

Study on Fracture Parameters of Bacterial Concrete

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ABSTRACT—In the study a comparison of fracture parameters of the bacterial concrete and conventional concrete is conducted. In order to investigate the fracture behavior the concrete beams of 500mm × 100mm × 100mm with 2mm wide notch of different notch depth were cast. Fracture parameters considered are Stress Intensity Factor (K), Fracture Energy (G_f), Crack Mouth Opening Displacement, Energy Release Rate (G) and Brittleness Number (S). The experimental results are compared with analytical results obtained by developing finite element model of the beams using ANSYS 12.0 of both conventional and bacterial concrete. The deflection obtained by the bacterial concrete is less than that of conventional concrete and the fracture is less in case of bacterial concrete because of the microbiologically induced calcite (CaCO₃) precipitation

Keywords—Bacterial Concrete, Bacillus subtilis, Stress Intensity Factor, Fracture Energy, Crack Mouth Opening Displacement, Energy Release Rate, Brittleness Number

1. Introduction

1.1 Fracture Mechanics

Cracking is an essential feature of the behaviour of concrete structures. Even under service loads, concrete structures are normally full of cracks. Clearly, cracking should be taken into account in predicting ultimate load capacity as well as behaviour in service. Fracture behaviour can be classified into three basic types, each associated with a local mode of deformation. In the field of fracture mechanics only mode I is of major interest because Mode II and III have been relatively less important in fracture testing and application except for testing of adhesive joints. Shailendra Kumar and S.V. Barai (2012) [4] have studied size-effect of fracture parameters for crack propagation in concrete. W C Tang, R V Balendran and A Nadeem (2005) [6] have studied the residual mechanical and fracture properties of HPC after exposure to elevated temperatures.

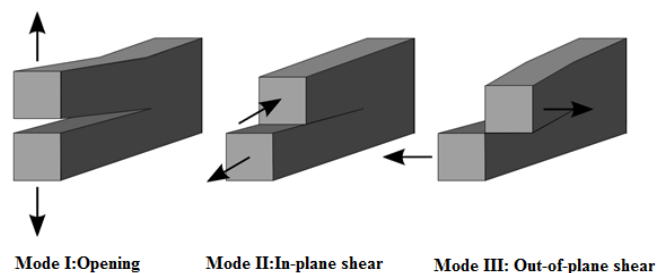


Fig.1. Modes of Fracture

1.2 Fracture Parameters

Some typical fracture parameters of interest are

1.2.1 Stress Intensity Factor

$$\text{Stress Intensity Factor, } K = \sigma_N \sqrt{(\pi a)} f_1(\alpha) \quad (1)$$

1.2.2 Fracture Energy

$$\text{Fracture energy } G_f = \frac{W}{A_s} \quad (2)$$

1.2.3 Crack Mouth Opening Displacement

$$CMOD = \frac{4a \times \sigma_N \times U(\infty)}{E'} \quad (3)$$

1.2.4. Energy Release Rate

Energy release rate, $G = \frac{K^2}{E'}$ (4)

1.2.5. Brittleness Number

Brittleness Number, $S = \frac{K}{\sigma_N \times \sqrt{d}}$ (5)

Where σ_N = nominal failure stress = $\frac{6P}{bd}$
 P = maximum load
 d = depth of beam
 a = critical crack length at peak load
 $f_1(\alpha) = \frac{[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{[\sqrt{\pi}(1+2\alpha)(1-\alpha)^{3/2}]}$
 $\alpha = \frac{a}{d}$

$W = P \times \text{deflection}$

$A_g = \text{Area of fracture} = a \times d$

$E' = \frac{E}{(1-\nu^2)}$; for plane strain

ν = Poisson's Ratio

$U(\alpha) = \frac{1.021 - (0.760\alpha)}{(1 - 2.149\alpha + 1.162\alpha^2)}$

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

2. Fracture Parameter Study

2.1. Experimental Setup

BEAM1 to BEAM4 are specimens of nominal M30 grade concrete mix and BAC1 to BAC4 are specimens of bacterial concrete with 10^5 cells/ml concentration. Bacillus subtilis bacteria are used to make bacterial concrete. All the beams had size 500mm×100mm×100mm. The beams were tested for standard bending using UTM (Fig.2) and the deflection of the centrally loaded beam was measured by using a deflectometer. Load and displacement data were recorded simultaneously before peak load being reached. At frequent intervals of loading the crack length was measured. Also the maximum deflection and crack length were measured. Crack patterns obtained from the experiment is shown in Fig.3 and load deflection curves are shown in Fig.4 and Fig. 5



Fig.2. Bending Test on Beam



Fig.3 Crack Pattern in Beams

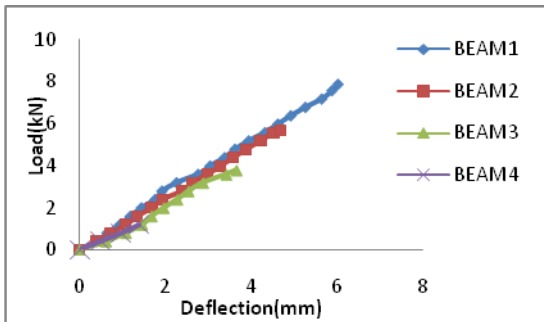


Fig.4 Load Deflection curve (Conventional Concrete)

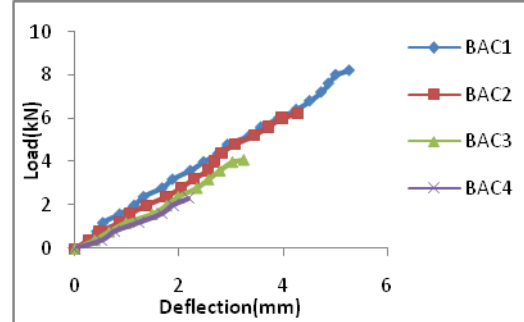


Fig.5. Load Deflection curve (Bacterial Concrete)

2.2 Calculation of Fracture Parameters

The calculations are made according to the preliminary details and summarised in Table 1

Table 1. Results of experimental work

Parameters	BEAM1	BEAM2	BEAM3	BEAM4	BAC1	BAC2	BAC3	BAC4
Notch Depth(mm)	-	10	20	30	-	10	20	30
P (kN)	7.9	5.7	3.8	1.8	8.2	6.2	4.1	2.3
Max Deflection(mm)	6.02	4.68	3.66	2.18	5.28	4.28	3.24	2.18
Crack Length(mm)	89	81	63	59	90	82	64	60
K(MPa√mm)	843.25	266.17	64.62	26.141	1011.1	314.18	72.7	34.7
G_f (N/mm ²)	0.0534	0.0329	0.022	0.00665	0.0481	0.0324	0.0207	0.0084
CMOD(mm)	2.58	0.717	0.10	0.037	2.39	0.724	0.096	0.042
G(N/mm)	24.63	2.45	0.144	0.024	29.19	2.82	0.151	0.034
S	17.79	7.78	2.83	2.42	20.55	8.44	2.96	2.51

3. Numerical Analysis

3.1. ANSYS Modelling

The two main aspects of this procedure are as follows

3.1.1. Modelling the Crack Region

The 2D concrete beam having original dimension of 500mm × 100mm was modelled in ANSYS 12.0. The most important region in a fracture model is the region around the edge of the crack. The edge of the crack is referred as a crack tip in a 2D model and a crack front in a 3D model. The recommended element type for 2D models is 8 node PLANE 183 elements. The model was meshed as triangular mapped elements. The support conditions provided are simply supported with an effective span of 400mm. This model was analysed as static, linear elastic, homogeneous material with modulus of elasticity of 28226 N/mm² for conventional concrete and 34221 N/mm² for bacterial concrete and Poisson's ratio, $\nu = 0.15$

3.1.2. Analytical Results

The beam was analysed as using ANSYS 12.0 for the ultimate load determined from experimental investigations. A modulus of elasticity of 28226 N/mm² and 34221 N/mm² for conventional concrete and

bacterial concrete respectively and poisons ratio of 0.15 is applied to the material. The models were meshed as triangular mapped elements. The support conditions provided are simply supported with an effective span of 400 mm. Fig. 6 and Fig.7 show the deformed shape of beams without notch (control mix and bacterial concrete) along with their midspan deflections. Similarly deformations of other beams with notch are found out and results are shown in the Table 2.

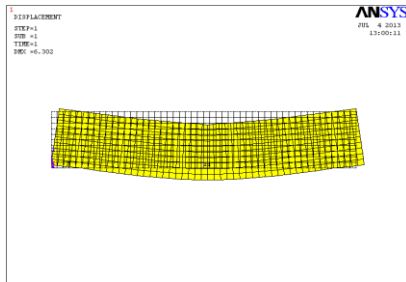


Fig.6. Deformed shape of BEAM1

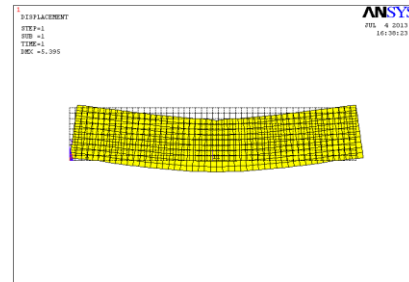


Fig.7. Deformed shape of BAC1

In LEFM the stress intensity factor ‘K’ is the relevant fracture parameter to characterize the stress and strain fields around the crack tip, as originally described by Irwin. Under mode I (crack opening) loading ‘ K_I ’ may be compared with the material’s fracture toughness ‘ K_{IC} ’ in order to predict the stability of crack. To compute K_I with the finite element method (FE) quarter- point crack-tip elements were introduced by Barsoum.

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**** CALCULATE MIXED-MODE STRESS INTENSITY FACTORS ****
ASSUME PLANE STRAIN CONDITIONS
ASSUME A HALF-CRACK MODEL WITH SYMMETRY BOUNDARY CONDITIONS <USE 3 NODES>
EXTRAPOLATION PATH IS DEFINED BY NODES:          47      52      56
WITH NODE          47 AS THE CRACK-TIP NODE

USE MATERIAL PROPERTIES FOR MATERIAL NUMBER      1
EX =      28226.      NUXY =      0.15000      AT TEMP =      0.0000

**** KI =      837.02      ,      KII =      0.0000      ,      KIII =      0.0000      ****
    
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Fig.8. Stress Intensity Factor of BEAM1

Fig.8 shows stress intensity factor of BEAM1. Similarly the K values of other beams were found out and listed in the Table 2

Table 2. Results of analytical work

Parameters	BEAM1	BEAM2	BEAM3	BEAM4	BAC1	BAC2	BAC3	BAC4
Notch Depth(mm)	-	10	20	30	-	10	20	30
P (kN)	7.9	5.7	3.8	1.8	8.2	6.2	4.1	2.3
Max Deflection(mm)	6.302	4.987	3.724	2.284	5.395	4.323	3.314	2.407
Crack Length(mm)	89	81	63	59	90	82	64	60
K(MPa√mm)	837.02	239.22	52.072	21.655	1006.8	295.58	64.543	32.781
G_f (N/mm ²)	0.0559	0.035	0.022	0.0069	0.0491	0.0327	0.0212	0.0092
CMOD(mm)	2.58	0.717	0.10	0.037	2.39	0.724	0.096	0.042
G(N/mm)	24.26	1.98	0.094	0.0162	28.95	2.496	0.119	0.0306
S	17.66	6.99	2.28	2.00	20.46	7.95	2.62	2.37

4. Results and Discussions

4.1 Fracture Parameter Study of Concrete

4.1.1. Comparison of Experimental and Analytical Results of Conventional and Bacterial Concrete

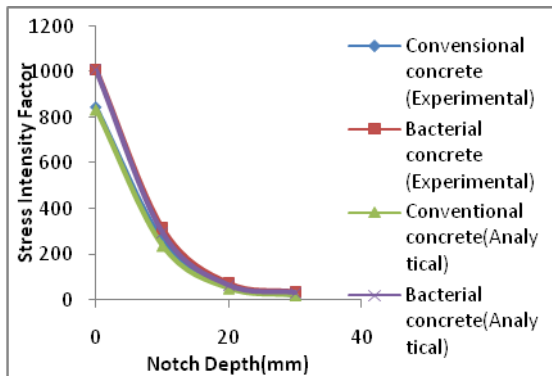


Fig. 9. Relation of Stress Intensity Factor with Notch Depth

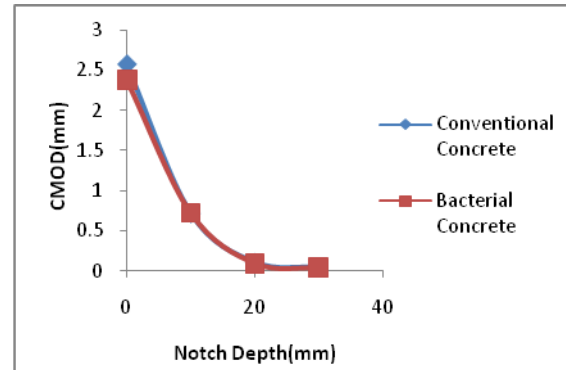


Fig.11. Relation of CMOD with Notch Depth

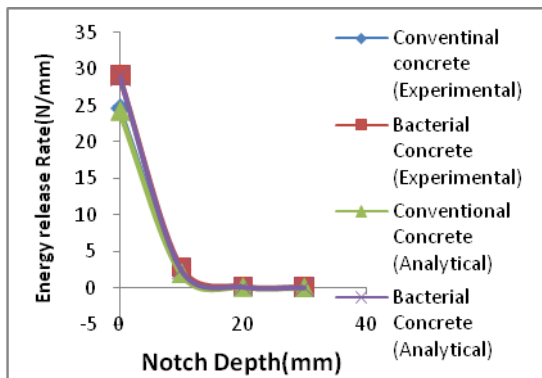


Fig.10. Relation of Energy Release Rate with Notch Depth

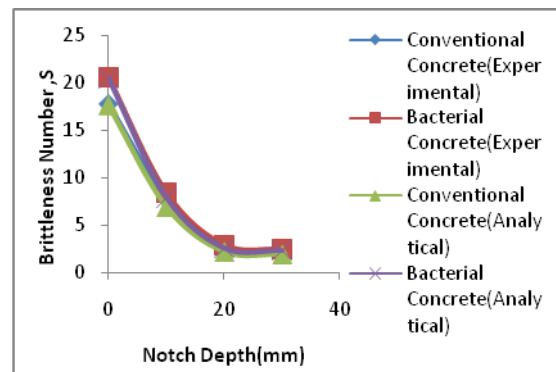


Fig.12. Relation of Brittleness Number with Notch Depth

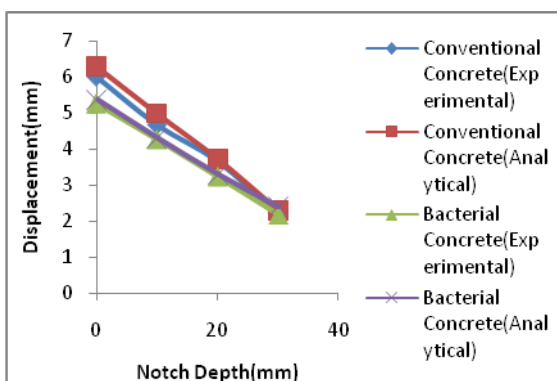


Fig.13. Relation of Displacement with Notch Depth

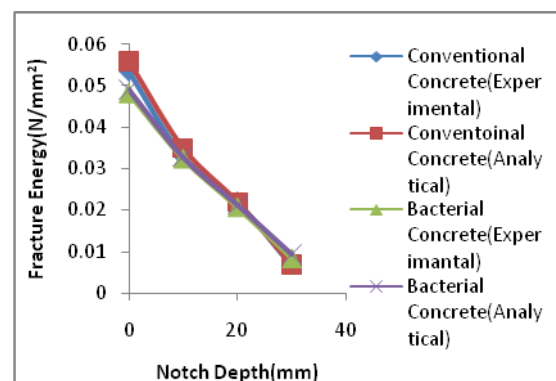


Fig.14. Relation of Fracture Energy with Notch Depth

- Stress intensity factor depends on critical load which in turn depends on the notch depth of specimen and is found to be reducing on increasing the notch depth. Also stress intensity factor for conventional concrete is less than that of bacterial concrete.

- Energy release rate is also found to be reducing with higher notch depths for both conventional and bacterial concrete. The experimental values obtained are higher than the corresponding analytical values. The energy release rate for conventional concrete is less than that of bacterial concrete.
- The values of CMOD are also decreasing with notch depths for conventional and bacterial concrete. CMOD is greater in the case of conventional concrete compared to bacterial concrete.
- Brittleness Number is a parameter which governs notch sensitivity. The brittleness number of conventional concrete is less than that of bacterial concrete and the values obtained by experimental investigation is slightly higher than the corresponding analytical values in both cases. It depends directly on stress intensity factor and hence indirectly depends on the notch depths.
- The values of the deflection of finite element model are higher than that of experimental values. Also deflection of conventional concrete is higher than that of bacterial concrete.
- The values of fracture energy are also decreasing with notch depths. The values of the fracture energy of finite element model are higher than the experimental values and fracture energy is higher for conventional concrete compared to bacterial concrete.

From the above figures it is clear that as the notch depth increases fracture parameters like critical stress intensity factor, brittleness number, fracture energy and energy release rate decreases. Also critical stress intensity factor, brittleness number and energy release rate is higher in case of bacterial concrete and fracture energy is higher in case of conventional concrete.

5. Conclusions

In conclusion of the present work, it may be emphasised that fracture mechanics offer a realistic and consistent approach to the analysis of cracking in concrete structures. From the experimental investigations, various fracture parameters such as critical stress intensity factor, crack mouth opening displacement, fracture energy, brittleness number and energy release rate of bacterial concrete and conventional concrete are evaluated. From the results the following conclusions can be made.

- ❖ Fracture in concrete is due to rupture of the interface paste and aggregate, and the presence of pores. Since the pores in bacterial concrete are less than that of conventional concrete due to the action of bacteria, fracture is less as compared to conventional concrete.
- ❖ Test results indicated that fracture parameters calculated was proportional to the critical load.
- ❖ The average deflections obtained for conventional concrete is greater than bacterial concrete. From the analytical results it is found that around 16.81% greater deflection is obtained in conventional concrete as compared to bacterial concrete. But in the case of experimental work it is around 14.02% which may be due to manufacturing defects.
- ❖ Since the stress intensity factor of bacterial concrete is higher, the stress required for the first fracture on bacterial concrete is higher than that of conventional concrete. So the fracture is less in bacterial concrete.
- ❖ Stress intensity factor can be used to rank materials within a similar yield strength range.
- ❖ Since fracture energy is less in bacterial concrete, energy required to propagate the fracture is less for bacterial concrete. So bacterial concrete is brittle as compared to conventional concrete.
- ❖ Since the brittleness number of bacterial concrete is less, notch is more sensitive than conventional concrete.
- ❖ Energy release rate is more in bacterial concrete. So more energy is released for unit increase in area during crack growth for bacterial concrete.
- ❖ The failure is due to formation of flexural cracks developed in beams. No shear cracks were visible.
- ❖ The critical load of the beam depends on the size of the notch and the value decreased with increase of notch depth in both type of concrete beams. Bacterial concrete has higher critical load compared to conventional concrete.

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