Steel Fibre Characterisation for Reinforcement of Shotcrete

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ABSTRACT

New measures of toughness indices, FTR (Flexural Toughness Rating) and RSR (Residual Strength Rating) have been defined for the steel fibre reinforced shotcrete and concrete (SFRS and SFRC). The toughness of the material is directly proportional to the number of fibres per unit cross-sectional area of the SFRS and SFRC layers. However, the flexural strength has been found to be independent to the fibre content up to 80 kg/m^3. Fracture width in the SFRS and SFRC beams is related to the beam geometry and the mid-point deflection. The analyses reveal that the toughness indices should be referred with respect to the fracture width rather than the mid-point deflection, which is the current practice. The $ASTMR_{30/10}$ toughness index is equivalent to toughness index RSR.

Key words: Steel fibre, shotcrete, concrete, mines, flexural toughness, flexural strength, fracture width, fibre dispersion, toughness indices, and residual strength.

1.0 INTRODUCTION

The purpose of fibre reinforcement is different for each of the classes of matrix materials. For polymers, it is to impart stiffness and strength; for metals, it is to inhibit plastic deformation - particularly creep; and for ceramics and other brittle material like concrete it is to introduce a certain measure of toughness. The traditional of use of fibres for modifying certain properties of a material is quite old. For example, husk and small pieces of straw have been used successfully for centuries to reinforce clay to control shrinkage cracking and to introduce toughness in clay structures.

Steel fibre reinforced shotcrete (SFRS) is designated for sprayed concrete reinforced with discrete fibres. The reinforcement of the shotcrete by fibre improves toughness, resistance to impact, durability and fatigue endurance limits (Vandewalle, 1996). It is progressively replacing the wire mesh reinforcement. The use of steel fibres as reinforcement in shotcrete (SFRS) is well established in many countries, including the USA, Canada, South Africa, Germany, Sweden, and Norway (Malmberg, 1993).

Based on the types of fibres used, Malmberg (1993) has classified fibre reinforcement in three categories:

- Type I: Steel-fibre-reinforced concrete or shotcrete.
- Type II: Glass-fibre-reinforced concrete or shotcrete.
- Type III: Concrete or shotcrete reinforced with synthetic fibres.

Recommendations for Type I fibre are given in Table 1.

Table 1 - Recommendations for steel-fibre reinforcement in shotcrete. The type of fibre used often refers to ASTM 820, e.g. Type I fibre (Malmberg, 1993)

Characteristic	Recommendation	Reference Sources
Equivalent diameter	0.5 mm (Type I, ASTM 820)	--
Fibre length	• ≤30 mm for dry mix • ≤20 mm for wet mix • <0.7 x internal dia. of pipes and hoses used	Austrian Concrete Society, 1990 EFNARC, 1992
Aspect ratio L/D (Length/Diameter)	• 40-60 (Type I, ASTM 820) • 65-100	JCI, 1991
Ultimate elongation	12-22%	JCI, 1991
Fibre amount	• Normally 50-80 kg/m^3 • < 5-6% (weight) or 120-140 kg/m^3, adapted to pumpability • Related to fibre length (I): ≥65 kg/m^3 for l ≤ 20 mm ≥50 kg/m^3 for 21 ≤ l ≤ 39 mm ≥ 40 kg/m^3 for l ≥ 40 mm	EFNARC, 1992 Norwegian Concrete Assoc., 1992

Some other recommendations, though not quantified, are as follows (Malmberg, 1993):

- Fibres must be dry, free from corrosion, oil, grease, or other contaminants or surface coating.
- Fibres should be of high strength, deformed, drawn or slit sheet steel fibres.
- A particular product should be specified (e.g., Harex HC 25 or Dramix ZC 30/0.50).

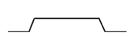
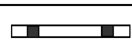
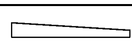
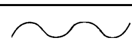
Galvanized fibres, which are sometimes used in aggressive environments, give very good bond to the concrete; however, there is a risk of gas generation in reaction with de-chromatized cement. The use de-chromatized cement is prescribed in some countries, like Sweden and Norway.

The critical parameters of the steel fibres are its length, length to thickness or diameter ratio (L/D) and the shape of the steel fibre (Melbye, 1994). Longer steel fibre, permits better overlapping of the same in the mass of concrete. However, the diameter of the spraying nozzle makes the use of fibres more than 35 mm in length impractical.

If the diameter of the steel fibre is reduced keeping the length unchanged, the number of fibres will increase thereby making their distribution more effective. The higher L/D ratio (around 100) will have greater effectiveness on the mechanical characteristics of the shotcrete. The number of fibres per unit weight (kg) indicates the degree of distribution of the reinforcement in the mass of concrete/shotcrete.

The fibre shape, tensile strength, and anchorage are some of the important characteristics. Table 2 shows the details about the various shapes and sizes of the fibres used in practice.

Table 2 - Different shapes and sizes of commercial steel fibres (Tesio & Allievi, 1991)

Make	Shape	Type	Package	Method of production	Length L (mm)	Diameter D (mm)	L/D
Bekaert		ZC 30/.50 ZC 30/.80	By soluble glue	Steel wire C10 cold drawn	30 30	0.50 0.80	60 37.5
ILM		25/60 25/90	Loose	Steel wire C10 cold drawn	25 25	0.60 0.90	41.6 27.8
Fibrocev		22 30	Loose	Lamina	22 30	0.63 0.63	34.9 47.6
Harex		1-32	Loose	Milled from steel	32	1.12	28.6
Draco		30/80	Loose	Drawn from steel wire	30	0.80	37.5
Edilchem		20 30	Loose	Lamina	20 30	0.55 0.73	36.3 41.1

Note: For fibres with a rectangular or deformed circular section the equivalent diameter was calculated using the formula: $Diameter = 2\sqrt{area/\pi}$

A variety of tests have been developed to measure and quantify the improvements achievable in steel fibre reinforced concrete and shotcrete

(Vandewalle, 1996). Two countries, the USA and Japan, have specific standards in this respect. In order to measure the influence of the fibres on the toughness, both countries have prescribed very similar bending tests in which the load has to be recorded according to an applied deflection of the sample.

This paper presents some alternatives to the performance characterization defined in ASTM C1018 and JSC-SF4 standards (JSCE, 1984). Various toughness standards (indices) have been related to fibre dispersion, and statistical linear relationships have been established. A method has been suggested to monitor the performance of steel fibre reinforced shotcrete support in the field.

2.0 THE FLEXURAL TEST SETUP AND PROCEDURE

The laboratory setup for bending tests as shown in Fig. 1 is described as follows:

Upper and Lower platens**:** The lower platen consisted of two rollers B-B, 300 mm apart (Fig. 1). The upper platen consisted of two rollers 100 mm apart. The specimen (350 x 100 x 50 mm) supported on the lower rollers B - B. The upper loading rollers A - A were set concentric with respect to rollers B - B on the specimen.

Displacement Transducer**:** Two LVDTs were used for displacement measurement with 0.01mm resolution. For measuring central deflection of the beam, two displacement transducers were mounted on both sides of the beam on a centrally glued steel strip 200 x 15 x 5 mm (Fig. 2). Average readings of the two displacement transducers were taken as central deflection of the beam specimen under going the bending test.

Load cell: Full bridge strain gauge based 500 kg capacity with rated output of 2 mV/V over full range. Resolution of 1 kg was achieved. The load cell was mounted between the platen consisting of rollers A-A and the upper loading platen of the Universal Testing Machine (Fig. 1).

Data Acquisition System: The load cell and displacement transducers were connected to a Signal Conditioner unit of the Data Acquisition System. The signal conditioner provided excitation voltage and received output signals from the transducers. The analogue signals received from the transducers were converted to digital signals and stored continuously on a PC and displayed on a monitor during the experiment.

The JSCE-SF4 standards as laid down in the paper, "Method of Tests for Flexural Strength and Flexural Toughness of Steel Fibre Reinforced Concrete" (JSCE, 1984) (using simple beam with four point loading) was followed as closely as possible. Testing machine was a standard hydraulic type Universal Testing Machine (UTM) having maximum capacity of 20 tones with an arrangement for attaching a flexural test apparatus. The prepared specimens were placed in the setup for the flexural testing. Each specimen was gradually loaded by the UTM. The load and the corresponding displacement were automatically recorded in the Data Acquisition System. Load - deflection curves were also displayed simultaneously on the monitor during the test.

The following observations were recorded after completion of the test:

a) The maximum load indicated by the testing machine was read very carefully and used as a check for the load recorded by the Data Acquisition System.
b) The width, b and height, h of the fractured cross-section were measured at three locations and the average values of width and height were recorded.
c) Distance of the fracture line from centre of the beam was measured. The test was accepted if this quantity is less than 50 mm i.e. if the fracture line lied within the upper loading rollers A-A (Fig. 1).
d) Fracture width, f_w. The opening between two fracture planes in the test beam was measured very carefully keeping the fractured surfaces intact. This was recorded as fracture width f_w.
e) The number of fibres per unit cross-sectional area (cm2), F_n: The beam specimens after conducting the flexural tests were broken in two halves. Numbers of fibres at the broken cross-section were visually counted at both the fractured surfaces. The number of fibres per unit cross-sectional area (cm^2), F_n was computed dividing the total number of fibres by the cross-sectional area of the beam at the fracture plane. Number and distribution of fibres normal to fracture surfaces are important to study their role in toughness of the material.
f) Fibre content, Fq (kg/m^3): Some specimens were crushed and the fibres were separated and weighed. The fibre content of a specimen was calculated dividing the weight of the fibre by volume of the specimen.
g) Slippage, breakage in elongation, shear and twist of fibres at the fracture plane were also studied with respect to strength and toughness of the concrete/ shotcrete.

3.0 MEASURE OF FLEXURAL STRENGTH AND TOUGHNESS

The Flexural strength from four point bending test of a beam was calculated by the formula

$$Fu = \frac{Pl}{bh^2} \qquad (1)$$

where,
Fu = flexural strength, MPa,
P = peak load, N,
l = clear distance between supporting roller, mm (B-B in Fig. 2),
b = width at fracture cross-section of the specimen, mm , and
h = height at fracture cross-section of specimen, mm.

According to this formula, the flexural strength is defined with reference to the maximum load, hence, is also called "Modulus of Rupture".

The JSCE-SF4 standard sets the maximum mid-point deflection equal to 1/150 of the distance l between the supporting rollers. This is 2 mm for 300 mm of distance between supporting rollers. The toughness of the flexural beam is defined as energy required to deflect the fibre reinforced concrete beam to a mid-point deflection of 1/150 of its span. As a measure of toughness of the fibre reinforced concrete in bending, JSCE-SF4 has defined Equivalent Flexural Strength, Fe as

$$Fe = \frac{T_b l}{\delta_{tb} b h^2} \tag{2}$$

where, T_b is energy absorbed by the specimen in N-mm and determined from the area below the load-deflection curve up to the mid-point deflection δ_{tb} equals to l/150 (Fig. 3). l, b and h are defined in Eq. 1. Fig. 3 shows a typical load-deflection curve OABCD of a four point bending test. T_b is the area under this curve up to δ_{tb} = 2 mm..

According to US standard C1018-89, flexural strength, Fu is defined at the first crack and subsequently the various toughness indices I_j (Vandewalle, 1996). The first crack is defined as the point at which the load - deflection curve deviates from the straight line. Toughness index is the ratio of the absorbed energy up to a given deflection to the absorbed energy up to the first crack. The area below the load - deflection curve is a measure of the absorbed energy. The standard toughness indices I_5, I_{10} and I_{30} are defined for a deflection up to 3δ, 5.5δ and 15.5δ, where δ is the deflection at the first crack. For example, I_5 is defined as ratio of the areas under the load deflection curve up to 3δ and δ. For a hypothetical SFRS mix with fully elasto-plastic behaviour after first crack (i.e. ability to continue to deform, without either loosing or gaining in load) the I_5, I_{10} and I_{30} toughness index values would be 5, 10 and 30 respectively (Vandewalle, 1996).

However, this standard is very much dependent upon the accurate registration of the mid-point deflection δ at the first crack. A big source of error is settlement of the beam supporting rollers such that the measured deflection consists of true beam deflection and downward movements of the beam as a rigid body. This is particularly true at the instant of first crack, where deflections are small and the error can be relatively large. If not properly considered, the settlement of the support can lead to a gross overestimation of the first crack energy and, hence, erroneous indices (Banthia and Trottier, 1995). Apart from various measuring errors, there is instability in the post-peak region of load-deflection curve of lower fibre contents. The nature of the curve traced in the instability region is dependent on stiffness of the testing machines. Therefore, the l_5 and l_{10} indices are likely to be measured in the unstable zone, are highly erroneous(Banthia & Trottier, 1995; and Morgan et al., 1995). An improved toughness index that is based on the ASTM indices l10 and l30 is defined as (Vandewalle, 1996),

$$R_{30/10} = 5(I_{30} - I_{10}) \quad (3)$$

If the material concerned is perfectly elasto-plastic, the value of $R_{30/10}$ obtained would be 100. For a real material, the number expresses the ratio of the average load a material can absorb in this deflection area verses the load at the first crack.

For clear understanding and measure of flexural toughness characteristics and post-peak load bearing capacity, two new indices for flexural toughness have been introduced in the line of Mishra and Singh (1996) namely- Flexural Toughness Rating (FTR) and Residual Strength Rating (RSR).

The Flexural Toughness rating, FTR is defined as (Fig. 3)

$$FTR = \frac{T_b}{P\,\delta_{tb}} \text{ X } 100 \quad (4)$$

where,

FTR = Flexural Toughness Rating, expressed in percentage,

T_b = area below load deflection curve OABCD of fibre reinforced shotcrete/concrete beam up to a deflection of δ_{tb}, N-mm. This is equal to energy absorbed by the specimen up to mid-point deflection $\delta_{tb,}$

p = first peak load, N, and

δtb = mid-point deflection of the specimen which is equal to l/150, where l is the clear distance between the supporting rollers, mm (B-B in Fig. 2).

$P\delta_{tb}$ is area under the curve $OABC^/D^/$ when the load remains constant equal to the first peak load up to displacement δ_{tb}. This is equal to the energy absorbed during perfectly plastic load deflection behaviour of the specimen.

The Flexural Toughness Rating, FTR, is a measure of energy required to deflect the specimen to a mid point deflection of l/150, compared to the perfectly plastic energy absorption of the specimen for the same mid-point deflection. The value of FTR nearer to 100 indicates very good toughness characteristic of the concrete and shotcrete, when load deflection curve closely follows the perfectly plastic behaviour $OABC^/D^/$.

The other toughness index, i.e. Residual Strength Rating (RSR) is defined as:

$$RSR = \frac{P_r}{P} \text{ X } 100 \quad (5)$$

where, P_r is residual load for the mid-point deflection of l/150 and P is the first peak load. For perfectly plastic post-peak behaviour of the SFRS and SFRC, the toughness indices FTR, RSR and $R_{30/10}$ are equal to 100 and equivalent flexural strength, Fe is equal to Fu, the flexural strength calculated at the peak load.

Banthia and Trottier (1995) has proposed a new toughness index named 'Post-Crack Strength' which is similar to JSCE SF4 equivalent flexural strength, Fe defined by Eq.2. The post-crack strength index considers the energy and deflection in post-peak region only instead of the total energy and deflection required for the Fe. The post-crack strength index is computed for the mid-point deflection 1/3000 and 1/150 span. The pre-peak energy and deflection are negligible compared to the post-peak energy and deflection. Therefore, the post-crack strength index becomes equivalent to the JSCE-SF4 one at the mid-point deflection 1/150 span.

Morgan et al. (1995) advocates 'Toughness Performance Level' method for specifying toughness that draws on ASTM C1018, JSCE SF4 and Norwegian NBP No. 7 test methods and procedures, and minimizes their weakness. The Toughness Performance Levels I, II, III, and IV represent increasing level of toughness. Each level specifies residual flexural strength by percent of the designed flexural strength (which is equal to the residual strength rating, RSR defined by Eq. 5) at the mid-point deflections l/600 and l/150. For example, the Level IV specifies 75 and 45 RSR at the mid-point defections 0.5 and 2 mm for 300 mm beam span.

Kirsten (1998) has compared ductility (toughness) of long fibre reinforced shotcrete with steel wire reinforced one. For this purpose, four point bending tests on beams (200 x 75 x 1600 mm) were conducted up to 150 mm mid point deflection. The distance between supporting rollers was 1000 mm. The long fibre and wire mesh reinforced shotcrete panels of 1600 x 1600 x 75 mm size were also tested up to a central deflection of 150 mm. The test panels were supported at a four-point grid of 1000 x 1000 mm by rock bolts with bearing plates. The ductility was defined as RSR (Eq. 5) with the residual load P_r measured at an arbitrary mid point deflection of 150 mm that is 1/10 span of the test beam. The fibre reinforced shotcrete having RSR $\geq$ 50 was accepted.

4.0 EXPERIMENTAL DESIGN

The beam samples prepared for flexural strength and toughness were 350x100x50 mm. The 50 mm thickness of the beam was selected because, in general, 50 mm or lesser thickness of shotcrete layer is applied on rock surfaces in mines.

For preparation of samples of Steel Fibre Reinforced Concrete (SFRC) beam, cement, sand, gravel and fibre were weighed separately and mixed manually by adding measured amount of water. The samples were prepared according to the JSCE-SF2, standard (JSCE, 1984). The moulds of beam were assembled and the internal sides were coated with a mineral oil prior to pouring of concrete mix. The casting of a sample for flexural strength was done with the longitudinal axis of the mould placed horizontally. The placing of concrete mix in the mould was done according to the order shown in Fig. 4. Striking the mould by a mallet approximately 30 times until irregularities on the surface had been flattened out consolidated the mix. Spading was performed along the side and end surfaces of the mould, and the sides of mould were lightly tapped with a mallet. The open surface of the mould was covered with a glass plate. The specimens were removed from the moulds after 24 hours and were cured in moist condition.

The Steel Fibre Reinforced Shotcrete (SFRS) beams were prepared by dry shotcreting in moulds (350 x 100 x 50 mm). Long axes of the moulds were kept inclined at 70^o on a sidewall of a gallery in underground coal mine. The shotcrete was sprayed on the mould by gradually moving the spraying nozzle from bottom to top until the mould was filled up. The top surface of the moulds were leveled off and kept for curing.. After 24 hours curing, the moulds were opened and shotcreted beams were taken out and numbered. Three out of six shotcreted beams were immersed in water and the rest were kept at the experimental site in underground for 28 days curing under the same condition to that of the shotcreted surface.

The concrete and shotcreted beams were prepared with combined aggregates (crushed stone and Damodar river sand) conforming to the standard grading curve (3) for -10 mm nominal size aggregates (Gambhir, 1995). The base mix proportion for the SFRS was 2.6:1.9:1(coarse chips : Sand : Cement) by weight and it was 2.3:1.7:1 for the SFRC. 150 mm cube compressive strength of the designed SFRC base mix was 25 MPa.

5.0 STEEL FIBRE SELECTION

Some of the deformed and straight steel fibres of different shapes were made in the laboratory of Indian School of Mines (ISM), Dhanbad The material used were (a) 24 gauge (0.5 to 0.55 mm diameter) GI wires, and (b) 24 and 30 gauges (0.3 mm diameter) carbon steel wires with 0.5-0.7% carbon. The dimensions of the fibres with their respective shapes are shown in the Fig. 5. The average breaking for load the 24-gauge carbon steel wire (Indian Standard IS 4452 Gr.-II) was measured 2500 N/mm^2. The breaking load of the same type of wire tested from a few bundles was as high as 4800 N/mm^2. Other physical properties of the fibres are listed in Table 3.

The Flexural strength and toughness of concrete beams reinforced with different shapes and diameter of steel fibres made in Indian School of Mines and imported ones, ZC30/.50 and Harex (20-25 mm long) were studied. The cement and steel fibre contents were kept 20% and 3.3% of the total mix. 3.3% steel fibre in the mix corresponds to 80kg steel fibre in one cubic meter concrete.

Table 3 - Physical properties of steel fibres prepared in the ISM Laboratory

Sl. No.	Fibre Shape	Length L (mm)	Dia. D (mm)	L/D	No. of fibres in one kg	Material	Breaking Load (N/mm^2)
1.	Wavy	28-32	0.55	55	14,000	Carbon Steel	2500
2.	Saw teeth	28-32	0.55	55	14,000	-do-	-do-
3.	End hooked	25-30	0.55	50	15,600	-do-	-do-
4.	End hooked	25-30	0.45	55	21,600	-do-	-do-
5.	End hooked	25-30	0.55	50	15,600	Galvanized Iron	-
6.	Plain	25-30	0.55	50	15,500	-do-	-

The tests revealed that for "End Hooked" type steel fibres (ISM, Dramix and Harex), the toughness ratings FTR varies from 60 to 90 and RSR varies from 51 to 90. The flexural strength Fu varies from 3.7 MPa to 4.7 MPa. There was no significant difference between ISM 'End Hooked' Fibre (0.45 mm 0.55 mm diameter) and the imported ZC30/.50 steel fibre reinforced concrete. The toughness characteristics of 'saw tooth' and 'end hooked' fibre reinforced concrete were similar. However, there was a marginal decrease in flexural strength in case of "saw tooth" fibre reinforced concrete. The flexural strength and toughness of 'wavy' steel fibre reinforced concrete were relatively poor. The toughness of 'straight' steel fibre reinforced concrete was the lowest one. The "end hooked" 0.55 mm diameter carbon steel fibre made in Indian School of Mines was selected for further studies in the laboratory and field. The 'end hooked' steel fibre was selected because its performance was found superior or at least equivalent to the other shapes investigated in this work.

6.0 STEEL FIBRE CONTENT

The "end hooked" carbon steel fibre reinforced concrete (SFRC) beams were prepared with fibre content varying from 19 kg/m^3 to 77 kg/m^3. The Condensed Silica Fume (CSF) (containing 85% SiO_2) was added 6% and 12% of the cement weight in the mix. The results of the flexural tests are given in Table 4.

The steel fibre reinforced shotcrete (SFRS) beams were prepared with fibre content varying from 40 to 64 kg/m^3 in feed mix. Due to rebound of the material, only 60-70% of the steel fibre in mix was retained in the shotcreted beams. Results of the flexural tests of SFRS beams are given in Table 5.

Table 4 - Results of four point bending tests of steel fibre reinforced concrete (SFRC) beams

(A) Condensed Silica Fume 6%

Sl. No.	Steel Fibre content		$F_{n,}$ no./cm^2	Fu, MPa	Fe, MPa	FTR	RSR	$R_{30/10}$
	Kg/m^3	%						
1a	37	1.58	0.66	6.0	2.9	50	52	57
1b	41	1.81	0.68	5.1	2.8	58	57	65
1c	36	1.52	0.80	6.4	3.9	64	68	68
2a	46	-	0.56	5.7	3.3	59	61	62
2b	46	-	0.92	6.3	4.3	73	74	96
2c	46	-	0.76	5.6	2.6	50	43	56
3a	57	-	1.10	6.4	4.8	79	86	98
3b	57	-	0.92	7.8	4.5	61	64	76
3c	57	-	1.36	6.8	5.4	84	77	92
4a	64	2.73	1.19	5.9	3.9	70	67	91
4b	62	2.68	0.80	6.4	4.3	71	73	89
4c	67	2.90	1.02	5.5	3.2	62	57	77
5a	76	-	1.04	6.1	4.9	83	81	84
5b	75	-	1.01	6.2	4.5	76	75	95
5c	77	-	1.26	5.5	4.4	88	102	122
6a	65	2.65	1.00	5.4	4.3	85	88	110
6b	69	2.92	1.05	5.8	4.1	75	68	86
6c	65	2.77	1.17	5.7	4.5	82	80	90
7a	19	-	0.46	5.1	1.8	38	31	36
7b	19	-	0.50	4.6	1.7	38	29	32
7c	19	-	0.44	5.0	1.8	38	34	37
8a	28	-	0.79	5.0	2.5	52	53	51
8b	28	-	0.73	5.1	1.6	32	25	30
8c	28	-	0.72	4.9	1.9	40	36	39

(B) Condensed Silica Fume 12%

9a	66	-	1.14	7.2	6.0	88	88	113
9b	66	-	1.09	6.5	6.5	86	86	113
9c	66	-	0.85	6.9	5.6	86	95	108
10a	28	-	0.61	5.7	2.3	42	40	39
10b	28	-	0.65	5.8	2.5	45	51	44

Note: '-' quantity not measured and determined

The beams after conducting the flexural tests were broken into two halves. Number of fibres at the broken cross-section was counted for all the specimens. Some samples were crushed and the fibres were separated and weighed to estimate the fibre content in the samples in terms of kg/m^3. The results are given in Tables 4 & 5. A statistical linear correlation between fibre content, F_q (kg/m^3) and the number of fibres per cm^2 cross-sectional area, F_n has been determined. The average value of slope m of the linear correlation is 0.011

with 95% confidence limit of 0.009 and 0.013. The average value of the intercept c is 0.335 with 95% confidence limits of 0.227 and 0.442. The 95% confidence interval of the mean F_n , the number of fibre/cm^2 cross-section is shown by shaded area in Fig. 6 for a given fibre content, F_q. The linear relation is

Table 5 - Results of 4 point bending tests of steel fibre reinforced shotcreted (SFRS) beams

(A) Condensed Silica Fume 6%

Sl. No.	Steel Fibre content		F_n , no./cm^2	Fu, MPa	Fe, MPa	FTR	RSR	$R_{30/10}$
	Kg/m^3	%						
1a	48	2.16	0.29	6.4	4.5	76	80	77
1b	50	2.26	0.82	5.1	2.6	56	40	44
1c	50	2.28	1.34	5.9	5.9	105	111	73
1d	52	2.38	1.11	6.0	5.1	93	86	78
2a	31	1.52	0.59	4.5	2.5	60	55	60
2b	27	1.24	0.50	6.0	2.4	43	35	42
2c	24	1.10	0.54	5.7	2.4	46	42	45
2d	-	-	0.60	4.9	2.6	58	55	72
2e	-	-	0.66	6.3	2.6	43	33	40
2f	-	-	0.61	3.6	1.3	39	28	35
3a	28	1.35	0.43	5.4	2.2	43	33	36
3b	-	-	0.55	3.9	3.2	88	96	99
3c	-	-	0.75	5.2	2.5	55	49	90
3d	-	-	0.72	5.3	2.2	44	40	45
3e	-	-	0.87	3.9	2.2	59	54	59
3f	-	-	0.76	4.8	3.2	73	79	74
4a	38	1.80	1.01	5.7	3.0	76	75	-
4b	49	2.26	1.09	5.2	3.9	83	72	62
4c	34	1.82	0.89	4.1	2.6	70	71	68
4d	-	-	0.82	4.7	2.5	57	50	53
4e	-	-	0.88	3.3	2.6	86	82	79
4f	-	-	1.26	5.0	3.6	83	83	97

(B) Condensed Silica Fume 12%

Sl. No.	Steel Fibre content		Fibre, no./cm^2	Fu, MPa	Fe, MPa	FTR	RSR	$R_{30/10}$
	Kg/m^3	%						
8a	28	1.27	0.70	6.0	3.0	56	52	54
8b	27	1.25	0.52	4.6	1.8	46	30	39
8c	32	1.43	0.76	4.7	-	-	-	-
8d	-	-	0.77	4.7	1.9	42	38	40
8e	-	-	0.84	4.4	2.4	60	55	78
8f	-	-	0.49	-	-	-	-	-

Note: '-' quantity not measured and determined.

$$F_n = 0.335 + 0.011\ F_q \text{ for } 80 \geq F_q \geq 20 \qquad (6)$$

where,
F_n = number of steel fibres per cm^2 cross-sectional area, and
F_q = steel fibre content, kg/m^3.

7.0 FLEXURAL STRENGTH

Flexural strength data for Steel Fibre Reinforced Concrete (SFRC) as given in Table 4 and the Steel Fibre Reinforced Shotcrete (SFRS) in Table 5 are plotted in Fig. 7 against the number of steel fibres per cm^2 cross- sectional area. Fu and F_n of both for the SFRS and the SFRC for the steel fibre content $F_q < 80$ kg/m^3 were studied. The mean value of the Fu and 95% confidence interval are given in Table 6. The statistical analysis shows that the mean flexural strength of the SFRS and SFRC containing 6% Condensed Silica Fume (CSF), and the SFRS containing 12% CSF (Table 6) are not significantly different, as indicated by their overlapping confidence intervals. Although, the mean flexural strength of the SFRC containing 12% CSF is significantly higher than that of the SFRC containing 6% CSF. No significant difference could be observed in flexural strengths of the SFRS containing 6% &12% CSF.

Table 6 - Statistical analysis of Flexural Strength (Fu) data of SFRC & SFRS

Sl.No.	Material	CSF, % of Cement wt.	Mean Fu (MPa)	95% Confidence interval (MPa)
1.	SFRC	6%	5.0	5.4, 5.9
2.	SFRS	6%	5.0	4.6, 5.4
3.	SFRC	12%	6.4	5.6, 7.2
4.	SFRS	12%	4.9	4.1, 5.7

8.0 FLEXURAL TOUGHNESS

The load-deflection curves of the flexural tests were stored on a digital format in a personal computer. The area under the curve up to a specified mid-point deflection was computed by a numerical integration scheme. The area up to the mid-point deflection δ_{tb} of 2 mm was computed for the estimation of toughness indices FTR and Fe. The first peak load P and the residual load P_r at the deflection δ_{tb} were numerically searched for computation of the toughness index RSR. Numerical identification of the displacement δ at first crack was difficult. Therefore, the first crack was assumed to occur at 90% of the first peak load P in the pre-peak region of the load-deflection curve. The deflection of δ at 0.9P was taken as the deflection at the first crack for all the samples, and the areas were computed by the numerical integration scheme for computation of $R_{30/10}$ using Eq. 3.

The toughness indices FTR, Fe, RSR and $R_{30/10}$ for SFRS and SFRC are plotted in Figs. 8, 9, 10, and 11 respectively. The plots reveal that there is a clear correlation between number of steel fibres per unit cross-sectional area, F_n at the fracture plane and the toughness indices. Further, the toughness indices of SFRS and SFRC containing 6% and 12% CSF are not statistically different. The statistical analysis of the linear correlation of the toughness data is given in Table 7. Further, the 95% confidence intervals of the means of the toughness indices FTR, Fe, RSR and $R_{30/10}$ for a given F_n are also shown shaded by areas in Figs. 8, 9, 10, and 11 respectively. The linear relations of toughness indices with Fn are

Table 7 - Linear Correlation y = mx + c of the flexural toughness data (y = toughness rating, x = number of steel fibre in one cm^2 cross-sectional area, m & c are coefficients)

Sl. No.	Toughness Rating (y)	Coefficients				Correlation Coefficient
		m	95% Confidence interval	c	95% Confidence interval	
1.	FTR	62	52, 72	10.7	2.1, 19.4	0.76
2.	Fe	3.95	3.08,4.83	0.05	-0.81,0.71	0.62
3.	RSR	71	58, 84	01	-10.2, 12.2	0.70
4.	$R_{30/10}$	78	60,96	02	-14,18	0.60

$$FTR = 10.7 + 62\ F_n\ , \quad (7)$$
$$Fe = 0.05 + 3.95\ F_n\ , \quad (8)$$
$$RSR = 1 + 71\ F_n\ , \text{ and} \quad (9)$$
$$R_{30/10} = 2 + 78\ F_n\ . \quad (10)$$

Equations 7 to 10 are valid for $1.25 \geq F_n \geq 0.5$.

Typical bending Load - Deflection curves of SFRS beams are shown in Fig. 12 for three different magnitudes of F_n. The curves clearly depict the role of the number of fibres per unit cross-section on the flexural toughness of the SFRS and SFRC. With increase in number of fibres per unit cross-sectional area, the toughness increases while the flexural strength remains unchanged.

9.0 DISCUSSIONS

The analyses of results obtained from the bending tests of Steel Fibre Reinforced Concrete (SFRC) and Steel Fibre Reinforced Shotcrete (SFRS) show that it is the number of fibres per unit area at the fracture plane that controls the toughness of the material. The number of steel fibres per unit area is directly proportional to the amount of fibres in the beam. The flexural strength, Fu has been found independent of the steel fibre content within the range 20 to 80 kg/m^3 in the concrete and shotcrete. There is a marginal increase in flexural strength by increasing the Condensed Silica Fume (CSF) from 6% to 12%.

The flexural toughness indices Fe and RSR can be directly used in design of SFRS support. The Fe represents the equivalent flexural strength up to mid-point deflection δ_{tb} and the RSR represents the percentage of the residual strength in the post-peak region at the same deflection δ_{tb}. For example, for F_n = 1, i.e. unit fibre in unit square centimeter cross- sectional area in SFRS, the computed values of Fe and RSR are 4 MPa and 72 respectively, using Eqs. 8 and 9. The RSR value 72 indicates that the flexural strength in the post-peak region is 72% of the Fu. This gives post-peak flexural strength equal to 5.4 MPa x 0.72 = 3.9 MPa that is close to the value of Fe determined independently.

The toughness ratings Fe, FTR and RSR were determined corresponding to the mid-point beam defection δ_{tb} = 2 mm. However, the tests were conducted for the mid-point deflection up to 8 mm. The load in the post-peak region remained almost constant within 2 mm to 8 mm mid-point deflection. Therefore, the Eqs. 7 to 10 are also valid up to 8 mm mid-point deflection.

The fracture width, f_w of SFRS and SFRC beams generally lied between 5 and 6 mm. Due to localization of the fracture in the central region of the beam, the flexural strain is also localized there in form of a fracture widening zone (Appendix-I). Thus, the progressive mid-point deflection δ progressively widens the fracture. The fracture width f_w can be kinematically related to the mid-point deflection δ and the beam geometry. The relation is derived in *Appendix-I* and is given as

$$f_w = \frac{4h}{l}\delta \tag{11}$$

where, f_w is fracture width. δ, the mid-point beam deflection and h, the beam height are small compared l the beam length. For 8 mm mid-point deflection, the computed fracture width is 5.3 mm (Eq. 11) for the particular geometry of the beam used in this article. This is done to the measured value of 5-6 mm. According to Eq. 11, for the same mid-point deflection, the fracture will be wider for a thicker beam and narrower for a longer beam. Therefore, it is recommended that the toughness indices Fe, FTR and RSR should be specified with respect to f_w instead of δ_{tb}, which is the current practice. By monitoring the fracture width of a SFRS layer of a given thickness in the field. The post-peak strength of the fractured shotcrete layer may be determined knowing the values of Fu and RSR. Further, the width of a fracture in SFRS layer applied on a rock surface may be easily measured and monitored in the field applications. However, it is not practical to measure the mid-point deflection in the field.

Relationship of the toughness indices with the fracture width is an important concept that has a bearing in the design and monitoring of SFRS support in mines and tunnels. In high and active stress regime, controlled deformation of the excavation surface is desired in mines and tunnels. This controlled deformation relieves the rock surface off the stresses. SFRS support of the walls permits controlled deformation. During the deformation process, the

SFRS layer may fracture, and the fracture width may be monitored on regular basis. Having related the toughness index RSR with the fracture width, it is possible to compute and predict the residual strength of SFRS support in the fractured state.

The Eqs. 7 to10 together with Eq. 6 may be used for controlling and monitoring the shotcrete toughness in the field. A 300 x 300mm shotcrete layer could be scraped very carefully so that it remains in form of a sheet. After 24 hours, the layer is broken and counting the number of fibres at the broken cross-section and measuring the cross-sectional area determine the Fn. One may also calculate F_n using Eq. 7 by measuring the fibre contents F_q in the sample of the SFRS layer by separating and weighing fibres from a known volume of the shotcrete sample.

A Comparison of the linear relations for RSR and $R_{30/10}$ as given in Eqs. 9 and 10 and 95% confidence intervals (Table 7), reveals that the both relationships are statistically similar. Therefore, the $R_{30/10}$ may be calculated in a simple manner by computing the RSR that is equal to the residual load at a given deflection expressed in percentage of the first peak load. Thus, for computing $R_{30/10}$, one requires to measure the first peak load and the residual load only, and thus, avoiding intricate computation of the areas under the load-displacement curve for various measures of the mid-point deflection at the first crack of the beam.

10.0 CONCLUSIONS

Major conclusions are as follows:

1. The numbers of fibres per unit cross-sectional area control the toughness of a SFRS/SFRC layer. The flexural toughness is directly proportional to the fibre contents from 20 to 80 kg/m^3. However, the flexural strength has been found constant for the fibre content in the range 20-80 kg/m^3.
2. The toughness indices should be specified with respect to the fracture width rather than the mid-point deflection, which is the current practice.
3. The residual flexural strength expressed in percentage of the first peak strength (load) i.e. residual strength rating, RSR specified for a given fracture width is a rational and practical measure of toughness of the fibre reinforced shotcrete and concrete. The fracture width should be specified based on the service requirement of shotcrete and concrete structures.
4. The residual flexural strength of a fractured shotcrete may be estimated in field by monitoring the fracture width. The residual flexural strength at a given fracture width is obtained by multiplying the flexural strength, Fu and the residual strength rating, RSR, and finally dividing by 100.
5. The toughness index RSR can be used as a substitute for $R_{30/10}$ index, as the computation of the former is simpler than the later.

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Appendix-1

Kinematic Relationship between Fracture Width and Mid-Point Beam Deflection

The flexural deflection of a beam leads to flexural strains and stresses in it. The first micro-fracture appears at a point where the flexural stress in the beam exceeds the flexural strength of the beam material. With progressive deflection of the beam, the flexural strains begin to localize at the micro-fracture initiation point (Singh and Degby, 1989). The process begins just before attainment of the peak load during the test. The micro-fractures progressively coalesce with progressive beam deflection, and finally, a distinct macro-fracture is formed. The flexural strains, now, are no longer ubiquitous in the beam, but are localized at the fracture plane. Hence, the mid-point deflection of the beam causes progressive widening of the fracture. The kinematic relationship between the deflection δ and the fracture width f_w is shown in Fig (AI.1). For small values of mid-point deflection δ, fracture width f_w and beam height h compared to the beam span l, the angle AOB (Fig. AI.1) is given by

$$\angle AOB = \frac{\delta}{l/2} \tag{AI.1}$$

Further, angle BCD is given by

$$\angle BCD = \frac{f_w}{2h} \tag{AI.2}$$

Angle BCD is equal to angle AOB due to kinematic deflection of the beam (Fig. Al.1). Therefore, equating Eqs. Al. 1 and Al.2, and solving for f_w we get

$$f_w = \frac{4h}{l}\delta \tag{AI.3}$$

Reference:

Singh,;U.K., and Degby, P.J. (1989). The application of a Continuum Damage Model in the Finite Element simulation of the progressive failure and localization of deformation in brittle rock structures, Int. J. Solids and Structures, Vol. 25, No. 9, pp. 1023-1038.

Table of symbols and acronyms, and their meanings

Symbol	Meaning
b	- width of fracture cross-section of SFRC/SFRS beam, mm
δ	- Mid-point beam deflection, mm
δ_{tb}	- Mid-point beam deflection equal to l/150, mm
Fe	- Equivalent flexural strength, MPa (JSCE SF4 toughness index)
F_n	- Number of steel fibres/cm^2 cross-sectional area of SFRS/SFRC layer
F_q	- Quantity of fiber in unit volume, kg/m^3
Fu	- Flexural Strength, MPa
f_w	- Fracture width, mm
h	- Height of fracture cross-section of SFRS/SFRC beam, mm
l_5, l_{10}, l_{30}	- ASTM flexural toughness indices defined at mid-point deflection δ, 5.5δ, 15.5δ respectively, where δ is mid-point deflection at the first crack
L/D	- Length/Diameter ratio of steel fiber
l(lower case L)	- Clear distance between supporting rollers of the beam specimen (beam span), mm
P	- First peak Load, N
P_r	- Residual load at δ_{tb},N
P	- Load, N
$R_{30/10}$	- ASTM index calculated as $5(l_{30}- l_{10})$
T_b	- Energy absorbed by the beam specimen up to mid-point deflection δ_{tb}

Acronym	**Meaning**
ASTM	- American Society for Testing and Materials
CSF	- Condensed Silica Fume
ISM	- Indian School of Mines, Dhanbad, INDIA
JSCE	- Japanese Society of Civil Engineers
RSR	- Residual Strength Rating (a toughness index defined in this article)
SFRC	- Steel Fiber Reinforced Concrete
SFRS	- Steel Fiber Reinforced Shotcrete
ZC30/.50	- Dramix End Hooked Fiber, 30 mm long, 0.50 mm diameter.

Sl – US Conversion Table

Unit	Sl	US
Lead	1 kN	224.8 lbf
Deflection,	1 mm	0.03937 inch
Distance, dimension		
Energy	1 kN-mm	8.850 lbf-inch
Stress	1 MPa	145.03 psi
Unit weight	1 Kg/m^3	1.685 lb/yd^3
Fiber dispersion	1 fiber/cm^2	6.452 fibers/inch^2

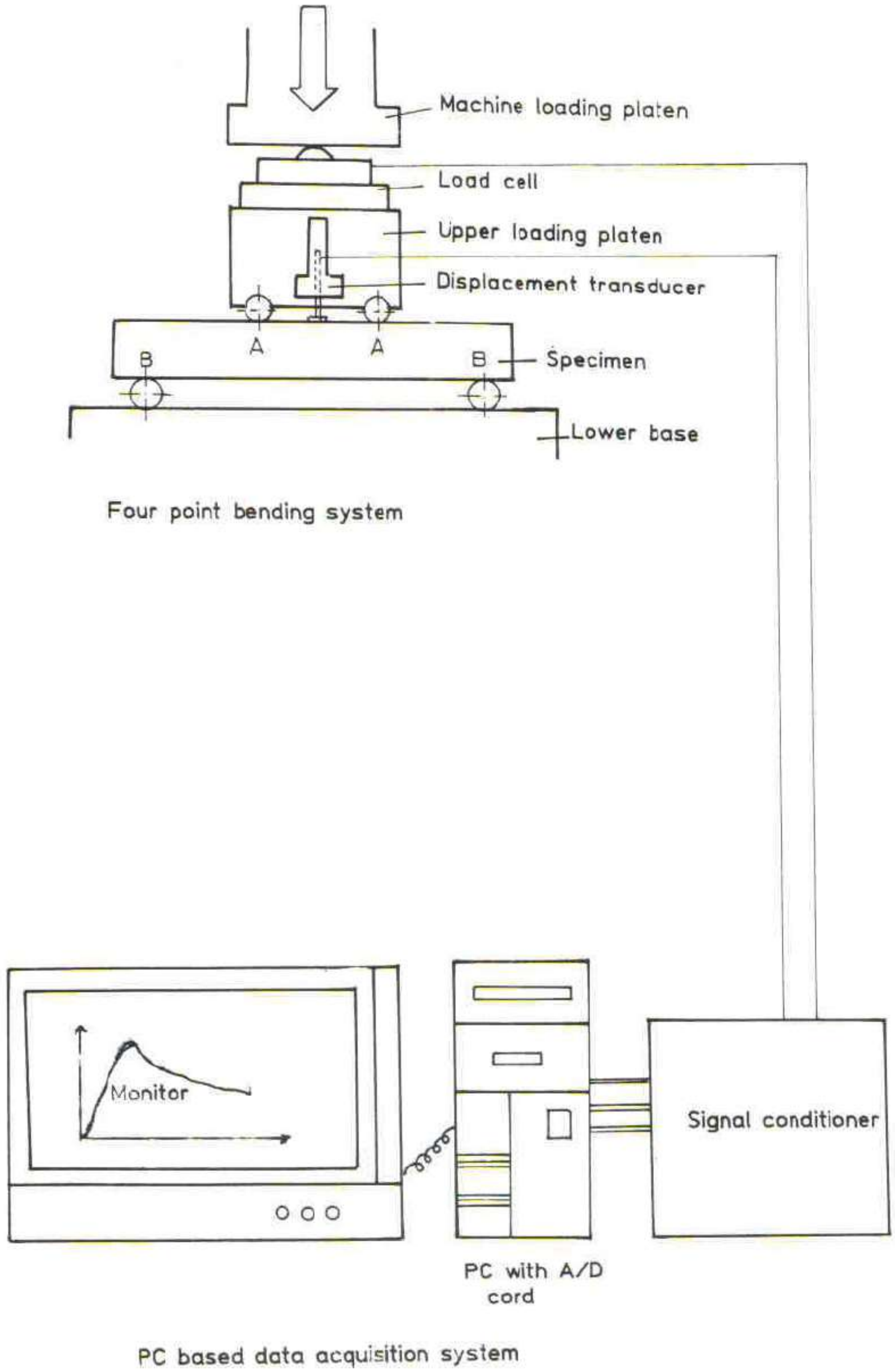

Fig. 1 - Four point bending test arrangement

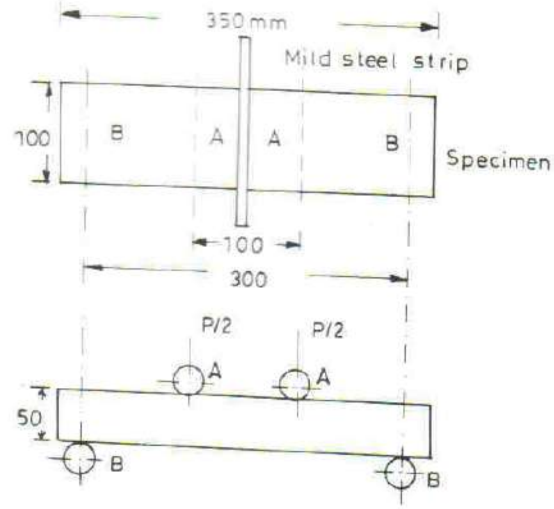

Fig. 2 - Mild steel strip position on the beam specimen

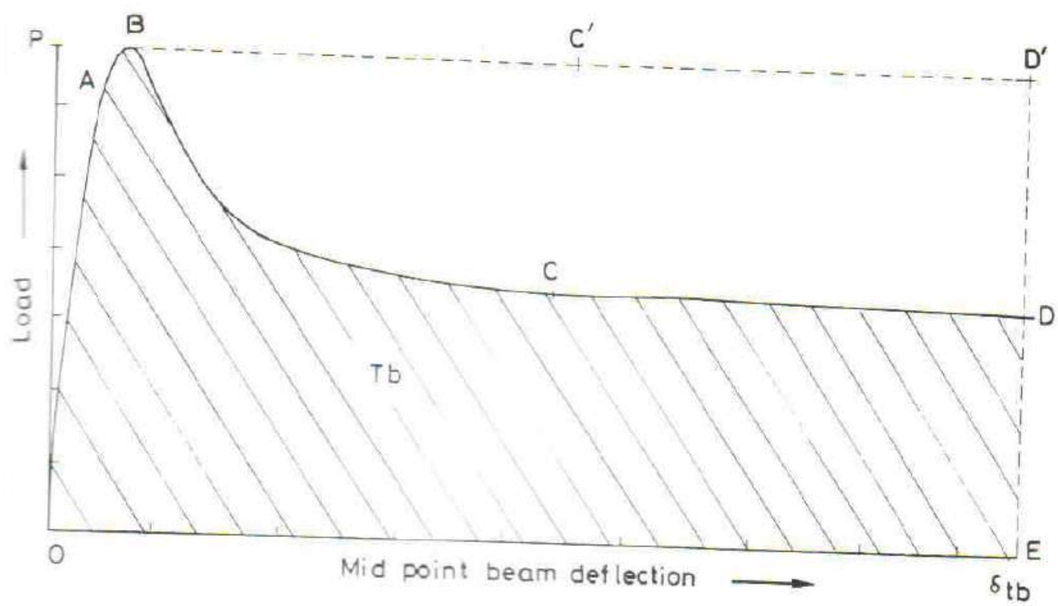

Fig. 3 - Typical mid-point beam deflection curve of 4 point bending test of SFRS/SFRC: Curve OABCD for SFRS/SFRC: curve OABC′ D′ for an ideal elasto-plastic material

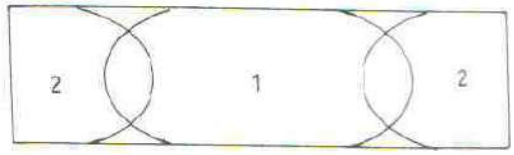

Fig. 4 - Procedure for casting SFRC in mould. 1 and 2 are order of pouring the concrete in the mould

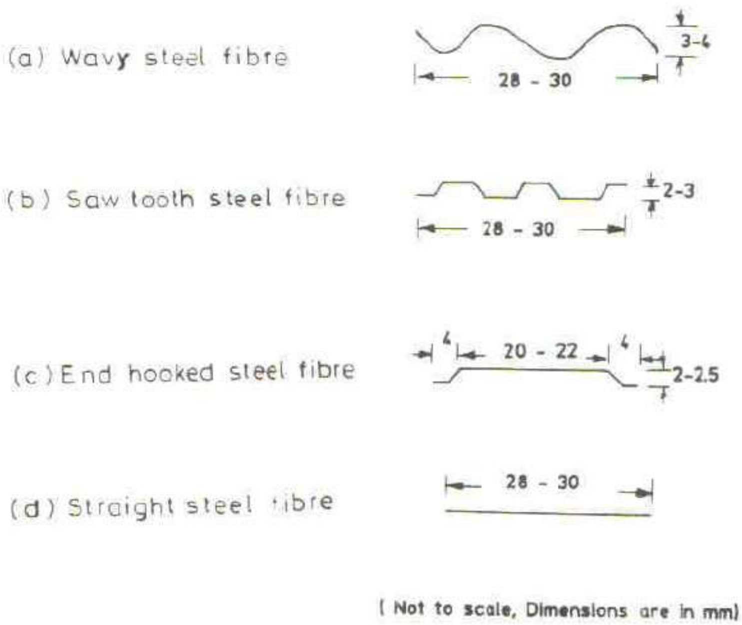

Fig. 5 - Different shapes of steel fibres made in ISM laboratory

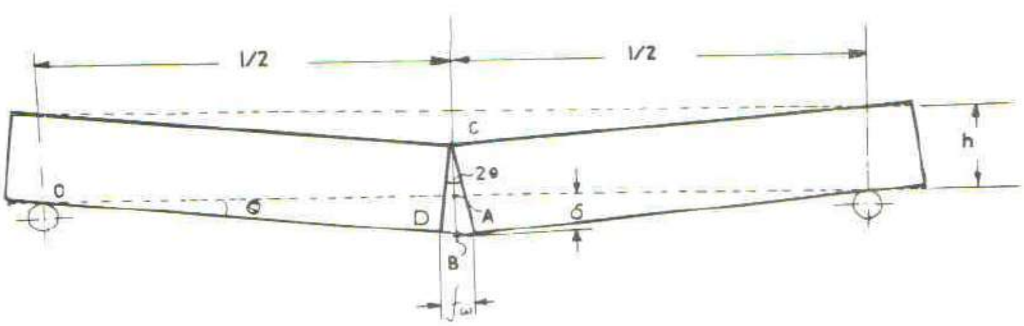

Fig. Al.1 - Kinematic relationship between the mid-point deflection and the fracture width of a beam in four point bending test

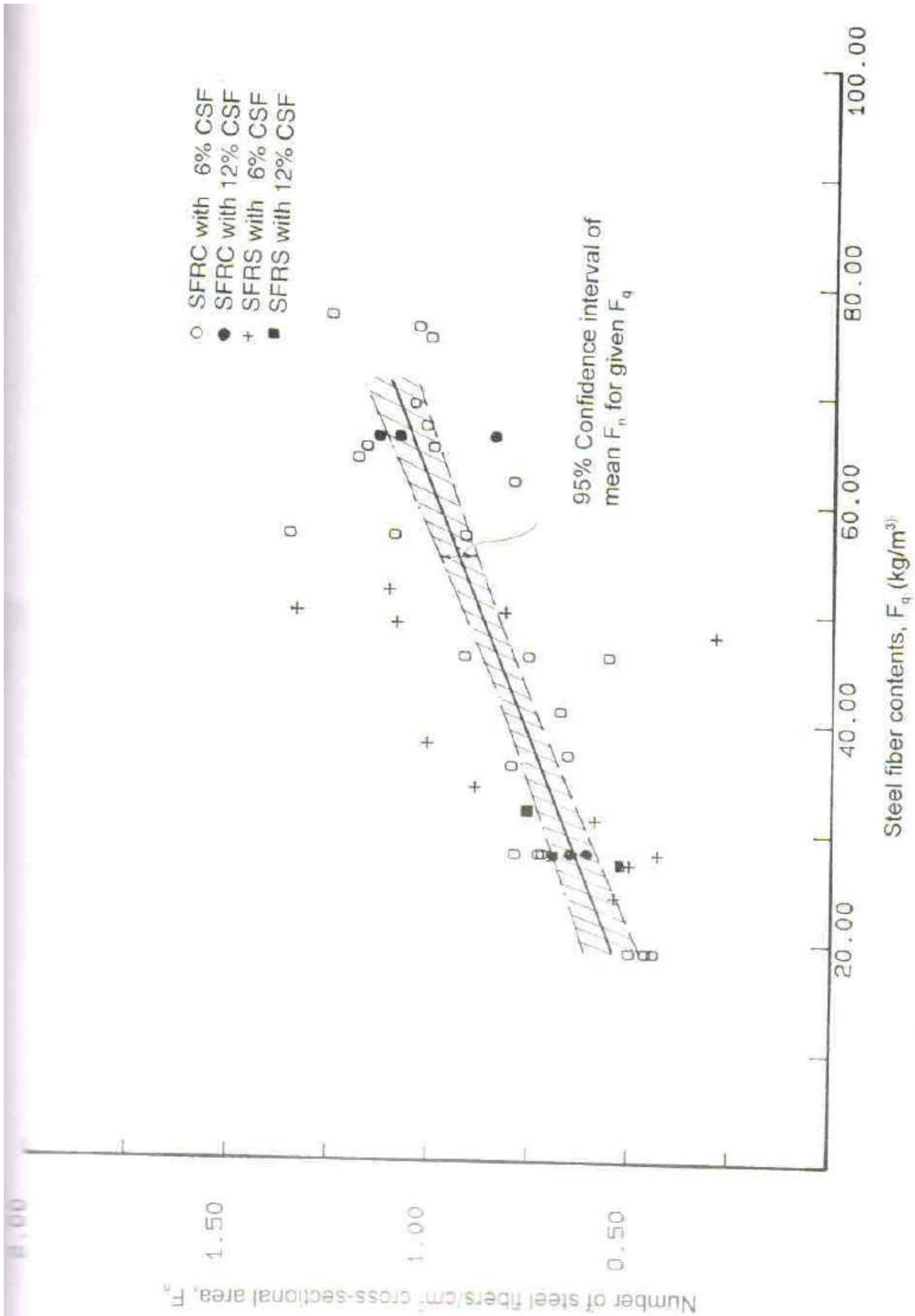

Fig. 6 - Relation of steel fibre content, Fq with number of steel fibres in one cm2 cross- sectional area of SFRS and SFRC layer Fn

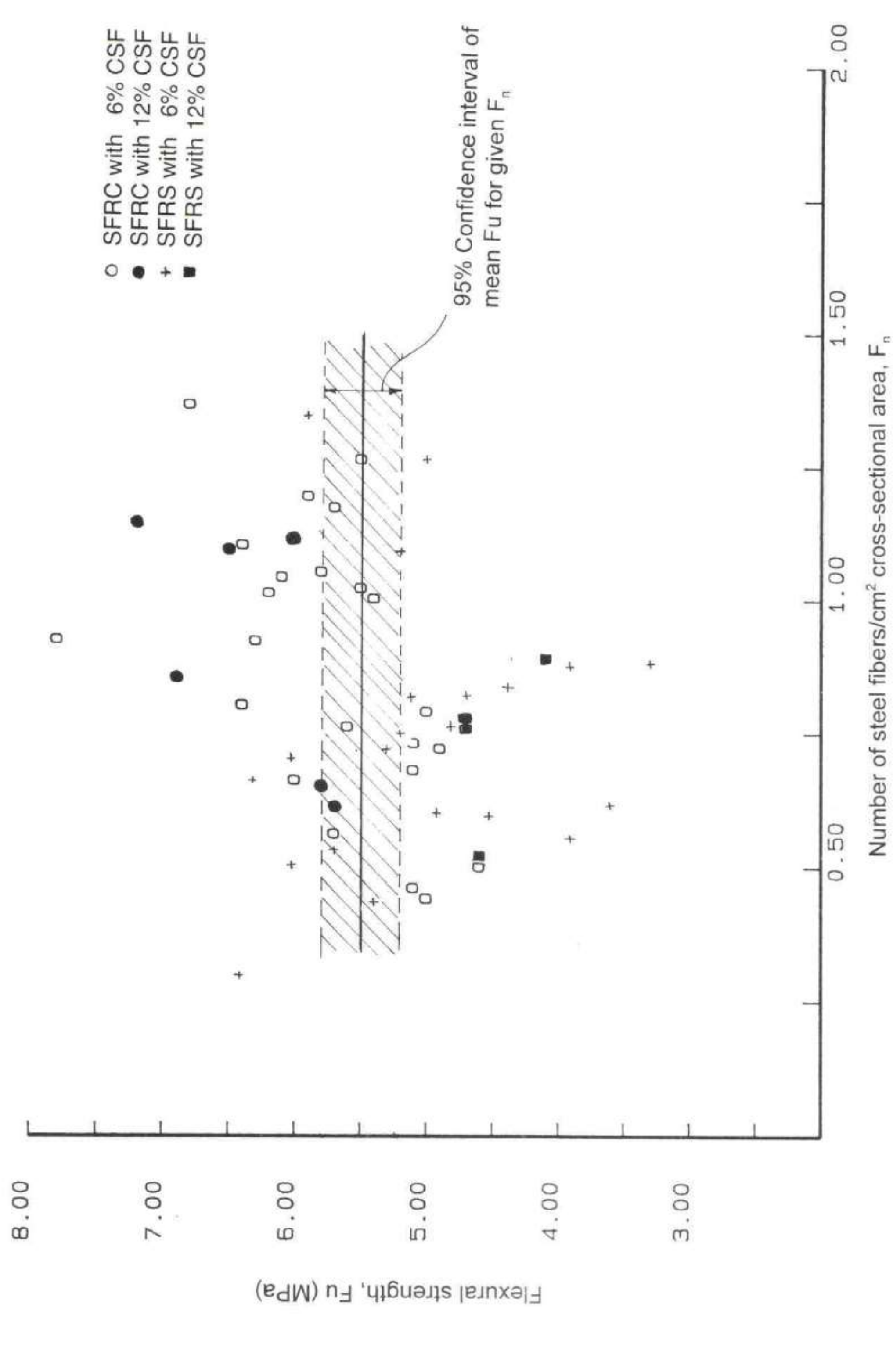

Fig. 7- Relation of flexural strength, Fu with number of steel fibres in one cm2 cross-sectional area of SFRS and SFRC layer F_n

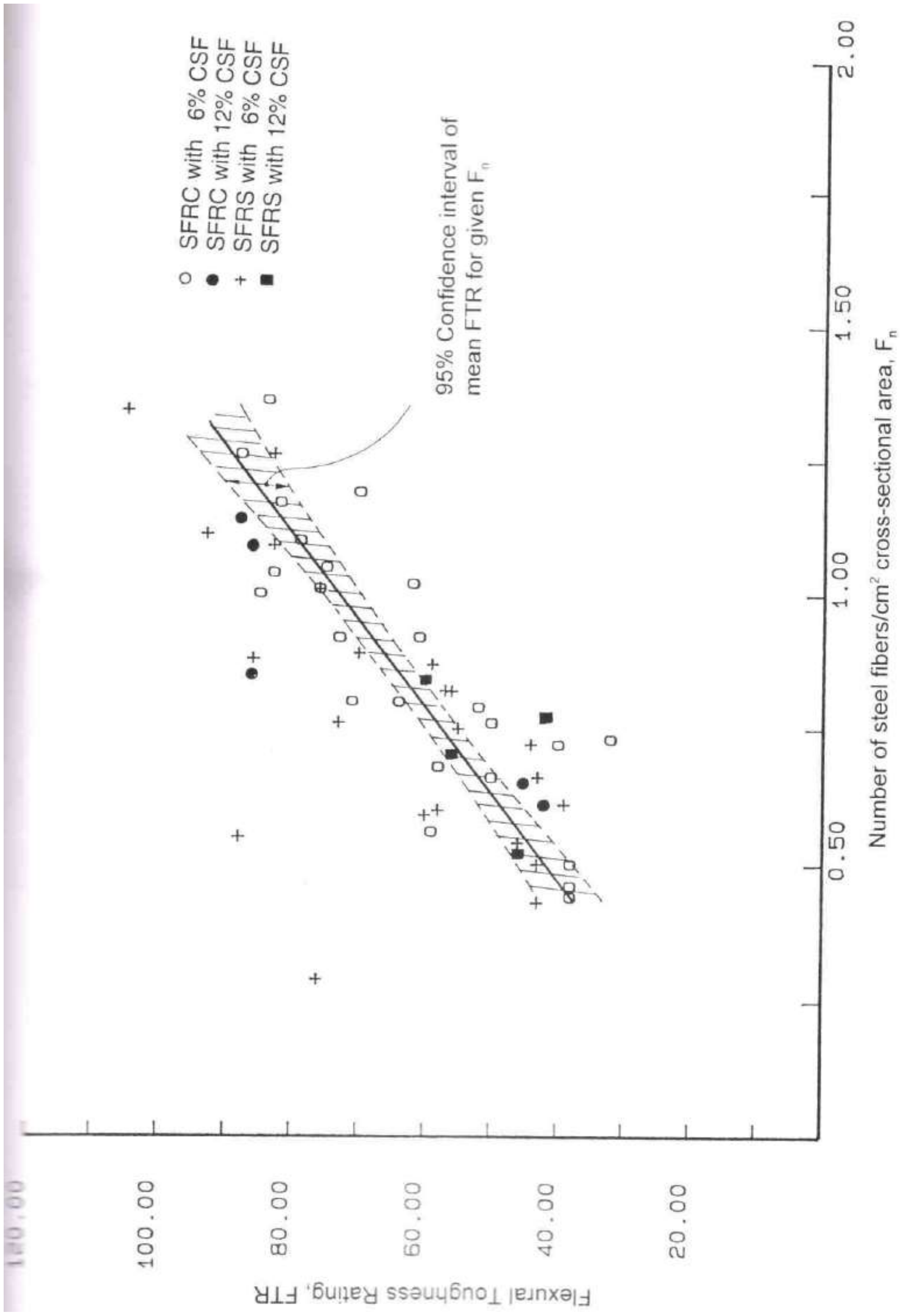

Fig. 8 - Relation of toughness index, FTR with number of steel fibres in one cm2 cross-sectional area of SFRS and SFRC layer, Fn

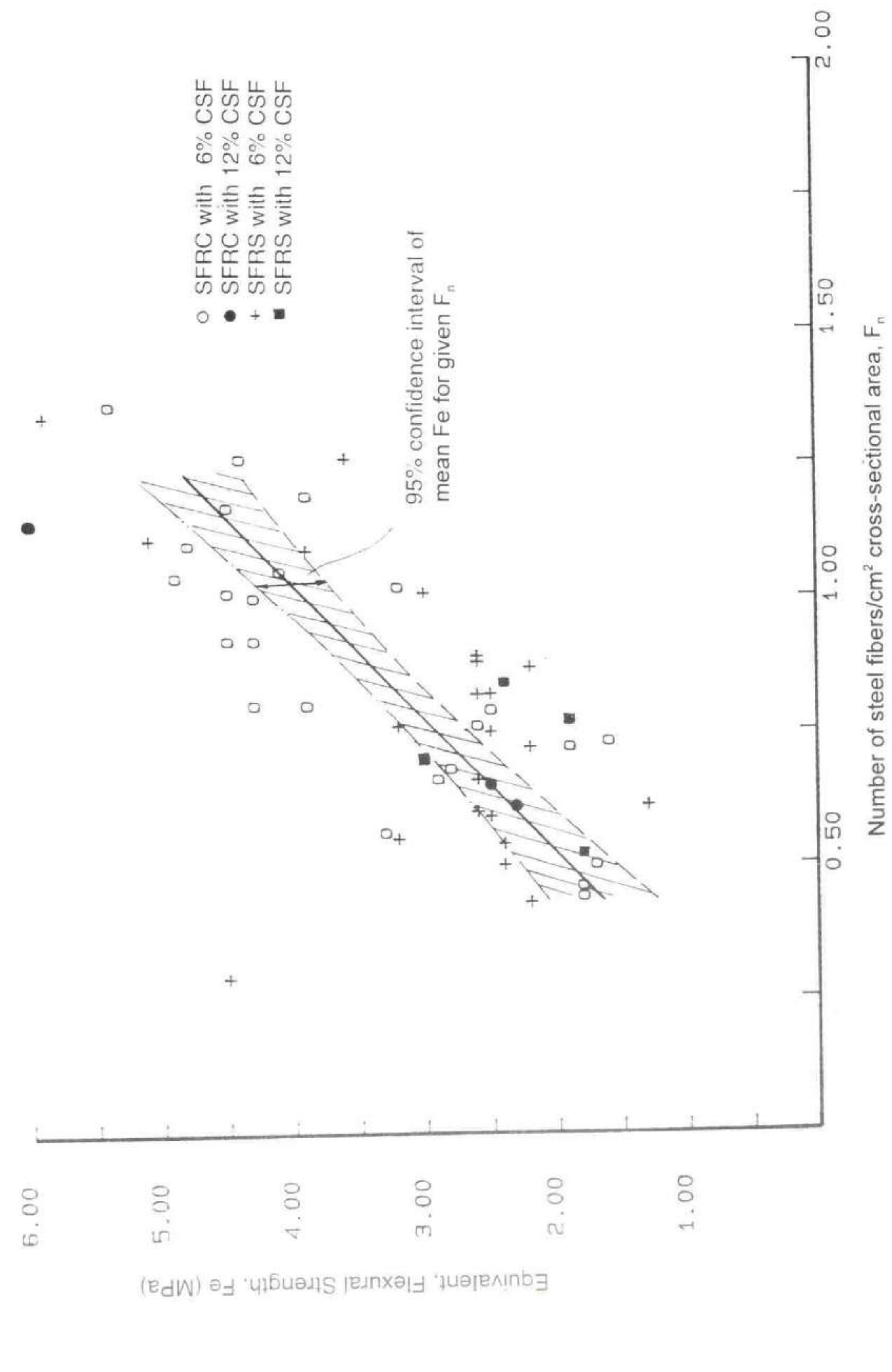

Fig. 9 - Relation of equivalent flexural strength, Fe with number of steel fibres in one cm2 cross sectional area of SFRS and SFRC layer Fn

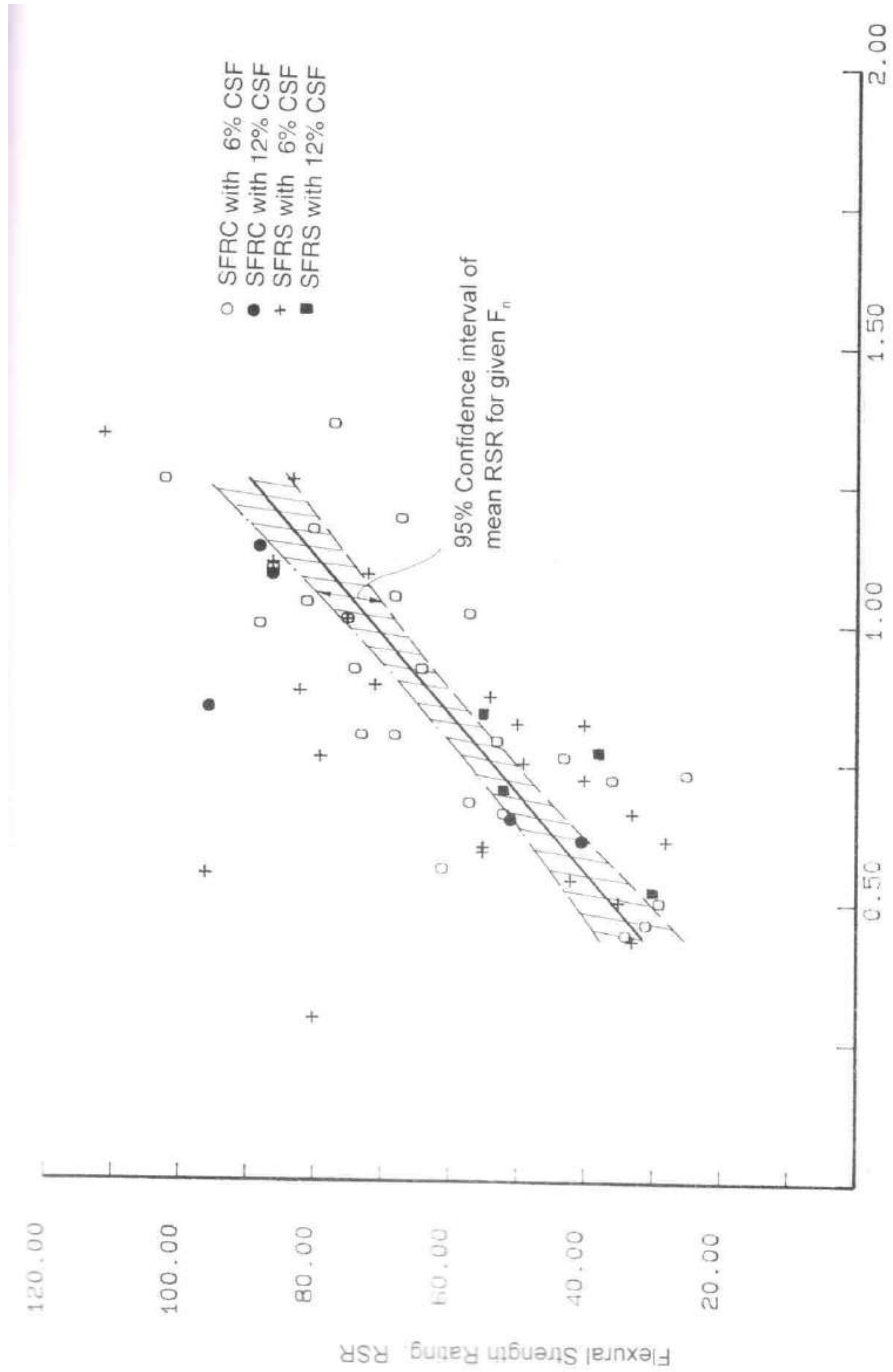

Fig. 10 - Relation of toughness index, RSR with number of steel fibres in one cm2 cross-sectional area of SFRS and SFRC layer Fn

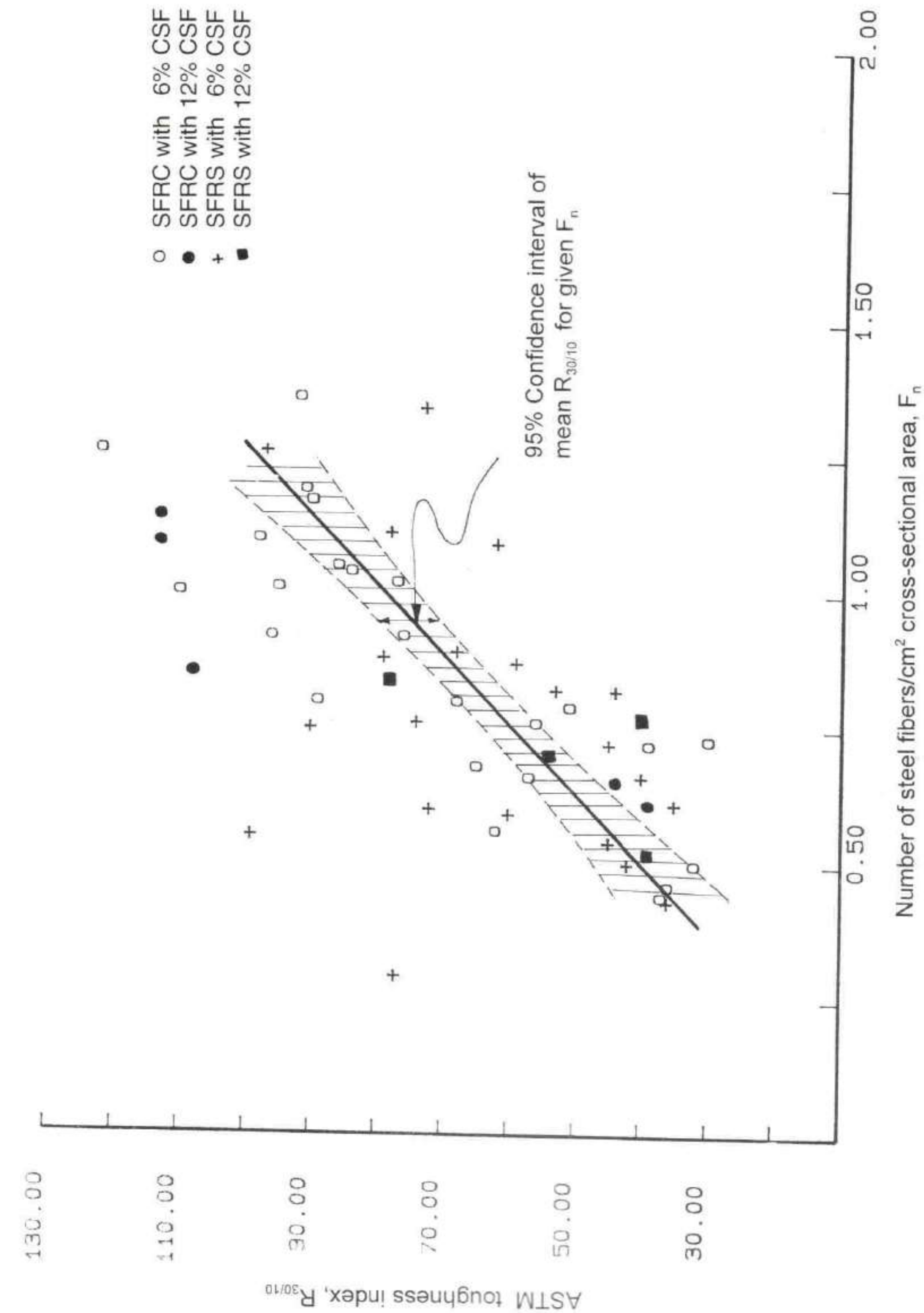

Fig. 11 - Relation of ASTM toughness index R30/10 with number of steel fibres in one cm2 cross-sectional area of SFRS and SFRC layer Fn

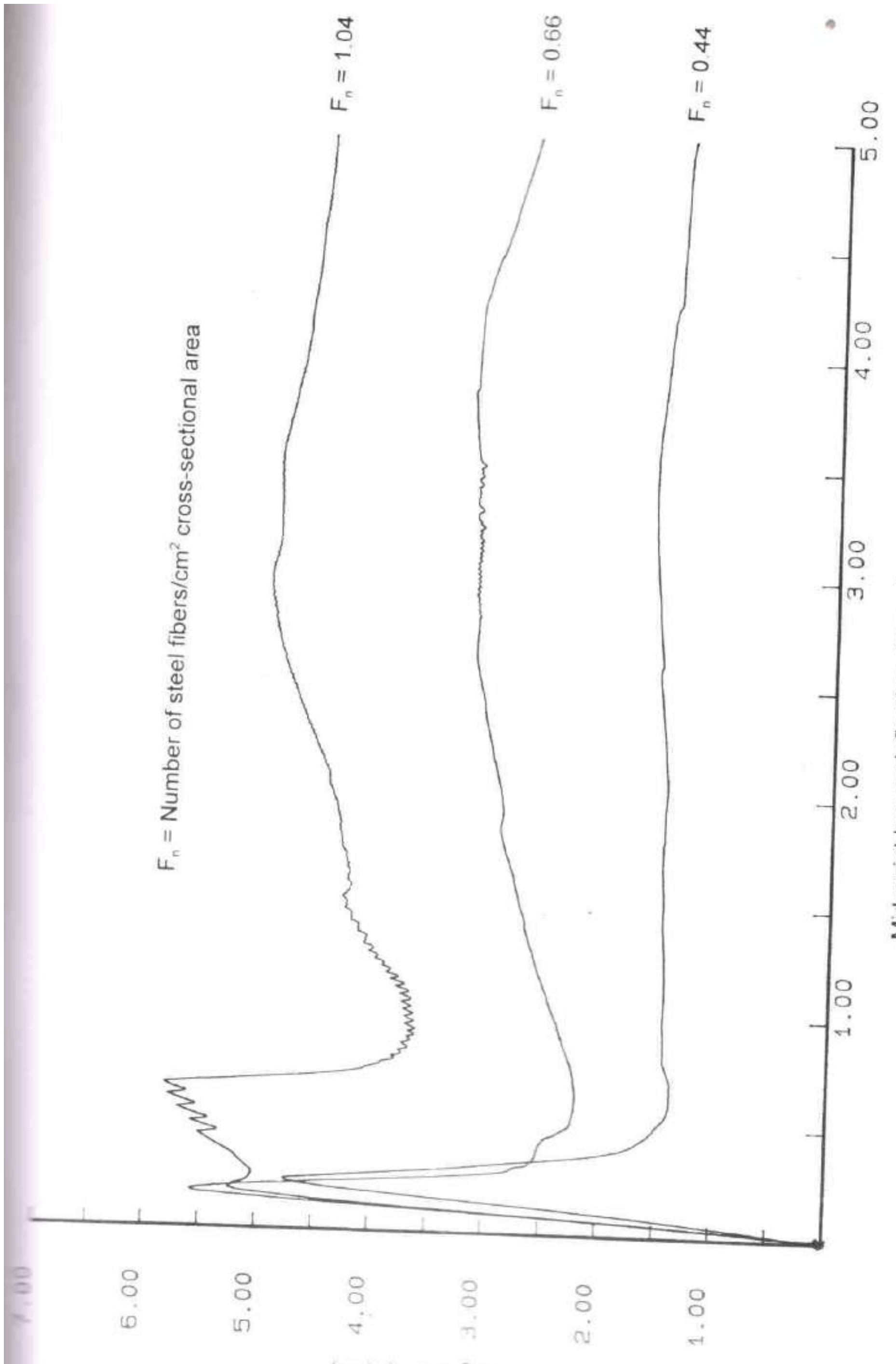

Fig. 12 - Typical bending load-deflection curves for SFRS/SFRC beams (300 x 100 x 50 mm) containing 0.44, 0.66, and 1.04 steel fibres/cm^2 cross-sectional area