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DETERMINATION OF FRACTURE PARAMETERS AND THE STUDY OF MIXED MODE CRACK PROPAGATION IN HIGH PERFORMANCE CONCRETE

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ABSTRACT

In the paper an experimental investigation was carried out to study the Mixed Mode Crack Parameters of High Performance Concrete beams subjected to three point bending. The cubes and cylinders will be tested on Universal Testing Machine to find out the Compressive strength and split tensile strength. For High Performance Concrete, the partial replacement of cement with Ground Granulated Blast Furnace Slag (GGBS) and sand with the ROBO sand (crusher dust) will be taken. In this investigation the study of Mixed Mode Crack Propagation in High Performance Concrete beams with eccentrically placed notch at a distance (L/4) from mid span of the beam under a three point bending test i.e., with a central point load will be done. In High Performance Concrete, the Variation of volume fractions of Ground Granulated Blast furnace Slag (GGBS) and ROBO sand in the casting of beams will carried out to find the Mixed Mode Fracture Parameters. Fracture parameters like Fracture energy $\mathbf{G_f}$, Cohesive fracture process Zone $\mathbf{C_F}$, Stress intensity factor K_I would be determined by using size effect method.

KEYWORDS: Crack parameter, concrete beam, concrete performance..

INTRODUCTION

Concrete structures are full of cracks. Failure of concrete structures typically involves stable growth of large cracking zones and the formation of large fractures before the maximum load is reached. Concrete cracks; to the average person this is common knowledge. It becomes obvious as one drives to work on the freeway, walks to the office on city sidewalks, and looks closely at the office structure as they make their way through the doors. This is because cracking in ceramic composites, such as concrete, is inevitable due to their brittle nature. However, most people may not know that although these structures have cracks they usually have not failed. This is due to strengthening mechanisms within the material, to be discussed, and the ability of the reinforcement to carry the load, even after the formation of cracks. It is for these reasons that current design practices allows for some amount of cracking in concrete structures (Wight and MacGregor 2009). As a means for design, fracture mechanics is a common method to analyze the failure of ceramic, steel, and polymer based materials (Anderson 2005). However, from a concrete design standpoint, the use of fracture mechanics is a relatively new concept. Even though fracture mechanics has been available since the 1950s, in its original form it was found to be not applicable to concrete structures. It wasn’t until the 1970s and 1980s that a valid formulation for concrete was available (Bazant and Planas 1998). One of the generally accepted reasons for using fracture mechanics is that strength based failure designs require modifications to account for the occurrence of premature failure, such as safety factors (Anderson 2005). Another example of a modification in design is the use of the Whitney stress block in the flexural design of concrete, in place of the more complicated softening behavior (Hawkins 1985). The use of fracture mechanics has the ability to account for effects that are not addressed in current design practices, to be discussed, by approaching the problem using energy criterion (Bazant and Planas 1998).

LITERATURE

In 2008 Rasmus Walter, John F. Olesen has studied on Cohesive mixed mode fracture modelling and experiments. A nonlinear mixed mode model originally developed by Wernersson [Wernersson H. Fracture characterization of wood adhesive joints. Report TVSM-1006, Lund University, Division of Structural Mechanics; 1994], based on nonlinear fracture mechanics, is discussed and applied to model interfacial cracking in a steel–concrete interface. The model is based on the principles of Hillerborgs fictitious crack model, however, the Mode I softening description is modified taking into account the influence of shear. The model couples normal and shear stresses for a given combination of Mode I and II fracture. An experimental set-up for the assessment of mixed mode interfacial fracture properties is presented, applying a bi-material specimen, half steel and half concrete, with an inclined interface and under uniaxial load. Loading the inclined steel–concrete interface under different angles produces load–crack opening curves, which may be interpreted using the nonlinear mixed mode model. The interpretation of test results is carried out in a two step inverse analysis applying numerical optimization tools. It is demonstrated how to perform the inverse analysis, which couples the assumed individual experimental load–crack opening curves. The individual load–crack opening curves are obtained under different combinations of normal and shear stresses. Reliable results are obtained in pure Mode I, whereas experimental data for small mixed mode angles are used to extrapolate the pure Mode II curve.

In 2008 Laura De Lorenzis has done his work on Modeling of mixed-mode debonding in the peel test applied to superficial reinforcements. His paper focuses on modeling of the interface between a rigid substrate and a thin elastic adherend subjected to mixed-mode loading in the peel test configuration. The context in which the investigation is situated is the study of bond between fiber-reinforced polymer (FRP) sheets and quasi-brittle substrates, where FRP sheets are used as a strengthening system for existing structures. The problem is approached both analytically and numerically. The analytical model is based on the linear-elastic fracture mechanics energy approach. In the numerical model, the interface is discretized with zero-thickness contact elements which account for both debonding and contact within a unified framework, using the node-to-segment contact strategy. Uncoupled cohesive interface constitutive laws are adopted in the normal and tangential directions. The formulation is implemented and tested using the finite element code FEAP. The models are able to predict the response of the bonded joint as a function of the main parameters, which are identified through dimensional analysis. The main objective is to compute the debonding load and the effective bond length of the adherend, i.e., the value of bond length beyond which a further increase has no effect on the debonding load, as functions of the peel angle. The detailed distributions of interfacial shear and normal stresses are also found.

In 2009 Matteo Bruggi has done modeling cohesive crack growth via a truly-mixed formulation. An alternative approach for cohesive crack growth in elastic media is proposed. Standard methods move from displacement-based formulations that are enriched to handle discontinuities in the inherently continuous displacement field. The herein adopted formulation is conversely based on a truly-mixed discretization that has stresses as main regular variables, while discontinuous displacements play the role of Lagrangian multipliers. The approach directly handles the analysis of propagating cohesive cracks in elastic media through the appropriate inclusion of interface energy terms that enrich the formulation when a crack is growing. In his work no edge element is introduced but simply the inherent discontinuity of the displacement field is taken advantage of. Furthermore, the continuity of traction vectors is imposed in an exact fashion within the formulation and not as an additional weak constraint, as classically done. The work has the main aim of investigating the features of the approach through numerical simulations that refer to well-known experimental results on concrete specimens. The capability of modeling size effect is firstly tested in case of a pure mode I growth. The accuracy of truly-mixed stress interpolation is also exploited to recover crack path and to handle energy dissipation in mixed mode simulations.

In 2009 Zihai Shi has done his work on Computer Program for Mixed-Mode Type Crack Analysis in Concrete Using EFCM. He focuses on a crack-analysis computer program, CAIC-M12.FOR, for mixed-mode crack analysis. The program CAIC-M12.FOR has been developed by extending the mode-I crack analysis program CAIC-M1.FOR, and except for the fracture mode involved, the main features, structure, and flow of the program are basically the same as those of CAIC-M1.FOR. It performs crack analysis of the mixed-mode type (mode I + mode II) in structural concrete. However, solving a mixed-mode crack problem requires additional operations of setting pairs of unit cohesive forces in the direction tangential to the crack surface, calculating sliding displacement and other coupled influence coefficients, and formulating the crack equation for mixed-mode fracture. Two types of shear-transfer model are employed in the program—the bilinear type and the trilinear type—and the variables are used to define these models. The chapter explains the formulation of the crack equation for mixed-mode fracture in matrix form, how the direction of shear force is determined based on the direction of crack surface sliding, and subroutines that have been added in CAIC-M12.FOR for mixed-mode crack analysis.

In 2009 Jeffery R. Roesler has done his work on a unified potential-based cohesive model of mixed-mode fracture. A generalized potential-based constitutive model for mixed-mode cohesive fracture is presented in conjunction with physical parameters such as fracture energy, cohesive strength and shape of cohesive interactions. He characterizes different fracture energies in each fracture mode, and can be applied to various material failure behavior (e.g. quasi-brittle). The unified potential leads to both intrinsic (with initial slope indicators to control elastic behavior) and extrinsic cohesive zone models. Path dependence of work-of-separation is investigated with respect to proportional and non-proportional paths—his investigation demonstrates consistency of the cohesive constitutive model. The potential-based model is verified by simulating a mixed-mode bending test.

EXPERIMENTAL PROGRAM

The experimental program was designed to study the stress intensity factor and fracture energy of plain-high performance concrete beams of size 75mm x 75mm x 350mm (Span is 300mm), 75mm x 150mm x 650mm (Span is 600mm) and 75mm x 300mm x 1250mm (Span is 1200mm) with eccentrically placed notch at a distance (L/4) from mid span of the beam under a three point bending test i.e., with a central point load. The influence of eccentrically placed notch at a distance (L/4) from mid span of the beam, the specimens on stress intensity and fracture energy was studied on beams of varying size effects with mix proportion (M30). This experimental program consists of three series of beams for each grade, namely small, medium, and large and having equal notch depth ratio (0.15).

3.1.Materials:

3.1.1Cement

Ordinary Portland cement conforming to IS 12269 – 1983 was used for the concrete mix and Specific gravity was found to be 3.5

3.1.2.Fine Aggregate

The fine aggregate (sand) used in the work was obtained from a nearby river course. The fine aggregate that falls in zone –II was used. The specific gravity was found to be 2.60.

3.1.3.Coarse aggregate

Crushed coarse aggregate of 20mm retained was used in the mix. Uniform properties were to be adopted for all the beams for entire work. Specific Gravity of coarse aggregate is 2.78.

3.1.4.Ground Granulated Blast Furnace Slag (GGBS):

GGBS is obtained by quenching molten iron slag (a by-product of iron and steel making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. GGBS is used to make durable concrete structures in combination with ordinary port land cement and/or other pozzolanic materials. The fineness modulus of GGBS using blaine's fineness is 320 m2/kg.

3.1.5.Robo Sand:

Robo Sand or crusher dust obtained from local granite crushers was used in concrete to cast the cubes and cylinders. The bulk density of ROBO sand or crusher dust is 1768 kg/m3. The specific gravity and fineness modulus of ROBO sand are 2.66 and 2.88 respectively.

3.1.6.Water

Potable water supplied by the college was used in the work

3.1.7.Moulds

Standard cast iron cubes and cylinders moulds were used for casting of cubes and cylinders. Three wooden moulds were prepared for casting of beams of sizes as follows

1. 300×75×75 mm
2. 600×150×75 mm
3. 1200×300×75 mm

3.1.8.Vibrator:

To compact the concrete, a plate vibrator and as well as needle vibrator was used and for compacting the Test specimens, cubes, cylinders and beams.

3.1.9.Casting:

The moulds were tightly fitted and all the joints were sealed by plaster of Paris in order to prevent leakage of cement slurry through the joints. The inner side of the moulds was thoroughly oiled before going for concreting. The mix proportions were put in miller and thoroughly mixed.

The prepared concrete was placed in the moulds and is compacted using needle& plate vibrators. The same process is adopted for all specimens. After specimens were compacted the top surface is leveled with a trowel.

3.1.10.Curing:

The NSC specimens were removed from the moulds after 24 hours of casting and HSC specimens were removed after 48hours of casting, the specimens were placed in water for curing

3.1.11.Marble Cutter:

The beams were cut with a marble cutter in to the hardened concrete (Fig 3.1).

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FIGURE 3.1 *cutting beam with marble cutter.*

3.2.Test Setup and Testing Procedure:

All the specimens were tested on the Servo controlled static testing Machine of 1000kN capacity under displacement control at a rate of 0.02mm/min. After 28days of curing the samples were taken out from the curing tank and kept for dry. Then notch is provided at the centre of the beam with notch to depth ratio of 0.15. After this the sample was coated with white wash. One day later the sample was kept for testing.

The notched beam specimen was kept on the supports of testing machine as shown in below figure 3.2.1. When performing a test, a gradually increased load is applied to the notched beam until a stress level is reached which results in crack propagation. Dependent on the notch depth and the stiffness of the material and of the loading frame, the resultant load-displacement diagrams exhibit catastrophic, semi-stable or stable fracture

Figure 3.2.2 loading frame in BEC structural engineering lab

Figure 3.2.3. Test setup

Table: 4 details of materials for 1 cubic meter of concrete

Grade of concrete	**Mix Proportion**	**Water wt. (kg)**	**Cement wt.(kg)**	**Weight of FA (kg)**	**Weight of CA (kg)**
M30	0.46:1:1.26:3.12	191.6	416.5	525.7	1300.3

Table 5: Mechanical properties of concrete

Grade of concrete	**% Robo-sand & %GGBS**	**Mix Proportion**	**Compressive strength f_{ck} (N/mm^2)**	**Tensile strength f_t (N/mm^2)**
M30	R-0%-G-0%	0.46:1:1.26:3.12	37.1	3.2
	R-25%-G-25%		40.12	3.6
	R-30%-G-50%		48.89	4
	R-50%-G-50%		46.79	4.1

Table: 6 Dimensions of beam specimens in Size Effect Method

Grade of concrete	Specimen	Aggregate Size (mm)	Length,L, (mm)	width,b, (mm)	Depth,d, (mm)	Span,S, (mm)	Notch Depth (a0)	a0/d	S/d
M30	Small	20	350	75	75	300	11.25	0.15	4
	Medium	20	650	75	150	600	22.5	0.15	4
	Large	20	1250	75	300	1200	45	0.15	4

Table 7: Quantities of Materials

S.No.	% Of Robosand and GGBS	Agg. Size mm	Specimen size (mm)	Wt. of water (Kg)	Wt. of cement (Kg)	Wt. of FA (Kg)	Wt. of CA (Kg)	Wt. of Robo sand (Kg)	Wt. of GGBS (Kg)
1.	R-0%-G-0%	20	75×75×350	0.527	1.147	1.147	3.582	0	0
	R-0%-G-0%	20	75×150×650	1.95	4.259	4.259	13.29	0	0
	R-0%-G-0%	20	75×300×1250	7.54	16.39	16.39	51.15	0	0
2.	R-25%-G-25%	20	75×75×350	0.527	0.860	1.860	3.582	0.286	0.362
	R-25%-G-25%	20	75×150×650	1.95	3.194	4.027	13.29	1.064	1.342
	R-25%-G-25%	20	75×300×1250	7.54	12.29	15.51	51.15	4.097	5.17
3.	R-30%-G-50%	20	75×75×350	0.527	0.573	1.013	3.582	0.573	0.4344
	R-30%-G-50%	20	75×150×650	1.95	2.129	3.759	13.29	2.129	1.611
	R-30%-G-50%	20	75×300×1250	7.54	8.195	14.47	51.15	8.195	6.204

4.	R-50%-G-50%	20	75×75×350	0.527	0.573	0.724	3.582	0.573	0.724
	R-50%-G-50%	20	75×150×650	1.95	2.129	2.685	13.29	2.129	2.685
	R-50%-G-50%	20	75×300×1250	7.54	8.195	10.34	51.15	8.195	10.34

RESULTS AND DISCUSSION

For calculation of the stress intensity factor the following formulas are used

$$K_1 = \sigma_n \sqrt{\pi * a_0}\, f(\alpha)$$

$$\sigma_n = C_N \frac{P_u}{bd}$$

a_0 = Notch depth

C_N = Arbitrary constant = 1.5(L/D)

$$f(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{1.772\ (1+2\alpha)(1-\alpha)^{3/2}}$$

For beams having geometry of L/D = 4
α = Notch/Depth ratio = 0.15
P_u = failure load
b = thickness of the beam
d = depth of the beam
After finding the value of stress intensity factor K_1 value then the value of the fracture energy is obtained in non linear fracture approach by the formula

$$G_f = \frac{g(\alpha)}{EA}$$

$$g(\alpha) = C_N^2 \pi \alpha f(\alpha)^2$$

E = young's modulus of concrete = 5700√fck
A = constant obtained from regression plot
Aft er obtaining the value of fracture energy G_f the brittleness number is obtained by formula

$$\beta = \frac{d}{d_0}$$

d = depth of beam, d_0 = C/A taken from regression plot
The formula for cohesive fracture zone length is

$$Cf = \frac{g(\alpha)}{g'(\alpha_0)} d_0$$

g'(α) = derivative of g(α) with respect to α

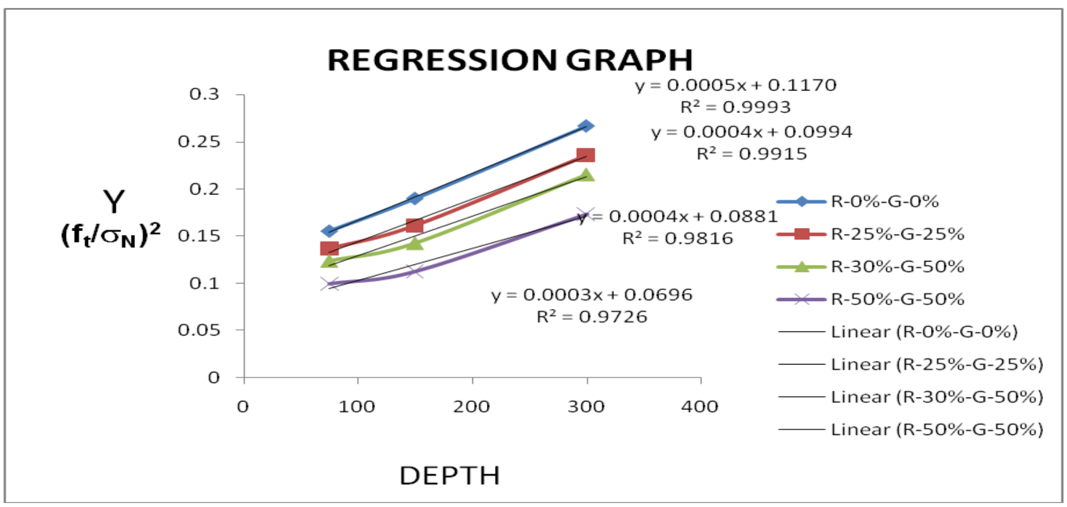

Fig 4.1: Regression graphs

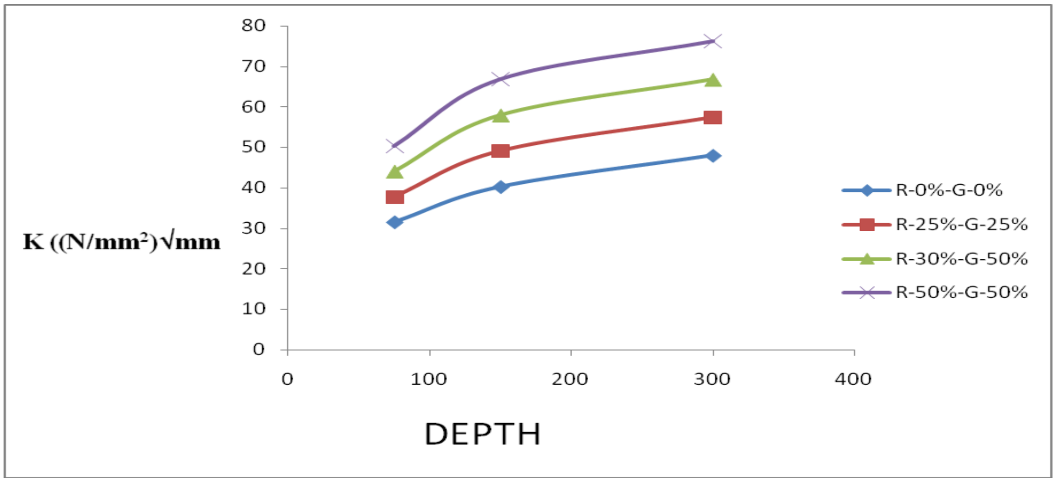

Fig 4.2: Stress Intensity Factor curves for Depth of beams

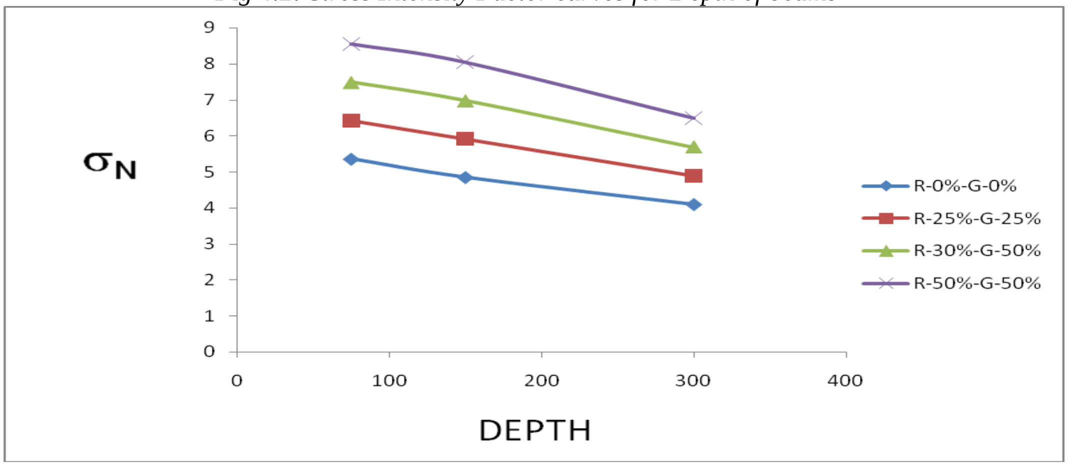

Fig 4.3. Nominal Stresses Vs Load graph

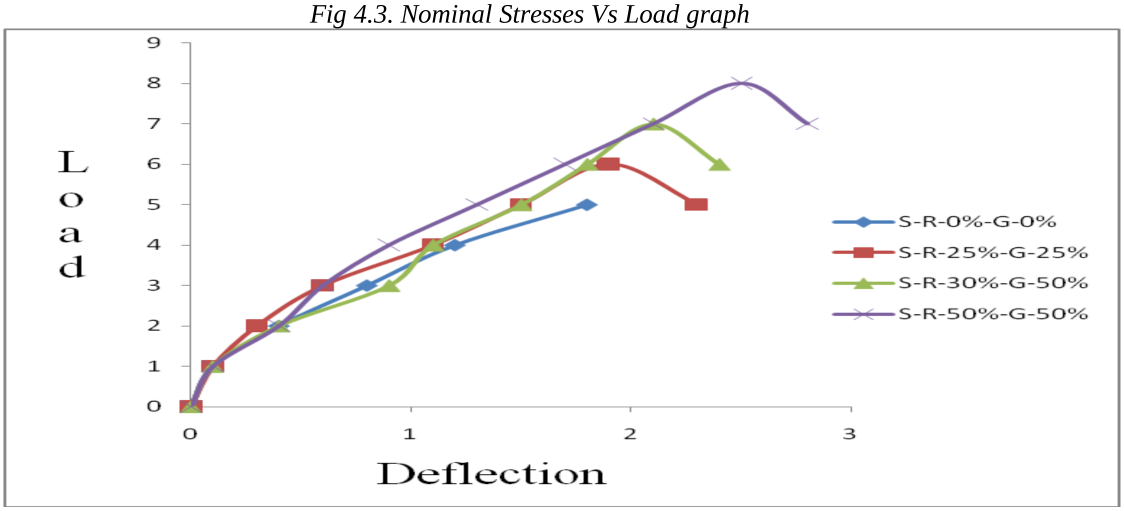

Fig 4.4: Load Vs Displacement graph for Small beams

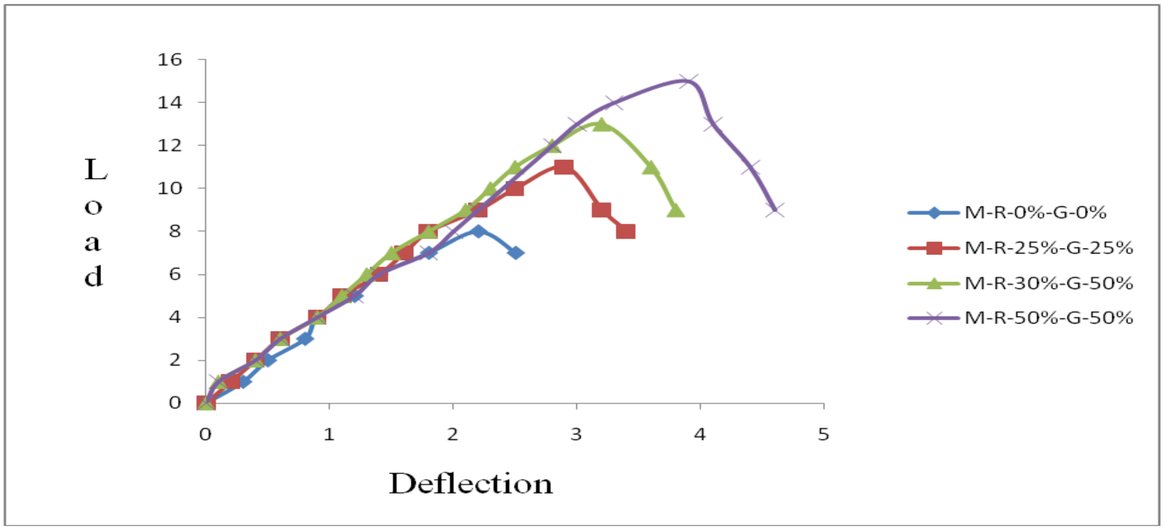

Fig 4.5: Load Vs Displacement graph for medium beams

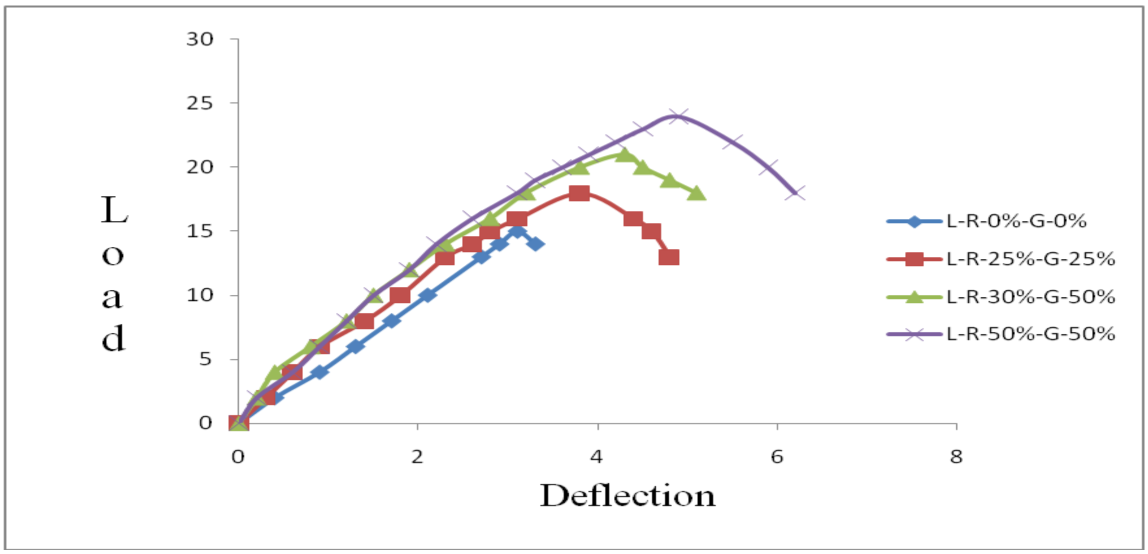

Fig 4.6: Load Vs Displacement graph for large beams

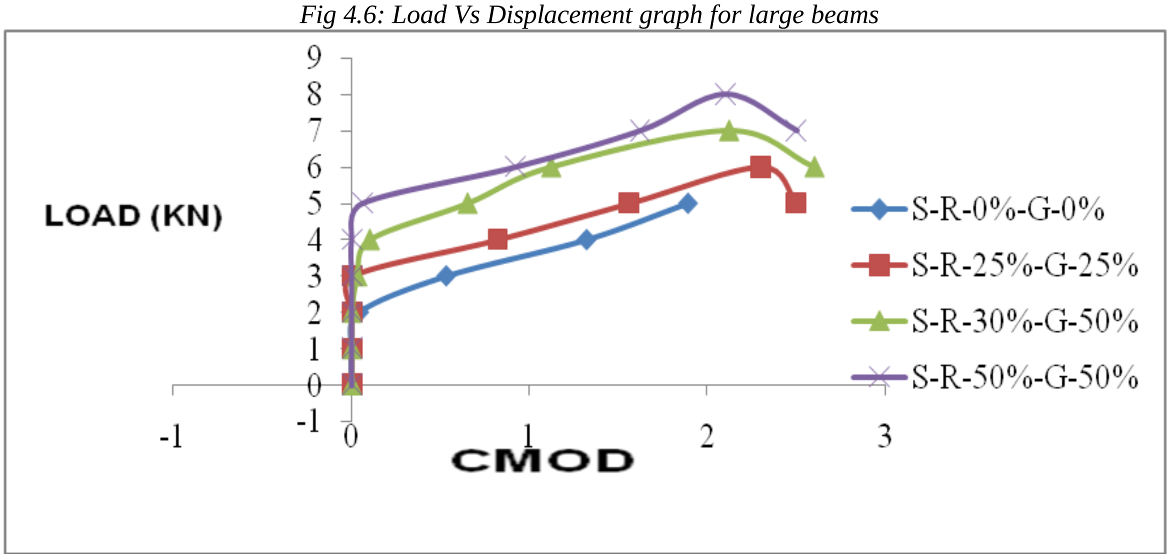

Fig 4.7: Load Vs CMOD graph for small beams

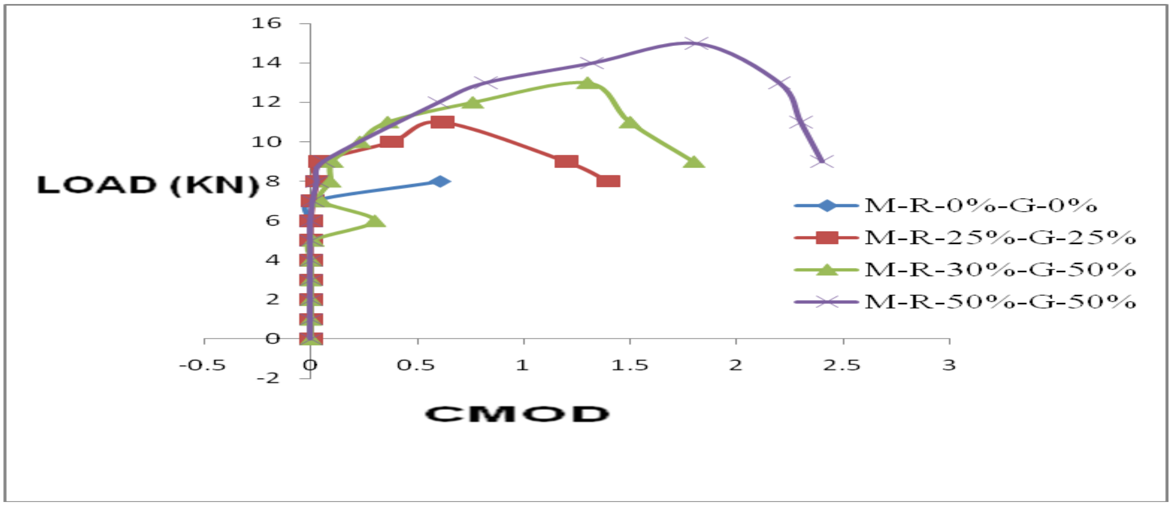

Fig 4.8: Load Vs CMOD graph for MEDIUM beams

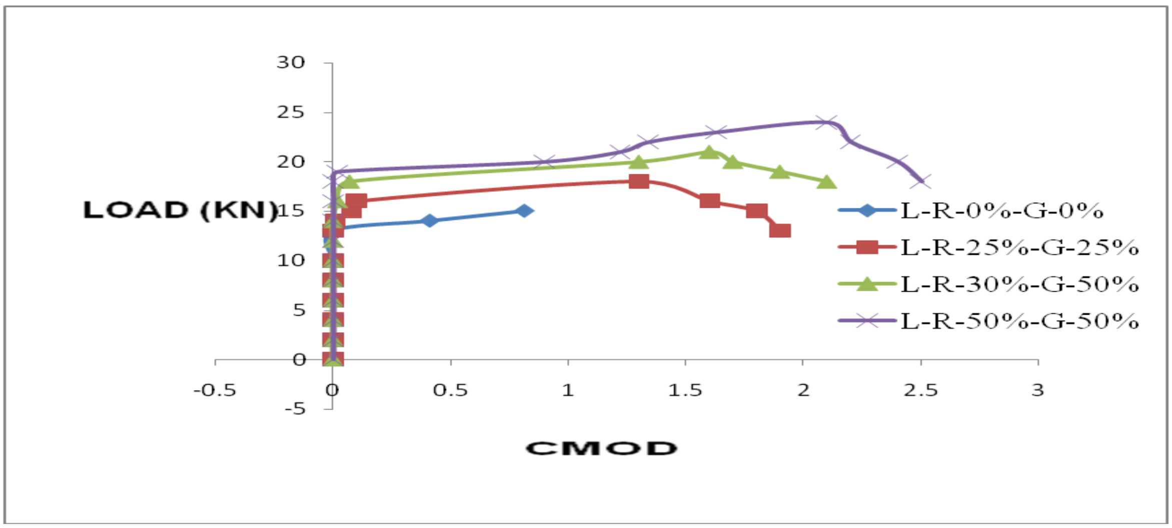

Fig 4.9: Load Vs cmod graph for large beams

BEFORE TESTING **AFTER TESTING**

Fig : 4.10.

CONCLUSIONS

Based on the tests on eighteen notched concrete beam specimens, the following conclusions have been drawn:

1. It is observed that, failure stresses (nominal stresses) decreases with increasing of beam sizes.
2. It is also observed that, stress intensity factor increases with increase in beam sizes f
3. It is also observed that, stress intensity factor increases with increase in compressive strength of beams.
4. It is also observed that, Fracture energy decreases with increase in compressive strength of concrete.
5. It is observed that,the stress intensity factor is increases when the beam proportions of GGBS and Robosand are increases.
6. The compressive strength of normal concrete is less than high performance concrete.
7. It is observed that,the Fracture energy is increases when the beam proportions of GGBS and Robosand are increases.

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