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Effect of Fibre Content on Double-K Fracture Parameters of Concrete

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Abstract—**Concrete is the most widely used construction material and the presence of cracks is inevitable in concrete. The investigation of the stability of cracks and improvement of the fracture properties is of greater concern in construction industry. The present study is on the experimental evaluation of improvement of fracture parameters of concrete by addition of hooked end steel fibres in varying volume fraction in the range 0-1.0%. The fracture test is conducted on notched beams as per International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) guidelines. The results show that the fracture parameters improve with the percentage of addition of fibre, reach an optimum value and then decrease. The ductility and load carrying capacity are also improved by addition of steel fibre.**

Keywords—Double-K fracture parameters; Fibre reinforced concrete; Mechanical properties

I. INTRODUCTION

Concrete is the most widely used structural material in civil constructions. However, the presence of cracks inside concrete is inevitable and it is necessary to investigate how far they are stable. Here, the concrete Fracture Mechanics proves to be a valuable method for studying concrete behaviour under static loading [1,2,3]. The severity of problem related to fracture varies with the type and importance of the structure.

Fracture can be defined as the separation of a component into, at least, two parts. Fracture in a material occurs when sufficient stress and work are applied on the atomic level to break the bonds that hold atoms together. The main causes of failure are uncertainties in the loading or environment, defects in the materials, inadequacies in design and deficiencies in construction or maintenance.

Fibres, mainly steel fibres in concrete found its application as a substitute for secondary reinforcement or for crack control in less critical parts of the construction initially. Today steel fibres are used as the main and unique reinforcing for industrial floor slabs, shotcrete and prefabricated concrete products [1,2,3,4].

Studies prove that by the addition of steel fibre, the properties of hardened concrete can be improved [7 and 8]. Besides mechanical properties, the fracture properties can also be improved by adding fibre [2 and 3]. This study aims at finding out the optimum fibre content for which the fracture properties as well as the mechanical properties are enhanced without compromising the workability and economic viability. Normal concrete mix of M30 grade is the most widely used mix for common purposes. Hence, the present study is conducted on M30 grade concrete.

II. METHODOLOGY

The experimental programme consists of studying of fresh and hardened properties of FRC mixes of grade M30 by varying the fibre content- 0%, 0.25%, 0.5%, 0.75% and 1.0%. The fracture parameters of concrete is determined by conducting three point bending test on notched beam specimens of size 100×100×500 mm with notch sizes of 30 mm for all the mixes with a span of 400 mm as per RILEM guidelines [6]. The test setup used for the three point bending test is as shown in fig 1.

The mid span deflection is determined with the help of the dial gauge and the crack mouth opening displacement (CMOD) using Linear Variable Differential Transformer (LVDT).

The fracture parameters were determined using the formulae given by the technical committee RILEM [6].

The parameters determined are the fracture energy, intrinsic brittleness and fracture toughness. Fracture energy (G_F) is determined using eq. 1.

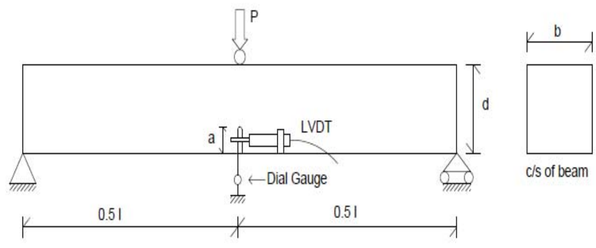

Fig 1 Three point bending test set up

$$G_F = \frac{W_0 + mg\delta_{max}}{b(d-a)} \quad (1)$$

Where, G_F = fracture energy (N/m),
W_0 = area under the load-deflection curve (Nm),
mg = weight of the beam between supports (N), b = width (m); d = depth (m)
δ_{max} = displacement corresponding to P_{max}(m)
and a = initial notch of the beam (m).

According to the RILEM, the fracture toughness K_{IC} is calculated using the equation 2.

$$K_{IC} = \frac{3PS\sqrt{\pi a}\, f(\alpha)}{2bd^2} \quad (2)$$

Where, K_{IC} = fracture toughness (MPa√m), P_{max}= Peak load + Self weight of beam(N);
S, d and b are the span, depth, and width in mm, respectively, of the tested beam.

f (α) is a geometry factor, which depends on the ratio of the initial crack length (a) to the depth (d) of the beam.The initial crack length = Initial notch depth.
In case of S = 4d as applied in the current study, f (α) can be written as follows

$$f(\alpha) = \frac{[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{(1+2\alpha)(1-\alpha)^{3/2}} \quad (3)$$

Where $\{\alpha = \frac{a}{d}\}$

Characteristic length (intrinsic brittleness) is a measure of the length of the fracture process zone and is determined by equation 4.

$$l_{ch} = \frac{EG_F}{f_t^2} \quad (4)$$

Where G_F = fracture energy (N/mm)
E = modulus of elasticity in [MPa] and
f_t = tensile strength of concrete [MPa].

The experimental investigations in recent years have showed that the fracture process in concrete structures includes three apparent stages: crack initiation, stable crack propagation and unstable fracture or failure [9, 10 and 11]. Hence, we look forward for a fracture model which considers these three stages and is also easy to be conducted in tests.

In order to reflect the different stages in concrete fracture, a double-K fracture criterion was proposed by ShilangXu and Reinhardt in 1999 [9, 10 and 11]. The double-K fracture model can predict both crack initiation and critical unstable propagation through double-K fracture criterion. In this criterion, two fracture toughness parameters are introduced, which are respectively denoted by K^{ini}_{Ic} and K^{un}_{Ic} and therefore called double-K fracture parameters. K^{ini}_{Ic} is explained as initiation fracture toughness and stands for crack resistance of concrete at the initial cracking load level below which concrete is assumed to be in elastic state and no macro crack development occurs.

On the other hand, K^{un}_{Ic} is defined as unstable fracture toughness and stands for crack resistance of concrete corresponding to the maximum load level at which crack is in critical unstable condition and the critical fictitious fracture process zone appear ahead of initial crack tip.
By inserting the measured maximum load P_{max}, and critical crack mouth opening displacement ($CMOD_C$) into the following formula the critical effective crack length $a_c$can be evaluated.

$$a_c = \frac{2}{\pi} d.arctg\sqrt{\frac{bECMOD_c}{32.6P_{max}} - 0.1135} \quad (5)$$

The preformed crack tip opening displacement $CTOD_c$at the critical situation shall be determined by the formula given below

$$CTOD_c = CMOD_c\left\{\left(1-\frac{a_0}{a_c}\right)^2 + \left(1.081 - 1.149\frac{a_c}{d}\right)\left[\frac{a_0}{a_c} - \left(\frac{a_0}{a_c}\right)^2\right]\right\}^{1/2} \quad (6)$$

In the simplified method proposed, it is only required to evaluate the amount of cohesive force σ_S (CTOD)at the end of the fictitious crack zone at the position of a_0 , the resultant P_e of the cohesive force σ(x) on the overall fictitious crack zone and its effective acting position $U_e = x_e/a$. For cohesive force, σ_S (CTOD), the stress versus crack width relationship proposed by Reinhardt et al. [11] can be utilized to evaluate the coefficient, β_C.

$$\beta_c = \left[1 + \left(c_1\frac{CTOD_c}{w_0}\right)^3\right] * e^{\left(-c_2\frac{CTOD_c}{w_0}\right)} - \left[\frac{CTOD_c}{w_o}\left(1+c_1^3\right)\right] * e^{(-c_2)} \quad (7)$$

For normal concrete, the material constants c_1, c_2 and w_0 are given as 3, 7 and 0.16mm respectively.
For a simple purpose, the resultant of the cohesive force σ(x) on the fictitious crack zone P_e and the effective relative acting position x_e/a_C at the critical situation can be evaluated as follows.

$$P_e = \frac{f_t}{2}(1+\beta_c)(a_c - a_0) \tag{8}$$

Where

$$U_e = \frac{x_e}{a_c} = \frac{1}{3(1+\beta_c)}\left\{2+\beta_c+(1+2\beta_c)\frac{\alpha_0}{\alpha_c}\right\} \tag{9}$$

$$\alpha_0 = \frac{a_0}{d}\,\alpha_c\,\frac{a_c}{d}$$

For evaluating the cohesive fracture toughness K^c_{Ic} due to the cohesive force σ(x) on the fictitious crack zone at the critical situation, oneonly needs to insert the above mentioned P_e and U_e into the following dimensionless formula. K^c_{Ic} at the critical situation is given by

$$K^c_{Ic} / f_t\sqrt{d} = \frac{2P_e}{f_t\sqrt{\pi a_c d}}.Z(U_e,\alpha_0/\alpha_c).F(U_e,\alpha_c) \tag{10}$$

where the calibration function $Z(Ue,\alpha 0/\alpha c)$and the geometric function $F(Ue,\alpha c)$ are given by the following formulae

$$Z(U_e,\alpha_0/\alpha_c) = \frac{6(1.025-0.1\beta)}{1+1.83(\alpha_0-0.2)}\left(\frac{\alpha_0}{\alpha_c}\right)^p\sqrt{\frac{\alpha_c}{\pi}}.U_e^{-0.2} \tag{11}$$

where $p = 1.5(\alpha_0 - 0.2) + 0.8$ when $0.2 \le \alpha_0 \le 0.6$;

$p = 3(\alpha_0 - 0.6) + 1.4$ when $0.6 \le \alpha_0 \le 0.7$;

$p = 6(\alpha_0 - 0.7) + 1.7$ when $0.7 \le \alpha_0 \le 0.8$

$$F(U,\alpha) = \frac{3.52(1-U_e)}{(1-\alpha_c)^{3/2}} - \frac{4.35-5.28U_e}{(1-\alpha_c)^{1/2}} + \left\{\frac{1.30-0.3U_e^{3/2}}{(1-U_e^2)^{1/2}} + 0.83 - 1.76U_e\right\}\{1-(1-U_e)\alpha_c\} \tag{12}$$

This is the stress intensity factor created by an external load at the effective crack tip at the critical unstable growth of crack. Forthe standard three-point bending test on notched beam with a ratio of span to depth of the beam, S/d =4, K_{Ic}^{un}can be evaluated according to the following formula.

$$K_{Ic}^{un} = \frac{3P_{max}S\sqrt{a_c}f(\alpha_c)}{2bd^2} \tag{13}$$

In case of S = 4d as applied in the current study, $f(\alpha_c)$ can be written as follows

$$f(\alpha_c) = \frac{[1.99-\alpha_c(1-\alpha_c)(2.15-3.93\alpha_c+2.7\alpha_c^2)]}{(1+2\alpha_c)(1-\alpha_c)^{3/2}} \tag{14}$$

The initiation toughness, K_{Ic}^{ini}can be easily gotusing the three-parameter law of the toughness in quasi-brittle materials.

$$K_{Ic}^{ini} = K_{Ic}^{un} - K_{Ic}^{c} \tag{15}$$

III EXPERIMENTAL PROGRAMME

A. General

Concrete mix of M30 grade was used in the study proportioned as per IS 10262-2009. The mix proportion and mix designation are given in Table 1 and Table 2 respectively. In mix designation C stands for concrete and F for fibre.

B. Properties of fresh concrete

The properties of fresh concrete were measured by conducting slump test and compacting factor test. The results of the tests are given in Table 3.

C. Fracture test

The fracture study was conducted on notched beams of size 100×100×500mm. All the beams were subjected to three point bending under simply supported end condition in a

TABLE 1 MIX PROPORTION

Material	Cement	Aggregate		
		Fine	Coarse	Water
Weight (kg/m^3)	420	764.4	1260	184.8
Ratio	1	1.82	3.0	0.44

TABLE 2 MIX DESIGNATION

SL. No.	Mix Designation	Volume fraction of fibre (%)
1	CF 0	0
2	CF 1	0.25
3	CF 2	0.50
4	CF 3	0.75
5	CF 4	1.0

TABLE 3 PROPERTIES OF FRESH CONCRETE

Sl No.	Mix Designation	Slump (mm)	Compacting Factor
1	CF0	60	0.842
2	CF1	49	0.830
3	CF2	39	0.816
4	CF3	15	0.779
5	CF4	8	0.693

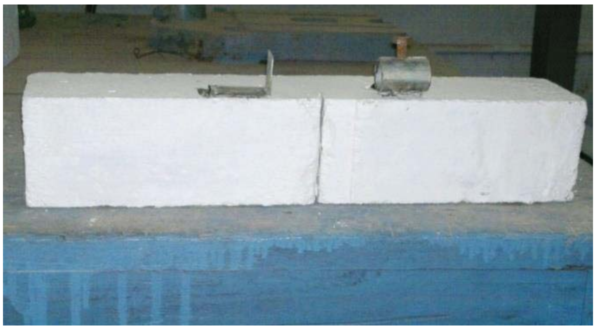

Fig 2 Fracture Specimen ready for testing

Fig 3 Fracture Test Setup

stress controlled state. The specimen with fixtures to connect LVDT and actual test setup are shown in figures 2 and 3 respectively.

IV RESULTS AND DISCUSSION

A. Mechanical properties

The properties of hardened concrete such as cube compressive strength, splitting tensile strength, flexural strength and modulus of elasticity were determined. The results of the tests are given in table 4.

B. Load-Deflection characteristics

Mid span deflections were noted at every 250 N load increments with the help of a dial gauge. Deflections of

TABLE 4 MECHANICAL PROPERTIES OF CONCRETE

Mix	Cube compressive strength (N/mm^2)	Splitting tensile strength (N/mm^2)	Flexural Strength (N/mm^2)	Modulus of elasticity ($x10^4 N/mm^2$)
CF 0	42.67	4.50	4.02	3.2254
CF 1	43.92	4.90	4.40	3.2421
CF 2	46.26	5.52	4.43	3.2629
CF 3	48.19	5.80	4.81	3.2917
CF 4	41.48	5.51	4.02	3.2128

control specimens and beams with fibre were observed to increase considerably after the first crack Load was reached to a stage at which the deflection increased predominantly without any load increment. The plot of load-deflection for fibre reinforced concrete is given in Fig. 4. The ultimate load of beams were found to increase with addition of steel fibre and it increased with the increment in the percentage of fibreupto 0.75% addition and then decreased. The reduction in the load carrying capacity of beams is due to the very poor workability of the mix CF4.

C. Load-CMOD characteristics

The Load - CMOD curves for FRC beams is shown in fig 5. Initially the CMOD was very small and then increased abruptly near the ultimate load. All the beams showed similar behaviour. The peak CMOD obtained for FRC beams, showed an increasing trend with fibre content.

D. Fracture parameters

The fracture parameters viz. fracture energy, fracture toughness and intrinsic brittleness (characteristic length) were determined as per RILEM guidelines. Table 5 shows the values of fracture parameters determined in the experiment. Fig 6 shows the normalized graph of fracture parameters (fracture energy, characteristic length and fracture toughness).

It can be seen that all the fracture parameters follow a similar trend. With increase in fibre content, the fracture properties are improved and also they improve with the increase in volume fraction of fibre upto a particular stage (0.75%) where they attain the maximum values and then decreases. The critical crack tip opening displacement $CTOD_C$, critical crack length to depth ratio, the cohesive fracture toughness and the double-K fracture parameters were calculated using the above mentioned test data and are presented in figures 7 and 8 as the variation in initiation nd unstable fracture toughnesses.

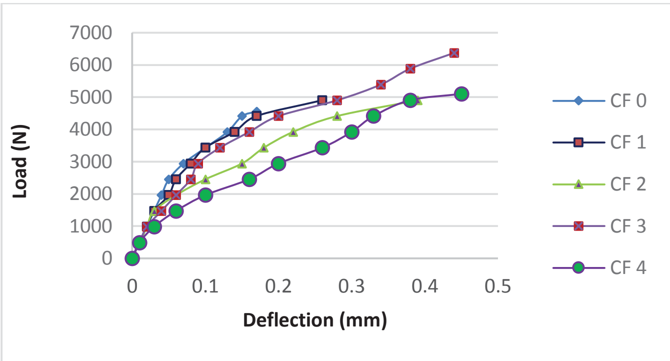

Fig 4 Load –Deflection behaviour of concrete beams

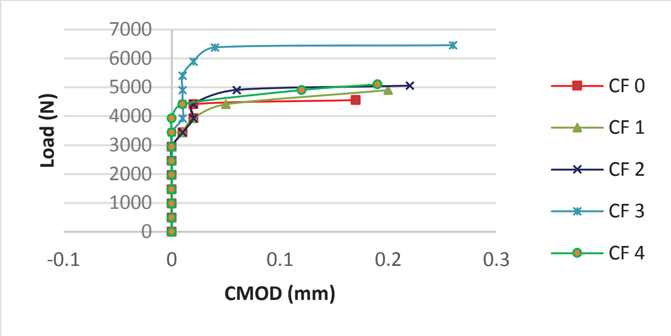

Fig 5 Load-CMOD curve of FRC beams

TABLE 5 FRACTURE PARAMETERS OF FRC BEAMS

MIX	Fracture Energy (N/m)	Characteristic Length (mm)	Fracture Toughness (MPa√m)
CF 0	74.36	148.42	1.59
CF 1	112.88	189.03	1.71
CF 2	215.45	357.56	1.76
CF 3	415.39	591.00	2.24
CF 4	260.85	439.65	1.78

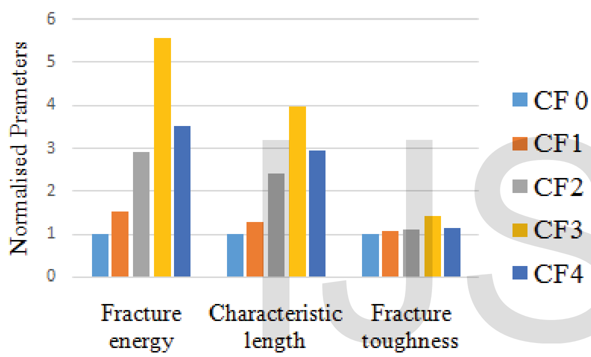

Fig 6 Normalised graph of variation of fracture parameters of FRC beams

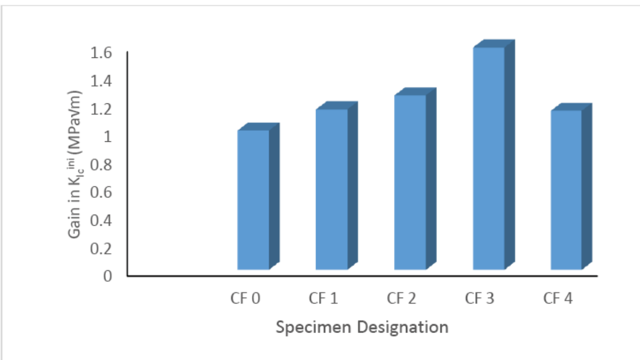

Fig 7 Comparison of Initiation Fracture Toughness of various mixes

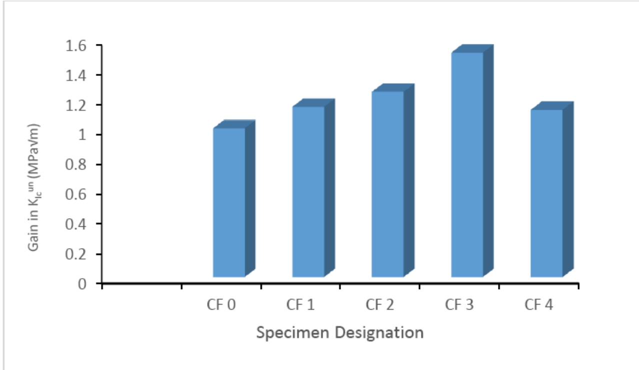

Fig 8.7Comparison of Unstable Fracture Toughness of various mixes

Based on the study it was observed that, the addition of steel fibres affects the properties of fresh concrete and demand use of superplasticizer to maintain the workability within a limit. Hardened properties of FRC showed considerable increase with addition of fibre and the increase was proportionate to the fibre content upto a limit and then decreased. This can be justified by the poor workability of the mix with increase in percentage of fibre which cancels out the bridging effect of fibres and brings down the mechanical properties. Addition of fibre modified the matrix characteristics and increased the bond strength.

It was observed that there is a substantial increase in the load carrying capacity and the fracture parameters of FRC beams compared to plane concrete beams. Fibre bridging action and crack arresting property increased the load carrying capacity of the specimens.

All the mechanical and fracture properties were found to be maximum for a volume fraction of 0.75%, Just after the first crack load, greater deflection occurred in most of the beams which can be attributed to the reduction in stiffness.

V CONCLUSIONS

Normal concrete mix of M 30 grade was prepared for the present investigation. Experimental studies were focused on the effect of steel fibre content on the fresh and hardened properties of concrete. From the results obtained the following conclusions were drawn**:**

- Addition of steel fibres in concrete mix improved all the hardened properties
- With the addition of fibre the workability was reduced considerably and observed to be minimum for a volume fraction of 1%.
- The maximum gain factor in the fracture parameters namely fracture energy, characteristic length and fracture toughness were 5.59, 3.98 and 1.41 respectively and corresponds to fibre volume fraction of 0.75%.

- Both load carrying capacity and ductility of concrete improves with addition of fibre.
- The optimum percentage of steel fibre in concrete both in terms of mechanical and fracture properties was found to be 0.75% by volume of concrete.

- Both the unstable fracture toughness and initiation fracture toughness of plain concrete is slightly lower than those of fibre reinforced concrete, which means the ability of concrete to resist crack is weaker than that of fibre reinforced concrete.
- The initial cracking load, ultimate failure load, initial fracture toughness, and unstable fracture toughness exhibit an increasing tendency with the increase in fibre content upto a limit (0.75 percent) and then falls.

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