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# ANALYSIS OF QUASI-BRITTLE FRACTURE AND CRITICAL CTOD OF HIGH VOLUME FLYASH CONCRETE NOTCHED BEAMS

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## ABSTRACT

Emission of $CO_2$ into atmosphere has been the main reason behind global warming. Production of one tonne of cement approximately emits one tonne of $CO_2$, the Greenhouse gas and major culprit for global warming, into atmosphere. Global warming is a great concern to humankind, and Scientists throughout the world do extensive researches to find out alternate green materials that could help in reducing the effect of global warming. Fly ash, once considered a waste material, has found usefulness in replacing cement up to 60% and experiments are conducted to determine the fracture parameter of plain cement concrete (OPC) and high volume fly ash concrete (HVFAC). The Beams of size 1200mm long x 100mm wide x 200mm deep are cast for the experiment. The critical Crack Tip Opening Displacement for plain cement concrete (OPC) and high volume fly ash concrete (HVFAC) are determined. Four numbers of M30 grade concrete notched beam specimens are cast with OPC concrete as reference specimens and four specimens each for 50% and 60% replacement of cement with fly ash are also cast. All the beams are tested under three point loading until failure. The parametric study of notch to depth ratio is kept as 0.2 and 0.3. From the test results, the rupture load of the specimens decreased with the increase in fly ash content.

**Keywords:** Fly ash; high volume fly ash concrete; critical stress; fracture energy; CTOD; notched beam.

## 1. INTRODUCTION

In the past, studies have been extensively carried out on concrete about its phenomena like size effect and fracture process zone. It is well known that compressive strength of concrete is larger than its tensile strength and concrete being inherently weak in tension it has been used as compression member, in most of the structures. However, even though static tensile loads on concrete members are avoided, it is difficult to prevent concrete members from dynamic or impact tensile stresses.

In general, accurate measurement of tensile strength for brittle or quasi-brittle materials such as ceramics, rocks and concretes is difficult. Although many investigations, not only on

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impact compressive strength of concrete materials but also on their impact tensile strength have been reported, there does not exist a standard test for impact tensile strength of concrete. The field of fracture mechanics was developed by Griffith [1] to explain the failure of brittle materials. Linear elastic fracture mechanics (LEFM) predicts the rapid propagation of a microcrack through a homogeneous, isotropic, linear-elastic material.

The inapplicability of LEFM to laboratory-sized concrete specimens is the result of the heterogeneity inherent in the concrete. This heterogeneity results in a relatively large fracture process zone that results in a substantial amount of crack growth (crack extension) preceding the critical (maximum) load and is responsible for the strong dependence of $K_{IC}$ on the size and geometry of test specimens. Pre critical crack growth (crack extension) for a notched beam [2] test is shown in Figure 1.

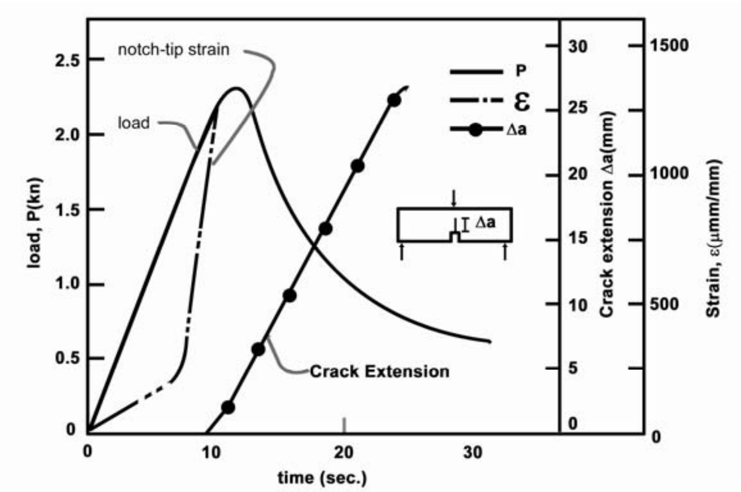


Figure 1. Pre critical crack growth (John and Shah [2])

The fracture process zone in concrete is substantially different from the plastic zone in metals. For metals, the plastic zone is defined as a zone where the material has yielded ahead of the crack. LEFM is based on the assumption that the plastic zone is substantially smaller than the dimensions of the test specimen. Laboratory-sized specimens satisfy this criterion for metals. For concrete, Bazant [3] stated that the fracture process zone has negligible effect if the cross sectional dimension of a member is at least 100 times the maximum aggregate size, which would lead to prohibitive size requirements. In view of these specimen size requirements, when LEFM is not applicable for many of the fracture tests that have been conducted on concrete.

Hillerborg et al. [4] developed the fictitious crack model, which has been used for finite element analysis of concrete fracture. Figure 2 illustrates the basic concept of the approach. For a beam in flexure, the left-side portion of Figure 2 shows the variation in stress along the crack path, reaching a peak at the fictitious crack tip, where the stress is equal to the tensile strength of the concrete, and the CTOD is zero. Moving to the left of the peak, the stress drops as the crack opens, with the real crack ending at the point where the stress across the crack has dropped to zero. If the shape of this softening curve is assumed to be fixed, then the fracture of the concrete is completely characterized by G*f*.

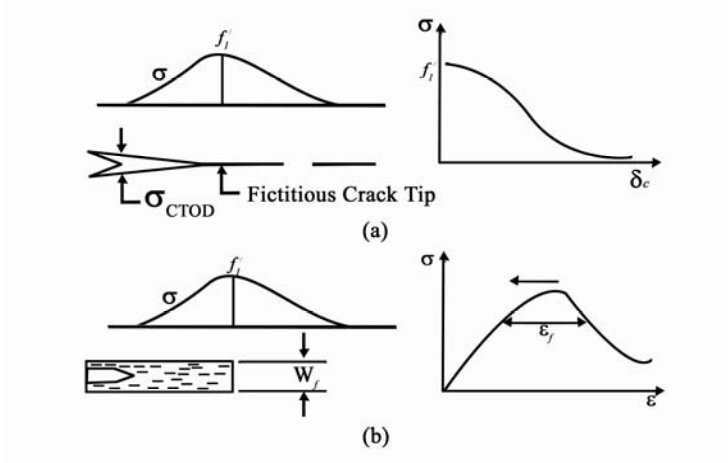


Figure 2. (a) Fictitious crack model; (b) Crack band model

Bazant and Oh [5] developed a crack band model to account for the fracture process zone in concrete in a smeared manner through the introduction of a strain-softening constitutive relation.

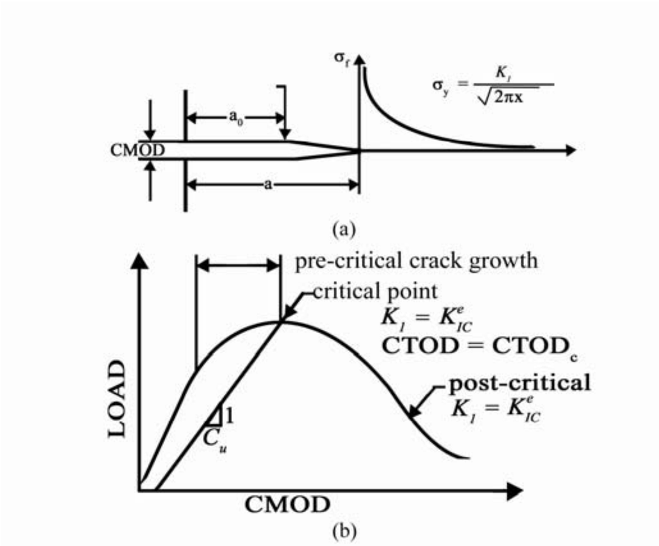


Figure 3. Effective Griffith crack and (b) Typical plot of load versus CMOD ([2])

In this model, the crack front has a width of $W_c$ that is equal to the width of a single finite element. The crack band model is designed to produce a response in a finite element model that essentially matches the results of the fictitious crack model. In the crack band model, the crack is represented by an equivalent change in material properties within an element. When used in conjunction with the two material properties used for the fictitious crack model, $G_f$ and, the two procedures produce nearly identical results of Leibengood Darwin, and Dodds [6].

Jenq and Shah [7] proposed a method to determine the effective crack length, which is then used to calculate a critical stress-intensity factor $K_{IC}$ and a critical crack tip opening displacement (CTOD). Figure 3 illustrates the effective crack-length concept. The effective crack length concept itself is the sum of a measurable crack visible on the side of a specimen plus the additional crack length represented by the fracture process zone. The effective crack length is evaluated using the unloading compliance measurement $C_u$ of the load-CMOD curve at the point of maximum load, as shown in Fig 3. Jenq and Shah found that the effective crack length calculated from compliance measurements is the same as that obtained using LEFM and assuming that CTOD has a critical value, which was found to be independent of the size and geometry of the beams tested and may be considered to be a valid fracture parameter.

**Size effect of fracture:**

The effect of structural size on the fracture of concrete is perhaps the most compelling reason for using fracture mechanics. For blunt fracture (as occurs in a crack with a diffuse fracture process zone in materials such as concrete), the total potential energy release caused by fracture in a given structure depends on the length of the fracture and the area traversed by the fracture process zone so that the size of the fracture process zone is constant and independent of the size of the structure. Dimensional analysis shows that the structural size effect for geometrically similar specimens or structures is governed by the simple relation, Bazant, et al. [8].

$$\sigma_N = \frac{Bf_t^{'}}{\sqrt{(1 + d/d_o)}} \tag{1}$$

where

Nominal stress at failure

$$\sigma_N = \frac{p}{bd}$$

P = maximum load at failure
b = thickness of specimen
d = depth of specimen

The applicability of LEFM models to concrete behaviour was made experimentally and it was concluded that the Griffith concept of a critical strain-energy release is convenient. Some observations on concrete behaviour that allow the use of LEFM are

1. Fracture of concrete tends to be brittle.
2. The strength of concrete depends on the loading rate.
3. The tensile strength of concrete is about 1/10 of its compressive strength.
4. Concrete and mortar are notch-sensitive.

Evaluation of $K_{IC}$ and $G_{IC}$ for concrete:

The critical stress intensity factor $K_{IC}$ is used to express the fracture toughness of concrete. $K_{IC}$ represents a measure of how much and how far the local stress field is altered. Equation (2) shows the mathematical expression of $K_{IC}$.

$$K_{IC} = g(\alpha).\sigma_c\sqrt{\pi.a_c} \tag{2}$$

The function g (α) depends on the geometry of the specimen especially loading arrangement and is provided by stress analysis, $a_c$ is the critical notch depth and $\sigma_c$ is the critical stress of the notched section. Similarly, $G_{IC}$ is the critical energy release rate usually used as a LEFM parameter to express the fracture toughness. $G_{IC}$ can be estimated using the plane strain relation shown in Eq. (3) where both $K_{IC}$ and E are determined experimentally.

$$G_{IC} = K_{IC}^{٢}\frac{(١ - \nu^{٢})}{E} \tag{3}$$

## 2. EXPERIMENTAL PROGRAM

*2.1 Casting of Beam Specimens*

In this experiment, twenty four numbers of PCC beams of 1200mm long, 100mm wide and 200mm deep with the variation percentage replacement of fly ash by weight to ordinary Portland cement were cast and cured for 28 days. Experiments were conducted on M30 grade concrete beam specimens. The material properties of the aggregate were found out as per the specifications in IS 383:1970[9]. The course aggregate from granite materials with particle size between 12.5mm was used. The fine aggregate was from river sand with maximum size of 4.75mm and conforming to zone II as per IS 383 – 1970. The specific gravity of fine aggregate and coarse aggregate were found to be 2.56 and 2.74 respectively. The beams were cast as per IS 10262:1982[10] with w/c ratio being 0.38. Four numbers of beams were cast for each parameter as detailed below.

OPC concrete beam specimens

HVFAC beams with 50% replacement of cement by fly ash.

HVFAC beams with 60% replacement of cement by fly ash.

The Specimens cast and being cured with wet gunny bags are shown in Figure 4.

Figure 4. Specimens cast and being cured with wet gunny bags

*2.2 Pre-cracking of Specimens*

In major structures like nuclear plant, dams etc., microscopic analysis of the concrete is important since the unknown existing crack can lead to aggressive disaster. In concrete, flaws are not avoidable but the knowledge on critical size of crack is mandatory in order to prevent sudden failure. Even a small crack can propagate and become critical during its life period that leads to catastrophic failures. The micro structural study of the concrete is needed to avoid the major damages. So crack study of the concrete is needed to avoid many structural collapses. To study into the propagation of crack, an initial crack (pre-crack) of 40 mm and 60 mm in length and 3 mm thick was made at the mid span of beam as single edged notched beam by using marble cutter. The notch to depth ratio was kept as 0.2 and 0.3.The specimens with pre-crack at centre of beams are shown in Figure 5.

Figure 5.The specimens with pre-crack

*2.2 Test set up and instrumentation*

The beams were tested in loading frame by three point loading method. The load was applied gradually using hydraulic jack of capacity 100 kN. The load was increased gradually with an increment of 0.5 kN. By using CMOD gauge, the readings were noted at the crack mouth at every incremental increase of load. Two digital dial gauges were used for monitoring deflection at one third and two third of span. Test set up and instrumentation are shown in Figure 6.


Figure 6. Test setup and instrumentation

## 3. RESULTS AND DISCUSSIONS

*3.1 Central Deflection of specimens with Notch to Depth Ratios of 0.2 and 0.3*

The specimen after failure is shown if Figure 7. The central deflection of specimens with notch to depth ratio 0.2 and 0.3 is shown in Table 1.


Figure7. Specimen (typical) after failure

Table 1: Central deflection of Specimens with notch to depth ratios of 0.2 and 0.3

| **Load 'kN'** | **Control (0.2)** | **Control (0.2)** | **50% Flyash (0.2)** | **50% Flyash (0.2)** | **60% Flyash (0.2)** | **60% Flyash (0.2)** | **Control (0.3)** | **Control (0.3)** | **50% Flyash (0.3)** | **50% Flyash (0.3)** | **60% Flyash (0.3)** | **60% Flyash (0.3)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 2.5 | 2.45 | 0.36 | 1.38 | 0.26 | 1.1 | 0.62 | 6.08 | 0.58 | 0.18 | 0.12 | 1.1 |
| 2 | 2.74 | 2.78 | 0.88 | 1.68 | 1.42 | 2.28 | 0.62 | 6.92 | 1.24 | 0.2 | 0.24 | 2.28 |
| 3 | 2.92 | 2.97 | 1.38 | 1.88 | 1.52 | 2.74 | 0.64 | 8.04 | 2.16 | 0.36 | 0.30 | 2.74 |
| 4 | 3.16 | 3.18 | 1.66 | 2.06 | 1.6 | 3.8 | 0.66 | 8.56 | 3.5 | 0.64 | 0.38 | 3.8 |
| 5 | 3.2 | 3.23 | 2.58 | 2.18 | 2.1 | 4.44 | 0.68 | 8.88 | 4.22 | 1.2 | 0.44 | 4.44 |
| 6 | 3.2 | 3.23 | 3.54 | 2.28 | 2.9 | 4.80 | 1.34 | 9.16 | 4.5 | 1.54 | 0.56 | 4.80 |
| 7 | 3.34 | 3.34 | 3.7 | 2.4 | 3.42 | 5.04 | 1.7 | 9.3 | 5.32 | 1.86 | 1.88 | 5.04 |
| 8 | 3.56 | 3.58 | 3.88 | 2.5 | | | 2.42 | 9.4 | - | 2.04 | | |
| 9 | 3.66 | 3.69 | | | | | 2.88 | 9.48 | | | | |
| 10 | 3.88 | 3.88 | | | | | 3.12 | 9.48 | | | | |
| 11 | - | - | | | | | - | 9.48 | | | | |
| 12 | - | - | | | | | - | 9.48 | | | | |
| 13 | - | - | | | | | - | 9.48 | | | | |
| 14 | - | - | | | | | - | 9.48 | | | | |
| 15 | - | - | | | | | - | 9.48 | | | | |

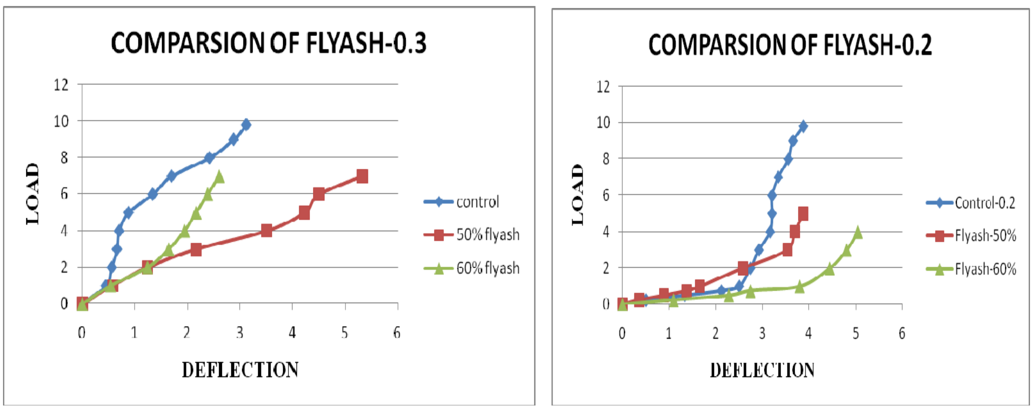


Figure 8. Comparison of load vs deflection curves of specimens with notch to depth ratio 0.3 and 0.2

### *3.2 Critical Crack Tip Opening Displacement (CTOD)*

The critical opening displacement of the original pre-crack tip, $CTOD_C$, is calculated from the maximum load registered and the value of the effective critical crack length, which is the initial notch depth plus the stable crack growth at peak load. The critical crack tip opening displacement is then calculated using the equation.

$$CTOD_c = \frac{6(P_c + 0.5\ W_h)Sa_c g_2(a_c/b)}{Eb^2 t}\left[(1-\beta)^2 + \left(1.081 - 1.149 - 1.149\ \frac{a_c}{b}\right)(\beta_o - \beta o^2)\right]^{\frac{1}{2}}$$

Table 2: Critical CTODc for 28days specimen

| **S. No** | **Specimen** | **Notch to depth ratio** | **Ultimate load in kN** | **$CTOD_c$** |
|---|---|---|---|---|
| 1. | Control specimen | 0.2 | 9.8 | 0.082 |
| 2. | Control specimen | 0.2 | 9.41 | 0.083 |
| 3. | Control specimen | 0.3 | 15.2 | 0.075 |
| 4. | Control specimen | 0.3 | 9.0 | 0.045 |
| 5. | 50% replacement by Flyash | 0.2 | 7.81 | 0.0694 |
| 6. | 50% replacement by Flyash | 0.2 | 7.63 | 0.0678 |
| 7. | 50% replacement by Flyash | 0.3 | 6.48 | 0.0331 |
| 8. | 50% replacement by Flyash | 0.3 | 6.0 | 0.0307 |
| 9. | 60% replacement by Flyash | 0.2 | 6.87 | 0.061 |
| 10. | 60% replacement by Flyash | 0.2 | 6.81 | 0.060 |
| 11. | 60% replacement by Flyash | 0.3 | 6.67 | 0.034 |
| 12. | 60% replacement by Flyash | 0.3 | 6.74 | 0.034 |

Where,

$$g_2\left(\frac{a_c}{b}\right) = \frac{1.99 - (a_c/b)(1-a_c/b)[2.15 - 3.93a_c/b + 2.70(a_c/b)^2]}{\sqrt{\pi}(1+2a_c/b)(1-a_c/b)^{\frac{3}{2}}}$$

$\beta_o = a_o/a_{c.}$
$P_C$ = Peak load.
$W_{ho}$ = self weight of the beam.

The evaluation of the critical value (δ) is done by using Critical Crack Tip Opening Displacement (CTOD) for high volume fly ash concrete specimens. CTOD measures the resistance of a material to propagation of a crack. CTOD Test is used to determine the fracture mechanics properties of ductile materials and can be thought of as the simulated opening of a pre-existing fatigue crack prior to fracture. The main parameters affecting the stiffness of the cracked concrete elements are Modulus of elasticity and effective moment of inertia [11].

### *3.3 Discussion on Test Results*

It is observed that strength increased with increase in load in control specimens when compared to specimens manufactured with 50% and 60% replacement of cement by flyash. Ductility and stiffness are higher in specimens manufactured with 60% replacement of cement by flyash. In strength point of view, there is no significant change in 50% and 60% cement replaced specimens. For Control specimen, stiffness is much greater than that of 50% and 60% cement replaced specimens. Deflection is more in specimens with 60% substitution of flyash when compared to control and 50% substitution of fly ash.

## 4. CONCLUSION

From the extensive study, the following conclusions are drawn:

1. From the test results, it is noted that rupture load of the specimens decreased with an increase in fly ash. On comparing with control specimen, the specimens with 60% cement replacement and a/w = 0.2 have been observed to behave in brittle manner leading to sudden failure.
2. From load Vs CMOD (Crack Mouth Opening Displacement) graph, it is found that the CMOD increases with increase in percentage of fly ash added. By increasing notch to depth ratio Critical CTOD is decreasing in all specimens.
3. The maximum rupture load of control specimen, specimens with 50% and 60% replacement of cement by fly ash are 9.8 kN, 7.3 kN and 6.67 kN, respectively.
4. It has been observed that fracture process zone (FPZ) plays an important role in the fracture analysis of quasi-brittle materials like concrete.
5. The present study shows that specimen boundary influences the fracture behavior of quasi-brittle materials, which actually leads to the apparent specimen size effect.

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