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NONLINEAR FRACTURE BEHAVIOUR OF FIBER REINFORCED SELF COMPACTING CONCRETE USING "R - CURVE"

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Abstract: In this paper the non-linear fracture behavior of plain and fiber-reinforced concrete is presented using R-Curve. Geometrically similar beam specimens of different sizes with (steel fibers and glass fibers) and without fibers were tested under three-point bending in a closed loop servo-controlled machine with crack mouth opening displacement control with a rate of opening of 0.0005 mm/sec. The non-linear fracture mechanics parameters such as, fracture energy (G_f), length of process zone (c_f), brittleness number (β), mode I fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_C$) and size of fracture process zone (l_0) are determined for different PSCC, GFRSCC and SFRSCC using the size effect method. The crack growth resistance curve (R-curve) is also developed for specimens with and without fibers. These properties are required for two main reasons: firstly the fracture behaviour of FRSCC could be understood in comparison with PSCC and secondly these properties serve as input parameters in fracture mechanics based analysis of structures having fibers in SCC.

1 INTRODUCTION

Self-compacting concrete (SCC) is a high-performance concrete that can flow under its own weight so as to completely fill the formwork and self-consolidate without any mechanical vibration [1-2]. This type of concrete is specifically designed to achieve excellent deformability, low risk of blockage, and good stability, ensuring a high formwork filling capacity. SCC is considered a suitable material for the construction of structural members with high volumes of steel reinforcement because of its ability to easily flow in highly congested areas [3-4].

There is an innovative change in the Concrete technology in the recent past with the accessibility of various grades of cements and mineral admixtures. However there is a remarkable development, some complications quiet remained. These problems can be considered as drawbacks for this cementitious material, when it is compared to materials like steel. Concrete, which is a quasi-fragile material, having negligible tensile strength.

Several studies have shown that fiber reinforced composites are more efficient than other types of composites. The main purpose of the fiber is to control cracking and to increase the fracture toughness of the brittle matrix through bridging action during both micro and macro cracking of the matrix. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action. In the beginning of macro cracking, bridging action of fibers prevents and controls the opening and growth of cracks.

The non-linear fracture mechanics parameters such as, fracture energy (G_f), length of process zone (c_f), brittleness number (β), mode I fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_C$) and size of fracture process zone (l_0) are determined for different PSCC, GFRSCC and SFRSCC using the size effect method. The crack growth resistance curve (R-curve) is also developed for specimens with and without fibers..

2 EXPERIMENTAL WORK

2.1 Constitute materials and Mix proportions

List of materials used for this study are given in Table 1 along with their specification. To achieve, self-capability, numbers of trail was done for different combination of materials. Binder contents varies between 450–700 kg/m^3 and Water/Binder (W/B) ratios varies between 0.29 to 0.34 (by weight) with corresponding variation in the paste volume to investigate the influence of binder. The aggregate combination of 50:20:30 (Fine aggregate: Coarse aggregate 10 mm maximum size: Coarse aggregate 20 mm maximum size) by volume was kept constant for all mixes.

Table 1: Example of the construction of one table

Material	Specification
Ordinary Portland cement	As describe in IS: 12269, specific gravity = 3.12
Fly ash	Dark, pozzocrete 60 confirming to IS: 3812 (Part 1) 2013, Specific gravity = 2.0
Superplasticizer	Master Glenium SKY 8276, BASF confirming ASTM C 494
Fine aggregate	Locally available river sand passing through 4.75 mm IS sieve confirming to IS: 3812 (Part 1) 2013
Coarse aggregate	Locally available crushed granite – maximum sizes 20 mm and 10 mm confirming to IS: 3812 (Part 1) 2013

Table 2: Composition of Reference Mix

Constituent	Quantity (kg/m^3)
Cement	354
Fly ash	96
Fine aggregate	634
Coarse aggregates (<10 mm)	224
Coarse aggregates (<20mm)	332
Water	160*
Superplasticizer	2.225*

*is in liter

A polycarboxylate-based high range water reducing admixture (HRWRA) was also used in the mixtures; dosage of superplasticizer was kept constant, 0.5% by weight of binder for providing the desired fluidity of the SCC. For all test, proportion of cement to fly ash was kept constant. (Cement: Fly ash = 70:30). Constitute of final mixes are presented in Table 2.

Fiber reinforced self-compacting concrete (FRSCC) was achieved by adding steel fiber (Dramix RCBN 35/65 hooked end) and glass fibres (Cem-FIL) in selected mix proportion of concrete as shown in Figure - 1. Steel fiber has a diameter of 0.55 mm, a length of 65 mm, and a tensile strength of 1000-1100 N/mm^2. CEM-FILL anti crack, high dispersion, alkali resistance glass fiber of diameter 17micron and 12 mm length was used in concrete. Number of trail was conducted with different dosages of fibers to achieved steel fiber reinforced self-compacting concrete (SFRSCC) and glass fiber reinforced self-compacting concrete (GFRSCC). The content of 32 kg/m^3 steel fibers and 50 gm per bag of cement glass fibers in self-compacting concrete satisfied the workability tests.

Figure 1: Glass and Steel Fibres used in the study

2.2 Specimen preparation

The details of the geometry and its nomenclature are shown in Figure 2 and Table 3, respectively. The concrete mixes are poured into their respective moulds of geometrically similar beams with three different sizes, each having a notch to depth ratio of 0.2 and span to depth ratio of 2.5. In order to create a notch, a fine metal strip of 2 mm thickness was introduce during casting at center for different notch size.

The rationale behind the selection of small, medium and large beams is to study the effect of specimen size on the fracture behavior by testing geometrically similar specimens as per the draft recommendation of the RILEM Technical Committee 89-FMT on fracture mechanics of Concrete RILEM [5]. Using this method, one can obtain a size effect plot, by which the size of the structure can be extrapolated to a very large structures like dam. The notch site is kept at the center of the beam under three point bending as recommended by RILEM [5]. While handling the specimens, great care is taken to prevent any falling or impact on the specimen.

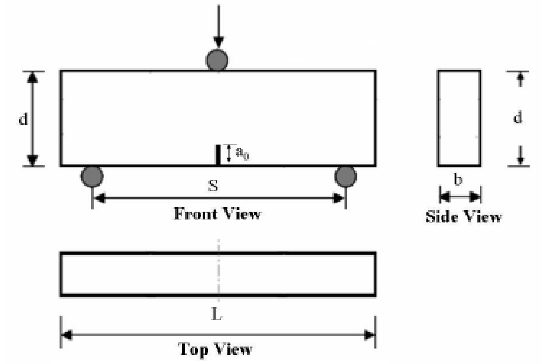

Figure 2. Details of geometry of the specimen.

Table 3: Dimensions of beams

Parameters	Beam designation		
	Small	Medium	Large
Depth, d (mm)	76	152	304
Span, S (mm)	190	380	760
Length, L (mm)	241	431	810
Thickness, b (mm)	50	50	50
Notch depth, a_0 (mm)	15.2	30.4	60.8

3 RESULTS AND DISCUSSIONS

3.1 Fresh properties

The fresh properties of SCC are as important as its hardened properties. To evaluate workability of fresh self-compacting concrete like filling ability, passing ability and segregation resistance, different test were carried out as per EFNARC [6] specifications as shown in Figure 4. The filling ability of SCC was measured using slump flow and V – funnel test. Passing ability of SCC was measured using J- ring, L- box and U – box test. Similarly resistance to segregation of self-compacting concrete was measured with the help of GTM Screen stability test.

Figure 4 J - Ring Test for SCC as per EFNARC Standard

3.2 Mechanical properties

After conducting test for fresh properties, concrete fill in cubes, cylinder and beam moulds for mechanical properties. The results of compression test, split tensile strength and flexural strength of plain and fiber reinforced self-compacting concrete are presented in Table 4.

Table 4: Hardened Properties of self-compacting concrete

Type of SCC	Compressive Strength (MPa)	Spilt Tensile Strength (MPa)	Flexural Strength (MPa)
SCC	62.64	4.56	4.38
GFRSCC	63.53	5.03	4.82
SFRSCC	66.59	5.99	5.89

3.3 Fracture tests

The specimens are tested in a closed loop servo-controlled testing machine having a capacity of 100 kN. A specially calibrated 50 kN load cell is used for measuring the load as shown in Figure - 3. The load-point displacement is measured using a linear variable displacement transformer (LVDT). The crack mouth opening displacement (CMOD) is measured using a clip gauge located across the notch. All the tests are performed under CMOD control with the rate of crack opening being 0.0005 mm/s. The results of load, vertical displacement, CMOD and time are simultaneously acquired through a data acquisition system.

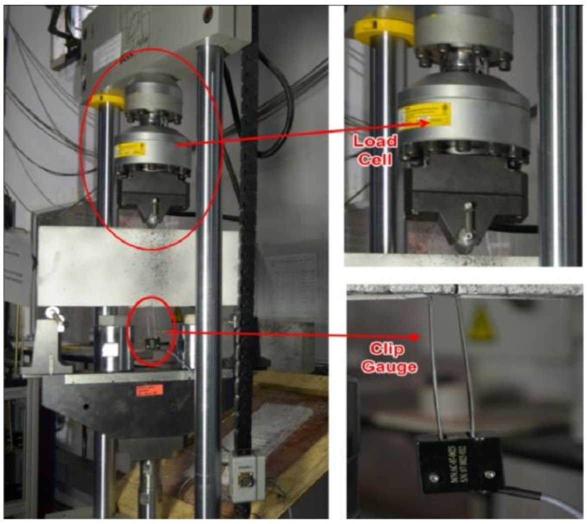

Figure 3 Closed loop Servo Controlled Test Setup used in the study

The load, CMOD and mid-span vertical displacement acquired during the test is analyzed. Peak load for plain and fiber reinforced specimens are presented in Table 5. Results show that Peak load, displacement and CMOD was increased with increased in size of specimen.

Table 5: Peak load of small, medium and large specimens in kN

Type of SCC	Small	Medium	Large
SCC	4.43	6.68	11.70
GFRSCC	4.43	6.70	11.88
SFRSCC	4.45	6.91	12.30

It was also observed that in same size of specimens, there was slightly increase in peak load due to addition of fibers in SCC but energy absorption capacity (are under load displacement curve) was increased tremendously as seen from Table 6. Energy absorption capacity was increased by 198% and 1096% in small specimens, due to addition of glass fibers and steel fibers respectively.
Similarly in medium specimens, energy absorption capacity was increased by 184% and 614% due to addition of glass fibers and steel fibers respectively. Also, in case of large specimens, energy absorption capacity was increased by 104% and 407% due to

addition of glass fibers and steel fibers respectively. It can be concluded that addition of fibers in specimens, increase the energy absorption capacity tremendously in all size of specimens.

Table 6: Area under load displacement curve for small, medium and large specimens in kN.mm

Type of SCC	Small	Medium	Large
SCC	0.53	1.71	5.06
GFRSCC	1.58	4.86	10.34
SFRSCC	6.34	12.21	25.69

3.4 Non-linear fracture parameters

The non-linear fracture mechanics parameters such as, fracture energy (G_f), length of process zone (c_f), brittleness number (β), mode I fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_C$) and size of fracture process zone (l_0) are determined [7 – 9]for different PSCC, GFRSCC and SFRSCC using the size effect method is calculated and presented in Table 7 as per the procedure described in the literature [10].

Results of brittleness number is presented in Table 8. Results shows that brittleness number (β) increased with increased in size of specimens. Plain, glass fiber reinforced and steel fiber reinforced self-compacting concrete follows Bazant's size effect law. Behavior of large specimens is more similar to linear elastic fracture mechanics (LEFM) graph which is for brittle material. It was also observed that all the specimens have the brittleness value between 0.1 and 10 which validate the applicability of the nonlinear fracture parameter. Figure 4 represent that all the data points lie in the transition zone between the LEFM criterion and the strength criterion. As size of specimens decrease, this behavior is similar to strength criterion.

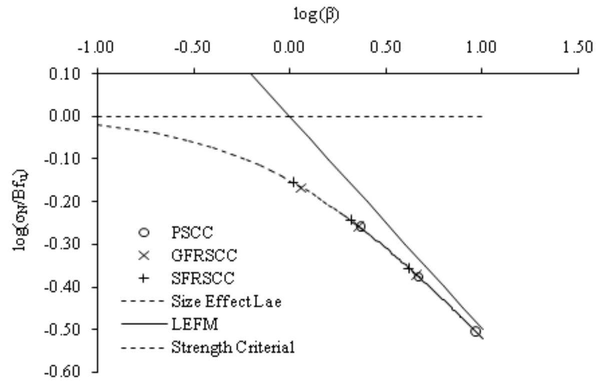

Figure 4: Experimental Data Following Size Effect Law

Table 7: Nonlinear fracture parameters from size effect law.

NLFM Property	SCC	GFRSCC	SFRSCC
G_f (N.m/m^2)	55.26	62.16	63.80
c_f (mm)	6.25	12.57	13.86
K_{IC} MPa√m	1.120	1.214	1.265
CTODc δc (μm)	12.45	18.31	18.95
Size of FPZ l_0 (mm)	102.43	120.45	130.63
G_F (WOF) N. mm/mm^2	0.261	0.723	2.069

Table 8: Brittleness Number

Beam Designation	β = Brittleness Number		
	SCC	**GFRSCC**	**SFRSCC**
Small	2.317	1.153	1.046
Medium	4.635	2.305	2.091
Large	9.269	4.610	4.182

SCC with steel fibers (Brittleness number = 2.440) behave much better than that of glass fibers (Brittleness number = 2.689). Both SCC with steel and glass fibers behave better than plain SCC (without fiber) because brittleness number of plain SCC (β = 5.407) is less than that of SCC with fiber.

Addition of fibers in self compacting concrete increased the size independent fracture energy (Gf). The size independent is higher for SFRSCC specimen than for the GFRSCC and PSCC specimens.

The dimensions of the fracture process zone (cf and l0) are smaller for PSCC compared to GFRSCC and SFRSCC specimens. This is because in the case of GFRSCC and SFRSCC specimens, a fracture process zone is formed ahead of the crack-tip in which mechanisms like micro-cracking, mortar inter locking with fibers, crack-branching, and crack-bridging and takes place. These mechanisms are either very small or absent in case of PSCC specimens. Furthermore, addition of fibers in self compacting concrete, the dimensions of the fracture process zone increase which is the reason for increase in the load carrying capacity.

Trend similar to Gf and dimensions of fracture process zone is observed for parameters K_{IC} as well as CTODc too.

Fracture energy is computed using the "work of fracture" method as per the recommendation of RILEM which is based on the Hillerborg's fictitious crack model [11]. It is seen that average fracture energy by work of fracture (WOF) method of SFRSCC is more compared to GFRSCC and PSCC specimens. It shows that more energy required to break fiber reinforced specimens.

3.4 R - Curve

For a fixed specimen geometry, and approximately also for a narrow range of similar geometries, the dependence of the energy, R, required for crack growth on the crack extension, c from the notch can be considered to be the material property, called the R-curve. The usual methods of measurement of the R-curve rely on some direct or indirect determination of the crack length. Bazant and co-workers [12] have shown that the R-curve can be easily determined from the size effect theory.

Various material properties required in the fracture analysis of quasi-brittle materials like concrete are defined above. These fracture properties are extracted for plain self compacting concrete (PSCC), glass fiber reinforced self compacting concrete (GFRSCC) and steel fiber reinforced self compacting concrete (SFRSCC) by conducting three-point bend tests as per RILEM recommendations [13].

The R-curve is computed for PSCC, GFRSCC and SFRSCC specimens as shown in Figure 5.

From the plot of the R-curve, the following observations are made:

1. Since the R-curve is the plot of resistance to crack propagation, it is seen that for SFRSCC specimen, the resistance offered to crack propagation is the more compared to GFRSCC and PSCC specimens.
2. Addition of fibers in SCC, increased the resistance to crack propagation of the specimens.

When the crack growth resistance R and the crack length c are normalized with fracture energy Gf and length of process zone cf , respectively, the R-curve gets transformed in to the curve as shown in Figure 6. This curve is same for all the specimens because it is a typical curve for three point bending (TPB) test [13]. It is observed that the R-curve obtained from Bazant's size effect method smoothly approaches the line of R=Gf at c=cf infinite size of specimen. The R-curve so obtained is interpreted as an envelope of Gq- curves for a series of geometrically similar structures with increasing size [12].

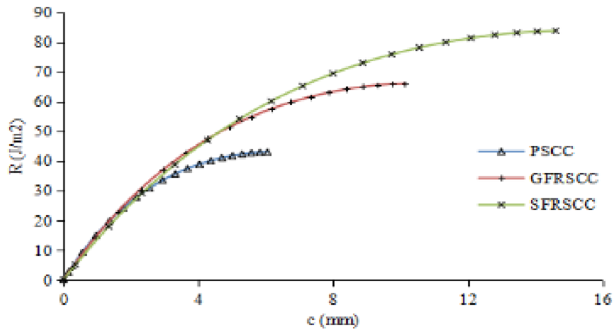

Figure 5: R - Curve for all the specimens

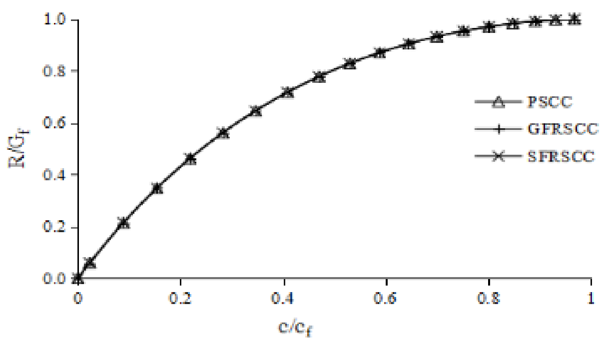

Figure 6: Normalized R - Curve for all the specimens

4 Conclusions

The non-linear fracture properties of plain and fiber reinforced self compacting concrete are experimentally determined using the Bazant's size effect model. Specimens are tested in closed loop servo controlled machine under three point bending using CMOD control. It is seen that the fiber reinforced specimens exhibit size effect similar to plain specimens. The experimental data points for specimens without fibers fall near to the zone of applicability of LEFM, which show the increase in brittleness due absences of fiber in self compacting concrete. The non-linear fracture mechanics parameters such as, fracture energy (G_f), length of process zone (c_f), brittleness number (β), mode I fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_C$) and size of fracture process zone (l_0) are determined for different PSCC, GFRSCC and SFRSCC using the size effect method is calculated and presented. It is also observed that the brittleness number of SFRSCC specimens is less than GFRSCC specimens because of steel fibers have better mechanical properties compared to glass fibres. All the specimen have the brittleness value between 0.1 and 10 which validate the applicability of the non-linear fracture mechanics parameters. The non-linear fracture mechanics parameters such as, fracture energy (G_f), length of process zone (c_f), brittleness number (β), mode I fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_C$) and size of fracture process zone (l_0) for are increasing in ascending order for PSCC, GFRSCC and SFRSCC respectively. This increase can be attributed to the addition of fibers in self compacting concrete.

The crack growth resistance curve R-Curve is developed for all the specimens. The resistance against crack growth (R) is high for fiber reinforced specimen compared to that plain specimens . The size independent normalized crack resistance (R/Gf) to normalized crack length (c/cf) curve is also obtained which is interpreted as an envelope of Gq -curves for a series of geometrically similar structures.

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