DETERMINING THE DOUBLE-K FRACTURE PARAMETERS FOR RECYCLED AGGREGATE CONCRETE USING THREE POINT BENDING TEST

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ABSTRACT

According to double-K criterion, the two size independent parameters can be used to describe the fracture process of concrete and can predict the different stages of crack propagation. The first parameter is termed as initial cracking toughness, K_{IC}^{ini}, which is directly calculated by the initial cracking load (P_{ini}) and initial-notch length (a_0) using LEFM principles. The other parameter is known as unstable fracture toughness, K_{IC}^{un}, which can be obtained by peak load and effective crack length (a_c) using LEFM principles. In the present study, totally 4 series comprising of 2 natural aggregate concrete (NAC) mixes, one having w/c of 0.50 and the other having w/c ratio of 0.45, 2 recycled aggregate concrete (RAC) mixes having w/c ratio of 0.5, and 0.45 have been investigated. As recommended by RILEM committee-TC-89, geometrically similar beam specimens for evaluation of fracture characteristics were cast. Notches of 3 to 4mm thick and notch depth/beam depth of 0.2 were cut in beam specimens using a concrete cutting machine before testing.

The geometrically similar beam specimens were tested using a servo-controlled UTM under constant displacement rate of 0.05mm/min. A single point loading system was adopted in which the beam was simply supported over a span equal to four times the depth of beam. The load and crack mouth opening displacement were measured till failure. A clip gauge of ± 4mm range over a gauge length of 25mm was fixed across the notch at the bottom face of the beam to measure the crack opening displacement (CMOD). The test was continued till the beam failed. Using load-CMOD data obtained from experiment double-K fracture parameters (K_{IC}^{ini}, K_{IC}^{un}) evaluated. From the results it was observed that the initial fracture toughness (K_{IC}^{ini}) and unstable fracture toughness (K_{IC}^{un}) of recycled aggregate concrete are size independent.

***Keywords**: Fracture parameters, double-K parameters, CMOD, recycled aggregates*

INTRODUCTION

Large amount of waste from construction and demolition are generated due to increase in population and urbanization or natural disasters. These wastes include wood, iron, ceramics, masonry, concrete etc. Therefore, majority of the developed/developing countries are facing the problem of handling and disposal of such construction and demolition wastes. Shortage of dumping sites and increase in cost of transport to dispose these wastes lead to difficulty for safe disposal. Considering this aspect it is beneficial to reuse the generated waste for effective utilization and to save the environment (Parekh and Modira 2011).

The fracture energy is defined as the post-crack energy absorption ability of the material and it represents the energy that the structure will absorb during failure. Appa Rao and Raghu Prasad (2002) studied the influence of maximum size of coarse aggregates in concrete having compressive strength varied between 40 and 75 MPa. They reported that fracture energy of 4.75mm sized aggregate was 76.6N/m and 20mm aggregate was 142N/m. This increase of fracture mainly depends on size of coarse aggregate. This was due to the increased aggregate interlock. As the size of the coarse aggregate increases cement paste-aggregate interface experience higher bond stress leading to bond failure. Cifuentes and Karihaloo (2013) reported that specific fracture energy of self-compacting concrete mixes is lower than that of vibrated mixes of the same strength. This was due to the lower content of coarse aggregate in the self-compacting concrete. Liam Butler et al (2013) used single edge notched double-cantilevered specimens to study the fracture energy. Test results reported that fracture energy of normal aggregate concrete was 32% more than RCA concrete for both 40 and 60Mpa mixtures. This was due to the higher modulus of elasticity if normal aggregate concrete. Merta and Tschegg (2013) reported that the fracture energy of concrete reinforced with hemp fibres, straw and elephant grass is 70%, 2% and 5% more than the normal concrete. This was because of the fact that, when fibres were present in concrete, the cracks could not extend without stretching and debonding the fibres.

Fracture toughness of concrete materials was determined by various fracture models such as the fictitious crack model(Hillerborg et al.1976),the crack bond model(Bazant and oh 1983),the two parametermodel(Jenq and Shah 1985 a,b),the size effect model(Bazant and kazemi 1990),the effect crack model(karihaloo and nallathambi 1990) and the double –K fracture model(Xu and Reinhardt 1999,2000). Among these the double-K frature model describes the complete fracture process of concrete, including crack initiation, crack propagation and unstable fracture. The initial cracking stress intensity factor created at the preformed crack tip by the initial cracking load P_{ini}, is defined as the initiation toughness K_{IC}^{ini}. The stress intensity factor calculated at the maximum load P_{max} and corresponding CMOD , is defined as the unstable fracture toughness K_{IC}^{un}. These two parameters are called double-K fracture parameters. Shailendra Kumar and Barai (2010) determined double-k fracture parameters for three points bending notched concrete beam using weight function. In the present paper double-K fracture parameters are evaluated for recycled aggregate concrete. Concrete beam specimens (geometrically similar) made with different w/c ratios (NAC and RAC) were prepared and tested under three point bending.

EXPERIMENTAL PROGRAMME

Totally 4 series comprising of 2 NAC mixes, one having *w/c* of 0.50 and the other having w/c ratio of 0.45, 2 RAC mixes having *w/c* ratio of 0.5, and 0.45 have been investigated. A pan type mixer machine was used for preparing the concrete mix. The mix proportions used are given in **Table 1**.

Table1 Details of concrete mix proportions

Sl. No.	Mix ID	Mix ratio	
		Cement (Kg/m3)	Cement: Sand: Coarse aggregates: water
1	NAC-0.5	340	1 : 2.57 :3.11 :0.5
2	NAC-0.45	377	1 : 2.28 :2.76:0.45
3	RAC-0.5	340	1 : 2.57 :2.85:0.5
4	RAC-0.45	377	1 : 2.28 :2.53:0.45

The geometrically similar beam specimens having constant notch-depth/beam depth ratio of 0.2 and span/depth ratio of 4 were cast as recommended by RILEM committee-TC-89.These specimen having size 50x50x200mm, 50x80x320mm and 50x130x520 mm. Notches of 3 to 4mm thick of various depths were cut in beam specimens using a concrete cutting machine before testing for fracture characteristics.

The compressive strength at the age of 28days was evaluated using 100mm cube specimens**.** The geometrically similar beams were tested using a servo-controlled UTM under constant displacement rate of 0.05mm/min. A single point loading system was adopted in which the beam was simply supported over a span equal to four times the depth of beam. The load, deflection and crack mouth opening displacement were measured till failure. A clip gauge of $\pm$ 4mm range over a gauge length of 25mm was fixed across the notch at the bottom face of the beam to measure the crack opening displacement (CMOD). Fig1 shows the test setup for geometrically similar beam specimens.

Fig.1 Test setup for testing geometrically similar beam specimen

Effective crack length

From the three point bending test P-CMOD curves for natural aggregate concrete and recycled aggregate concrete were obtained. LEFM principles were used to determine effective crack length (a_c) using maximum load and corresponding CMOD. According to LEFM formulae for S/D=4,

$$CMOD = \frac{6PSa}{BD^2E} V_I(\beta) \qquad (1)$$

$$V_I(\beta) = 0.76 - 2.28\beta + 3.87\beta^2 - 2.04\beta^3 + \frac{0.66}{(1-\beta)^2}$$

Where

$\beta = \frac{a+H}{D+H}$, a=a_c, effective crack length at maximum load, H=thickness of the clip gauge holder, B, D and S are the width, depth and span, respectively of the beam. The value of Young's modulus (E) was computed from compressive cylinder test. In equation (1), substituting P=P_{max}, CMOD=$CMOD_c$ (CMOD at P_{max}) , B,D,S,E and β values, effective crack length (a_c) can be evaluated.

Determination of the double-K fracture parameters

According to the definition of the unstable fracture toughness K_{IC}^{un} , if one obtains the maximum load P_{max} and critical crack length a_c from the test, the unstable fracture toughness K_{IC}^{un} can be evaluated by the following expression:

$$K_{Ic}^{un} = \frac{3P_{max} S\sqrt{a_c} F_I(V_c)}{2D^2B} \quad \ldots\ldots\ldots (2)$$

$$F_I(V_c) = \frac{1.99 - V_c(1-V_c)(2.15 - 3.93V_c + 2.7{V_c}^2)}{(1+2V_c)(1-V_c)^{\frac{3}{2}}}$$

Where S,B and D are the span, thickness, and depth of the beam, respectively, V_c=ac/D and the geometry factor F_I (V_c) is given as follows for standard three-point bending beam:

The definition of the initial fracture toughness K_{IC}^{ini} is given as the initial cracking stress intensity factor created by the initial cracking load P_{ini} at the initial crack tip. Therefore, the value of K_{IC}^{ini} can also be evaluated by inserting the initial cracking load P_{ini} and initial crack length a_0 into Eq (2).

$$K_{Ic}^{ini} = \frac{3P_{ini} S\sqrt{a_0} F_I(V_0)}{2D^2B}$$

$$F_I(V_0) = \frac{1.99 - V_0(1-V_0)(2.15 - 3.93V_0 + 2.7{V_0}^2)}{(1+2V_0)(1-V_0)^{\frac{3}{2}}} \quad \ldots\ldots\ldots(3)$$

Where V_0 =a_0/D, so the geometry factor F_I (V_0) is given by Eq as (3)

The calculated results for K_{Ic}^{ini} and K_{Ic}^{un} of high-performance concrete are listed in table 3 and 4.

RESULTS AND DISCUSSIONS

The compressive strength at 28 days for the various mixes are given in **Table 2.**

Table 2 Results of mechanical properties

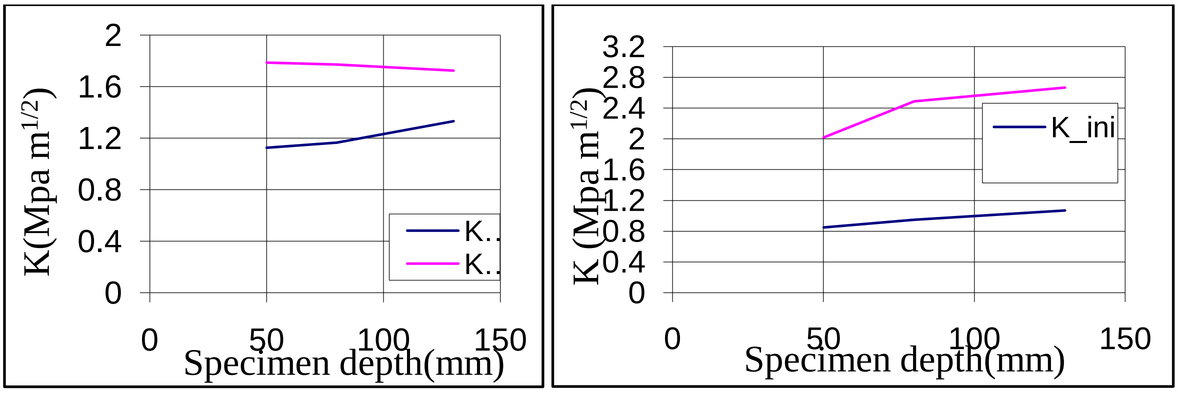
Sl.No.	Mix ID	w/c ratio	Compressive strength (MPa)
1	NAC-0.5	0.5	42

2	NAC-0.45	0.45	55
3	RAC-0.5	0.5	36
4	RAC-0.45	0.45	50

The double-K fracture parameters were evaluated for geometrical similar concrete beams. The values of the initial fracture toughness and unstable fracture toughness of the two NAC mixes, one having *w/c* of 0.50 and the other having w/c ratios of 0.45 and two RAC mixes having w/c ratio of 0.5 and 0.45 are listed in table 3. Fig.2 and Fig.3 shows the comparison of the double–K fracture parameters for NAC and RAC concrete mixes. From table 3 and Fig 2 it can be seen that double–K fracture parameters were increased with increasing compressive strength. Double-K fracture model describes the fracture process of concrete, including crack initiation and unstable fracture.

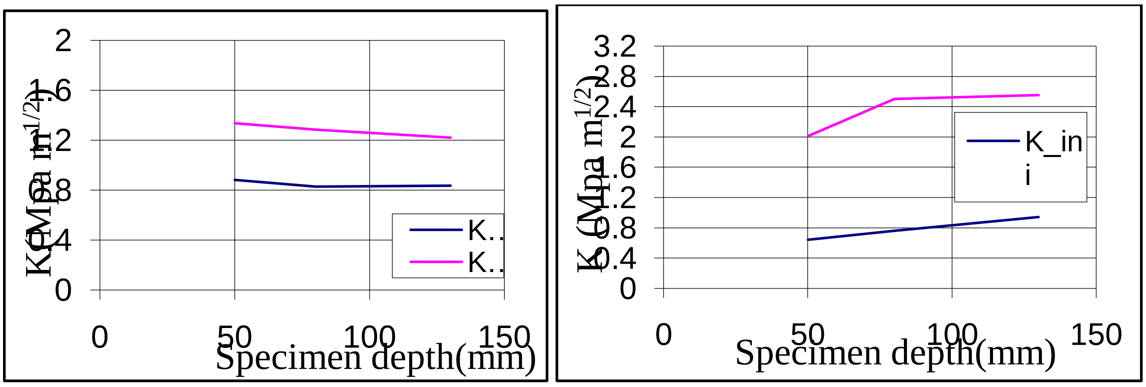
Table 3: Double-K fracture parameters a_0/D=0.2, H=3.2mm, B=50mm, S=4D

Mix ID	D(mm)	ac/D	P ini(N)	Pmax(N)	CMOD(mm)	fc(MPa) cube	K_{IC}^{ini} (MPa $m^{1/2}$)	K_{IC}^{un} (MPa $m^{1/2}$)
NAC-0.5	50	0.3509	2681	2878	0.0316	42	1.1269	1.7874
	80	0.3408	2506	2981	0.0457		1.1663	1.7712
	130	0.2584	5113	5679	0.0357		1.3329	1.7239
RAC-0.5	50	0.3028	2098	2439	0.0223	36	0.8819	1.3370
	80	0.3680	2074	2502	0.0313		0.8292	1.2856
	130	0.2568	3212	4041	0.0272		0.8373	1.2217
NAC-0.45	50	0.4679	2018	2338	0.0439	55	0.8482	2.0165
	80	0.4928	2855	3379	0.0670		0.9487	2.4875
	130	0.4651	4100	5025	0.0833		1.0688	2.6653
RAC-0.45	50	0.5611	1531	1723	0.0554	50	0.6435	2.0139
	80	0.5796	2288	2531	0.0873		0.7603	2.5004
	130	0.4831	3612	3981	0.0764		0.9416	2.5530



a) w/c ratio 0.5 b) w/c ratio 0.45

Fig 2: Comparison of double-K fracture parameters for NAC mixes



a) w/c ratio 0.5 b) w/c ratio 0.45

Fig 3: Comparison of double-K fracture parameters for RAC mixes

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The experimental evidence showed that the double-*K* fracture parameters K_{IC}^{ini} and K_{IC}^{un} are size-independent and can be considered as the fracture parameters to describe cracking initiation and unstable fracture for high performance concrete. To determine the double-K fracture parameters only ascending branch of load-CMOD curve is required. Therefore we can do test in a common machine without a closed loop testing system.

CONCLUSIONS

The double-K fracture parameters were evaluated for geometrical similar concrete beams. The values of the initial fracture toughness and unstable fracture toughness of the two NAC mixes, one having *w/c* of 0.50 and the other having w/c ratios of 0.45 and two RAC mixes having w/c ratio of 0.5 and 0.45 were evaluated. The experimental evidence showed that the double-*K* fracture parameters K_{IC}^{ini} and K_{IC}^{un} are size-independent and can be considered as the fracture parameters to describe cracking initiation and unstable fracture in high performance concrete.

ACKNOWLEDGEMENT

This paper is being published with the kind permission of The Director, CSIR – Structural Engineering Research Centre, Chennai. The authors would like to thank the staff members of Advanced Materials Laboratory at CSIR – Structural Engineering Research Centre, Chennai for the support rendered by them during the experimental investigations.

REFERENCES

1. Parekh D.N and Modhera C.D, "Assessment of recycled aggregate concrete", Journal of engineering research and studies, vol-II, Issue I, January-march, pp.1-9, 2011.
2. Appa Rao G , Raghu Prasad B.K, Fracture energy and softening behavior of high-strength concrete, Cement and Concrete Research 32 (2002) 247–252.
3. Héctor Cifuentes , Bhushan L. Karihaloo, Determination of size-independent specific fracture energy of normal- and high-strength self-compacting concrete from wedge splitting tests, Construction and Building Materials 48 (2013) 548–553.
4. Liam Butler, Jeffrey S. West, Susan L. Tighe ,Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength, Construction and Building Materials 47 (2013) 1292–1301.
5. Merta I., E.K. Tschegg, Fracture energy of natural fibre reinforced concrete, Construction and Building Materials 40 (2013) 991–997
6. Bazant, Z.P. and Oh, B.H., "Crack Band Theory for Fracture of Concrete", Material and Structure, Vol.16, 1983, pp.155-157
7. Bazant, Z.P. and Kazemi, M.T., "Determination of Fracture Energy, Process Zone Length and Brittleness Number from Size-effect with Application to Rock and Concrete", Int. Jou. of Fracture, Vol.44, 1990, pp.111-131
8. Hillerborg, A., Modeer, M., and Petersson, P.E., "Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements", Cement Concrete Research, Vol.6, 1976, pp.773-782
9. Jenq, Y.S. and Shah, S.P., "A two-parameter Fracture Model for Concrete", ASCE Journal of Engineering Mechanics, Vol.111, 1985a, pp.1227-1241
10. Jenq, Y.S. and Shah, S.P, "A fracture Toughness Criterion for Concrete", Engineering Fracture Mechanics, Vol.21, No.5, 1985b, pp.1055-1069
11. Karihaloo, B.L. and Nallathambi, P., "Effective Crack Model for the Determination of Fracture Toughness of Concrete", Journal of Engineering Fracture Mechanics, Vol.35, 1990, pp.637-645
12. RILEM Committee FMT 89, "Determination of Fracture Parameters K^{S}_{IC} and $CTOD_C$ of Plain Concrete using Three-point Bend Tests", Material and Structures, Vol.23, 1990(a), pp.457-460

13. Shailendra Kumar and SV Barai, "Determining the double-k fracture parameters for three point bending notched concrete beam using weight function" Fatigue and fracture of Engineerin materials & structures,2010,33,pp-645-660.
14. Shilang Xu and HW Reinhardt.," Determination of double-K criterion for crack propagation in quasi-brittle fracture, Part-I: Experimental investigation of crack propagation", International Journal of Fracture, 1999, Vol 98, pp 111-149.
15. Shilang Xu and HW Reinhardt.," Determination of double-K criterion for crack propagation in quasi-brittle fracture, Part-II: Analytical evaluating and practical measuring methods for three-point bending notched beams", International Journal of Fracture, 1999,Vol 98, pp 151-177.
16. Shilang Xu and HW Reinhardt, "A simplified method for determining double-K fracture parameters for three-point bending tests", International Journal of Fracture, 2000, Vol 104,pp 181-209.