2.36	54.3	5.75	15.38	74.8
53	30	5	57.8	5.42	3.20	2.24	5.87	10.76	15.47	23.31	14.67	2.78	24.7	6.20	14.96	24.5
54	60	5	57.5	6.28	4.76	3.81	7.12	14.08	20.80	32.01	25.42	4.65	49.2	6.34	28.22	49.5
55	5	5	54.5	5.15	0.89	0.52	3.23	4.40	5.45	7.34	4.08	0.85	49.8	5.51	4.03	51.7
56	10	5	52.7	4.94	1.66	1.02	4.43	7.06	9.39	13.39	7.29	1.45	76.2	4.64	9.21	92.5
57	15	5	51.7	5.24	2.81	1.96	5.57	10.05	14.08	20.86	12.07	2.55	126.5	5.35	12.29	110.7
58	30	5	57.5	5.75	2.81	2.12	5.50	9.70	13.70	20.74	13.74	2.63	24.0	6.20	14.96	24.5
59	30	5	42.5	5.16	2.07	1.60	4.69	8.28	11.68	17.64	9.51	2.06	20.0	4.58	10.29	26.3
60	30	5	54.3	6.12	2.67	1.01	4.98	8.64	11.19	14.49	9.22	2.03	26.0	6.53	9.63	23.5
61	30	5	35.3	4.75	2.48	1.86	5.59	10.07	14.45	22.11	11.03	2.36	27.2	5.03	11.38	22.0
62	30	5	57.8	5.88	2.94	1.27	5.23	9.15	12.20	16.51	10.84	2.30	23.0	7.00	11.25	21.8
Overall Mean			**50.8**	**6.51**										**6.82**		
Mean within-set COV# (%)			**1.8**	**5.1**	**20.0**	**21.0**	**11.0**	**14.0**	**14.8**	**15.5**	**17.5**	**17.3**	**14.0**	**9.1**	**16.7**	**12.5**

[a] Double value indicates dosage of fibre types 1 and 2 respectively, [b] Unconfined Compressive Strength found using 100x200 mm cylinders

* Joules, # Coefficient of Variation = Standard Deviation/Mean expressed as a percentage,

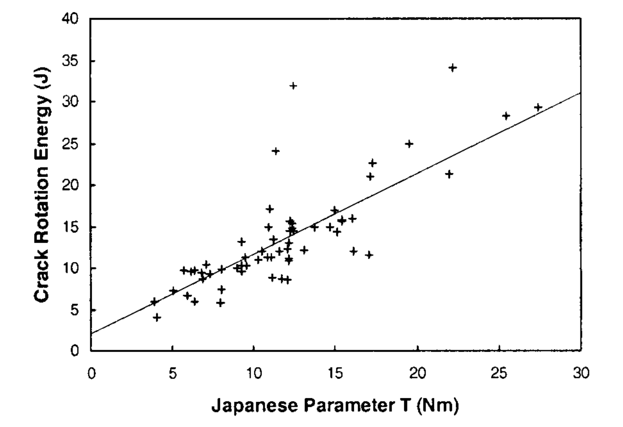

Fig. 5 – Post-crack performance parameters derived from both beam tests.

3.2 Correlations in post-crack performance parameters

The post-crack performance of the third-point loaded beams has been plotted against energy absorption in the centrally loaded beams in Fig. 5. Since energy absorption in the centrally loaded beams is measured at a relatively high degree of deformation (a crack rotation of 0.05 radians is equivalent to a central deflection of 5 mm), only the Japanese Toughness parameter T_{JSCE} has been examined among the many third-point beam parameters available. This parameter shows a weakly linear correlation with energy absorption in the centrally loaded beam.

The correlation in energy absorption between the two types of panel used in this investigation is shown in Fig. 6 to be strongly linear (r^2 = 0.90). The linearity of this relationship indicates that the performance of EFNARC and Round Determinate panels is largely inter-changeable. The conversion factor is: 1000 Joules of energy absorption at 25 mm deflection in an EFNARC panel is equivalent to 400 Joules of energy absorption at 40 mm deflection in a Round Determinate panel. The breadth of the distribution of results shown in Fig. 6 is revealed by the error bars (at one standard deviation) around each of the same data points. This indicates that the exact position of each point relative to all others is not particularly accurate. Because the post-crack performance of the two panels is so strongly related, further correlations with other beam-derived parameters will principally be determined on the basis of the Round Determinate panel alone.

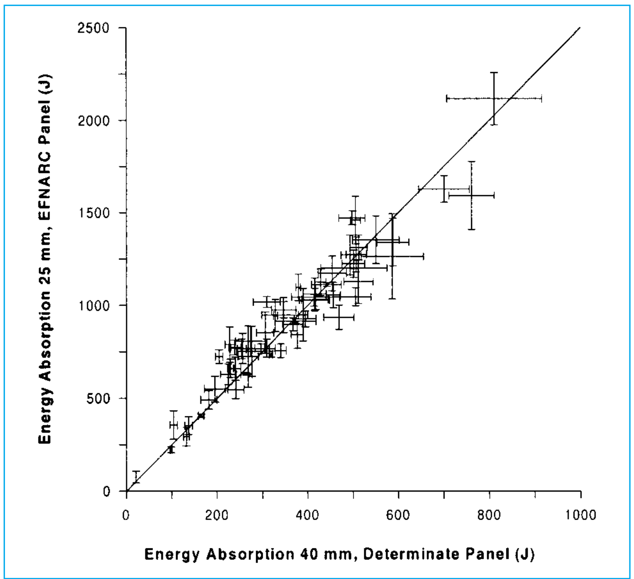

Fig. 6 – Correlation in post-crack performance parameters derived from both panel tests.

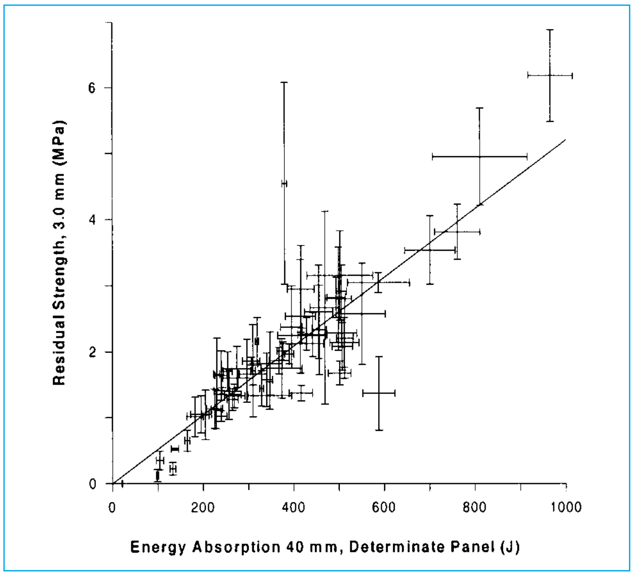

Fig. 7 – Correlation in post-crack performance parameters derived from EFNARC beams and Round Determinate panels at 40 mm central deflection.

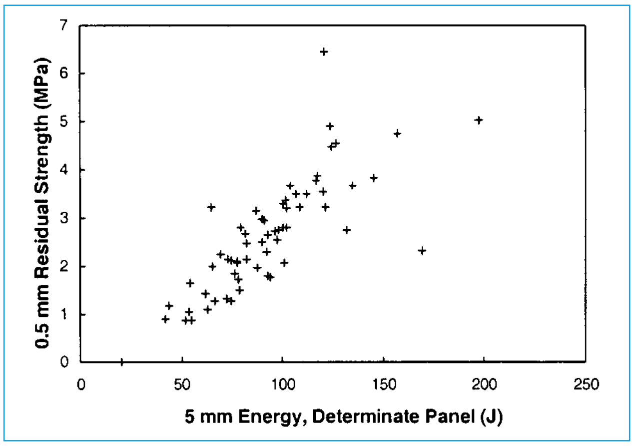

Fig. 8 – Correlation in post-crack performance parameters derived from EFNARC beams and Round Determinate panels at 5 mm central deflection.

The post-cracking performance of the third-point loaded beams has been plotted as a function of energy absorption in the Round Determinate panels in Figs. 7 and 8. From these figures it is evident that the residual strength at 3.0 mm deflection demonstrates a relatively strong correlation with energy absorption at 40 mm in the panels (residual strength in MPa = energy/192, energy in Joules, r^2 = 0.71). However, beam performance parameters derived for relatively low levels of deformation (0.5 mm residual strength) are less strongly related

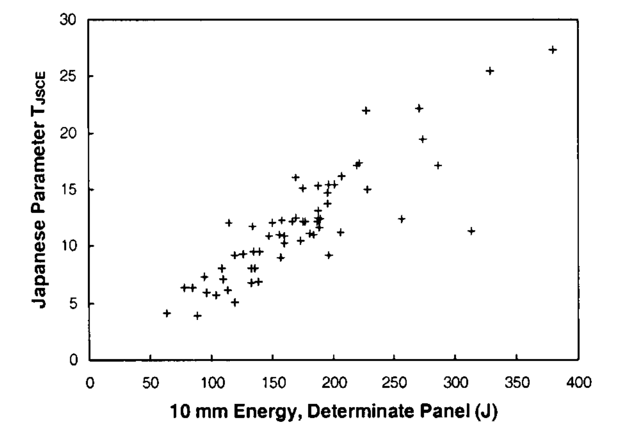

Fig. 9 – Correlation in post-crack performance parameters derived from EFNARC beams and Round Determinate panels at 10 mm central deflection.

to energy absorption in the panels (Fig. 8).

The relationship between beam performance and energy absorption in the Round Determinate panel at 10 mm central deflection is shown in Fig. 9. The value of 10 mm deflection has been chosen because this corresponds to a similar crack rotation as occurs in the third-point loaded beams at 3 mm central deflection. This figure indicates that relatively good correlations exist between some post-crack performance parameters derived from beams and performance as measured in the panels at comparable levels of deformation.

4. DISCUSSION

4.1 Correlations in performance between beams and panels

A number of beam parameters demonstrated relatively good correlation with performance parameters derived for the panels. Strong correlations were found between beam and panel-derived parameters assessed at similar crack widths [8] but poor correlations were generally found between performance parameters assessed at low levels of deformation compared to parameters assessed at high levels of deformation. The residual strength at 3.0 mm central deflection in the third-point loaded beams appeared to correlate particularly well with energy absorption at 40 mm central deflection in the Round Determinate panels. These parameters represent high levels of deformation in the EFNARC beams and round panels, respectively.

Considering the behaviour of the beams, it is apparent that the MOR of the centrally loaded beams showed a strong correlation with the MOR derived from conventional third-point loaded beams. The post-crack energy absorption also showed a relatively strong correlation in these two types of beam, indicating that centrally loaded beams represent a form of performance assessment very similar to third-point loaded beams. However, the data produced in the centrally loaded beam test is of much greater *structural relevance* because it directly describes the relation between rotation at a crack in a FRS lining and moment capacity.

The strong correlation between energy absorption in the EFNARC and Round Determinate panels indicates that either of these would be a suitable measure of post-crack performance under severe deformations. Since energy absorption was summed to a very high level of deformation, it appears that the panels are most suited to applications such as mine drives and temporary linings in civil tunnels in which wide cracks are acceptable.

4.2 Overall suitability of procedures

Experience gained in performing the four toughness tests examined in this investigation can be used to judge the suitability of the respective procedures for routine toughness testing. The most obvious result from the investigation is that *reliability* in post-crack performance has been shown to differ significantly between parameters derived from beams and panels, and even between different parameters derived from the same test. In assessing the overall suitability of a test, it is clear that a high level of reliability is preferred over low reliability. The mean within-batch Coefficients of Variation listed at the base of Tables 2 and 3 indicate either of the two panel tests are more attractive in this respect than the beam tests.

The correlations in the performance parameters derived from the beam and panel procedures also indicate differences in the *structural relevance* of the parameters themselves. The study has shown that performance parameters determined at comparable levels of deformation are relatively well correlated between beams and panels, but that correlations between parameters derived at different levels of deformation are poor. An application requiring shotcrete that exhibits good performance at small crack widths should therefore be assessed using beams or panels deflected to a low deformation, probably at a crack width of around 0.5 mm. Shotcrete intended for highly deformed applications should be assessed using beams or panels deflected to a high level, say 3.0 mm in the EFNARC beams or 40 mm in the Round Determinate panels. However, it appears that the residual strength of a third-point loaded beam is the least attractive parameter of those investigated because it displays very poor reliability compared to the panels (Tables 2 and 3).

The comparative *economy* of the four procedures must take into account the expense and duration of the test procedure itself, the cost of specimen production, and the reliability of the resulting performance parameters. The beams were the most expensive specimens to produce as they required careful cutting prior to testing. Both the beam tests required a similar level of skill and sophistication in the test procedure, and a similar duration. The Round Determinate panel resulted in the lowest variability in post-crack performance of any of the procedures examined, despite being the easiest test to perform. The form work for this specimen was also the easiest and cheapest to fabricate, and there was no cutting required prior to testing.

5. CONCLUSIONS

A large number of shotcrete mixes incorporating different fibre types and dosages were assessed for pre- and post-crack mechanical performance. Two types of beam test and two types of panel test were used as the basis for performance assessment. The objective was to investigate possible correlations in the performance of beams and panels produced from the same material and determine which was the most appropriate test for a given application.

Based on 62 sets of specimens, representing more than 360 beams and 360 panels, the principal conclusion to be drawn is that relatively linear relationships generally exist between beam and panel-based post-crack performance parameters determined at similar crack widths. Of the beam-derived parameters examined, residual strength at 3.0 mm deflection for a third-point loaded EFNARC beam appeared to be most strongly related to post-crack energy absorption in the panels. It was also concluded that FRS panels display a markedly lower variation in post-crack performance than beams, and that the most reliable of all means of post-crack performance assessment is by energy absorption in the Round Determinate panel.

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