Fracture Mechanics of Concrete Structures,
Proceedings FRAMCOS-2, edited by Folker H. Wittmann,
AEDIFICATIO Publishers, D-79104 Freiburg (1995)

THE EFFECTS OF MIX VARIABLES ON CONCRETE FRACTURE MECHANICS PARAMETERS

Y.-C. Kan
Taipei Department of Rapid Transit System, Taipei, Taiwan
S.E. Swartz
Civil Engineering Department, Kansas State University, Manhattan, KS, USA

Abstract

An extensive testing program using three-point bend specimens has been conducted to ascertain the influence on fracture mechanics parameters of the concrete mix variables: aggregate-matrix bond and strength, cementitious bindings, and gradation of fines. Specifically, the variables were: crushed limestone, crushed and polished limestone, quartzite, river gravel, expanded shale, normal graded sand, gap graded sand, W/C ratio, fly ash and silica fume. These were organized into twenty-four groups of tests involving 352 beams. Testing was conducted using notched beams according to proposals by RILEM -- G_F (Hillerborg), K^S_{IC}, E_C (G^S_{IC}), $CTOD_C$ (Jenq and Shah) and by Karihaloo/Nallathambi. Precracked beams in which dye was inserted to reveal the crack front prior to testing to failure were also used to evaluate the same parameters.

1 Introduction

This research was conducted to study the influence of a wide spectrum of mix parameters on the fracture mechanics properties of concrete as defined by the RILEM (1985) work-of-fracture method, the RILEM (1990) two-parameter method, and the effective crack method of Karihaloo and Nallathambi (1991). The tests included beams which were notched and then loaded to failure- denoted "notched" - and beams which were notched, cracked, dye inserted following the method of Swartz and Refai (1989), and then loaded to failure - denoted "precracked". Note that for the notched beams the measured load-displacement curve will reflect the initial formation of a process zone while for the precracked beams this will not be reflected in the measured load displacement curves. All beam tests were conducted using a closed loop testing system with sufficient stiffness.

2 Organization of tests

All beams were tested in three-point bending in an inverted position. Displacement measurements included CMOD and load point (LPD) and due consideration was given to avoiding measurement of spurious deformations - see Swartz and Kan (1991) and Kan (1993). The beam dimensions were depth b = 10 in. (254 mm), thickness t = 5 in. (127 mm) and span S = 40 in. (1016 mm). The tests were organized in groups according to the type of aggregate used in the mix as shown in Table 1. All mixes had a maximum coarse aggregate size between 13 and 19 mm.

All beams were cast in steel molds along with companion 3 in. x 6 in. (75 x 150 mm) cylinders. After curing one day, the specimens were demolded and placed in a fog room for 84 days. They were then removed and placed in an air-dried environment for 7 days and tested on the 92nd day. On the test day, four beams and companion cylinders were tested. The cylinder tests included uniaxial compression (f_c' and stress-strain) and split-cylinder tension. All tests were conducted using strain control on the crack mouth opening displacement and load-displacement plots were obtained.

The notched beams had notch/depth = 1/3 and the precracked beams had starter notch/depth = 1/10.

Table 1. Testing program

Group ID	Aggregate Type	W/C	Sand	Other Cementitious Materials
NC	Crushed Limestone	.64	N	
		.64	G	
		.30	N	
		.30	G	
		.30	N	Fly Ash, FA
		.40	N	Silica Fume, SF
NP	Crushed & Polished Limestone	.64	N	
		.30	N	
		.64	G	
		.30	G	
HC	Crushed Quartzite	.64	N	
		.30	N	
		.30	N	FA
		.40	N	SF
RG	River Gravel	.64	N	
		.30	N	
		.30	N	FA
		.40	N	SF
LS	Lightweight Expanded Shale	.64	N	
		.30	N	
		.64	G	
		.30	G	
		.30	N	FA
		.40	N	SF

N = normal graded sand,
G = gap graded sand, grain size < 1.2 mm.

3 Test results

Average values of the fracture parameters G_F and K^S_{IC} are given in Table 2 for beams using only Portland Cement. It is seen that in all cases the notched beams had higher values than the companion precracked beams. The differences are generally smaller for the weaker aggregate (e.g., LS - expanded shale) versus stronger aggregate (e.g., NC - crushed limestone). For constant W/C - and approximately equal f_c' - the G_F values for notched beams change by 40% for W/C = 0.30 and 46% for W/C = 0.64 (excluding

Table 2. Average fracture values for beams

Mark		f_c' psi (MPa)	G_F lb/in. (N/m)		K^S_{IC} psi $\sqrt{in}$ (k Pa $\sqrt{m}$)	
			No	Pr	No	Pr
W/C = 0.30	NC	9820	0.679	0.454	1308	1063
		(67.7)	(119.0)	(79.5)	(1439)	(1169)
	NP	8880	0.727	0.621	1266	1184
		(61.2)	(127.4)	(108.8)	(1393)	(1302)
	LS	6110	0.331	0.321	969	829
		(42.1)	(58.0)	(56.2)	(1066)	(912)
	RG	9050	0.897	0.649	1101	1032
		(62.4)	(157.2)	(113.7)	(1211)	(1135)
	HC	9900	0.952	0.669	1523	1211
		(98.0	(166.8)	(117.2)	(1675)	(1332)
W/C = 0.64	NC	5730	0.565	0.356	922	775
		(39.5)	(99.0)	(62.4)	(1014)	(852)
	NP	6190	0.570	0.469	980	709
		(42.6)	(99.9)	(82.2)	(1078)	(780)
	LS	4710	0.234	0.209	714	542
		(37.5)	(41.0)	(36.6)	(785)	(596)
	RG	5350	0.689	0.571	954	762
		(36.9)	(120.7)	(100.0)	(1049)	(838)
	HC	5830	0.824	0.674	1206	989
		(40.2)	(144.4)	(118.1)	(1327)	(1088)

Notes: No = notched beam, $a_o/b = 1/3$.
Pr = pre-cracked beam, various a_o/b.
G_F based on RILEM proposal
K^S_{IC} based on Jenq/Shah proposal
All beams used Portland Cement only and normal graded sand.

the expanded shale mix which had significantly lower f_c'). Corresponding changes in K^S_{IC} were 38% and 31%. It should be noted that only results where the process zone is fully developed are presented. In all cases, fracture toughness and fracture energy decreased with increasing W/C as shown in Figs. 1 and 2.

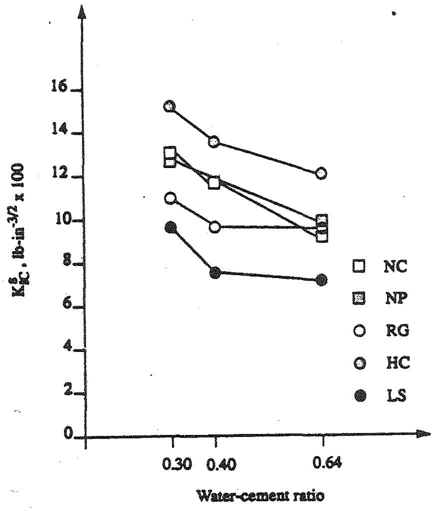

Fig. 1: Fracture toughness versus W/C

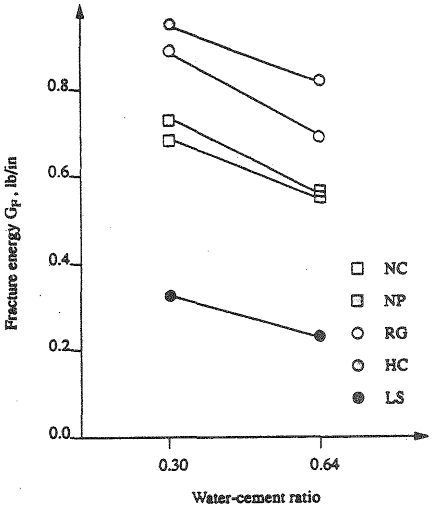

Fig. 2: Fracture energy/versus W/C

Changes in fracture toughness related to different types of aggregate for mixes without and with fly ash are shown in Figs. 3 and 4 respectively. The results from the Jenq and Shah (J/S) method are presented with those from the Karihaloo and Nallathambi (K/N) method. A significant variation in values with type of aggregate is evident - even when the compressive strengths are

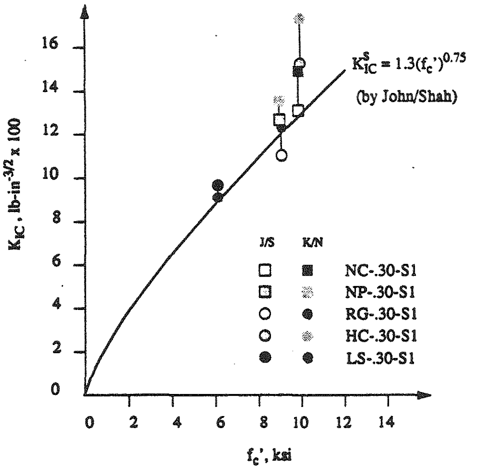

Fig. 3. Fracture toughness of concrete with W/C = 0.30

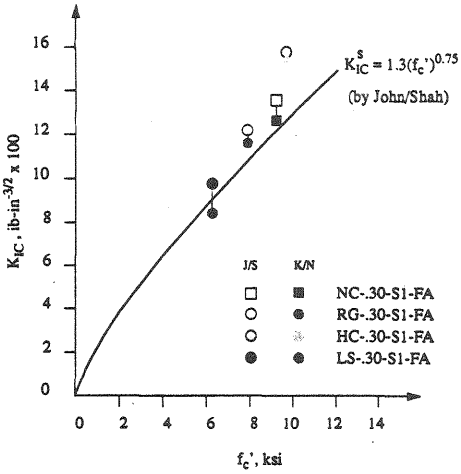

Fig. 4. Fracture toughness of concrete including fly ash at W/C=0.30

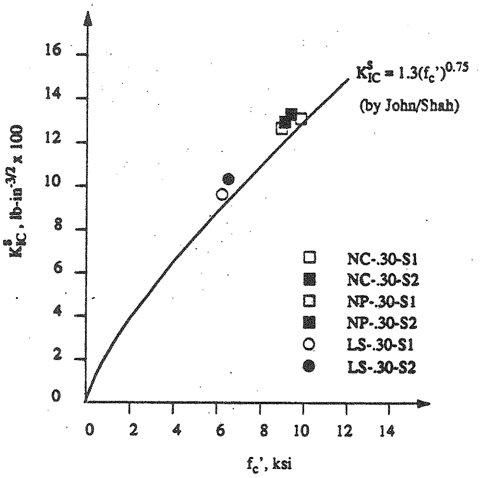

Fig. 5. Fracture toughness of concretes with normal sand and gap-graded sand at W/C = 0.30

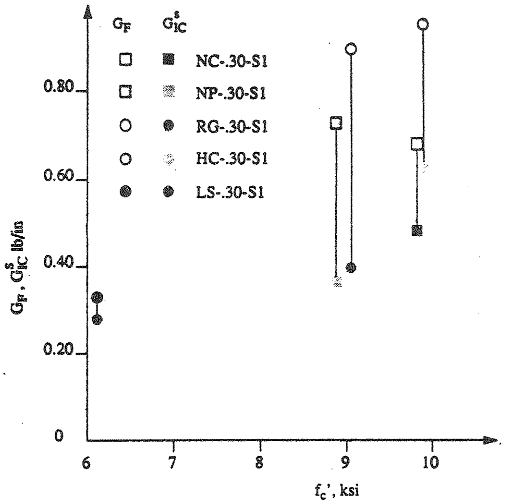

Fig. 6. Fracture energy G_F and energy release rate G^S_{IC} of concrete with W/C = 0.30

about the same. The proposed formula by John and Shah (1989) relating K^S_{IC} to f_c' is plotted. The trends seem to follow this rather well. The effect of fly ash is to lower the compressive strength without changing K^S_{IC}. The fracture toughness values in terms of normal graded sand and gap graded sand are shown in Fig. 5. It is seen that the sand gradations had little effect on the toughness.

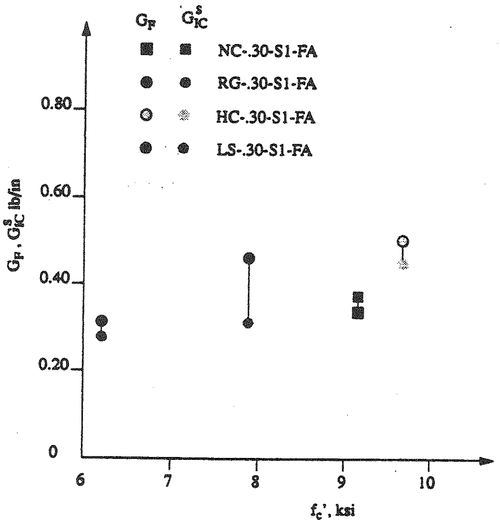

Fig.7. Fracture energy G_F and energy release rate G^S_{IC} of concrete including fly ash at W/C = 0.30.

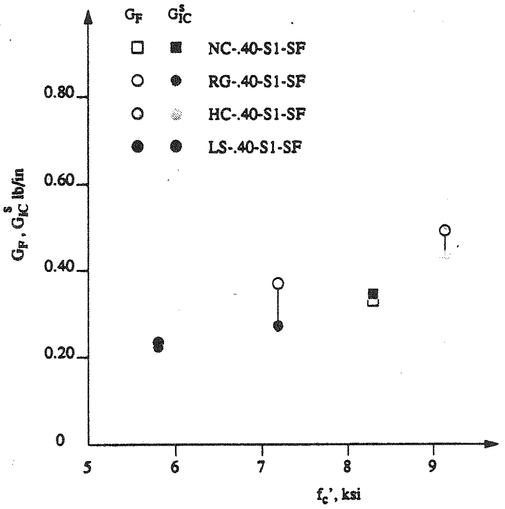

Fig. 8. Fracture energy G_F and energy release rate G^S_{IC} of concrete including silica fume at W/C = 0.40.

Results for fracture energy G_F and energy release rate, G^S_{IC}, are presented in Fig. 6 (Portland Cement only), Fig. 7 (Portland Cement plus fly ash) and Fig. 8 (Portland Cement plus silica fume). For the mixes using only Portland Cement it is seen the fracture energy values are always higher than energy release rate values except for the expanded shale mix where the values are almost the same. For this mix the crack surface was fairly smooth. The depth of the process zone was also smaller for this mix. The effect of fly ash (Fig. 7) and silica fume (Fig. 8) is to reduce the differences between G_F and G^S_{IC}.

4 Conclusions

The following overall observations were made:

1. In general, results for toughness and energy parameters by the RILEM methods were lower for the precracked beams than for the notched beams - the differences were greater for beams with rougher fracture surfaces, eg. river gravel and minimized for beams with smoother fracture surfaces, eg. expanded shale.
2. For a given W/C there is a wide range of values of K^S_{IC} (G^S_{IC}) and G_F for the different aggregates.
3. G^S_{IC} values approached G_F values for mixes where the matrix strengths were closer to or higher than the aggregate strengths when good bonding was available, eg. low W/C with crushed limestone or quartzite, low and high W/C with expanded shale.
4. The inclusion of fly ash to concrete decreased the concrete strength while tending to increase the fracture toughness (K^S_{IC}).

5 Acknowledgment

The research reported here was supported by the National Science Foundation, Grant No. MSM-8919449. This support is gratefully acknowledged.

6 References

John, P. and Shah, S.P. (1989) Fracture mechanics analysis of high-strength concrete. **Jnl. Mat. C.E.**, 1, 4, 185-98.

Kan, Y.-C. (1993) Influence of Concrete Constituents on Mode I Fracture Characteristics of Portland Cement Concrete, PhD Dissertation, Kansas State University, Manhattan, KS, U.S.A., 1993.

Karihaloo, B.L. and Nallathambi, P. (1991) Notched beam test: mode I fracture toughness. In **Fracture Mechanics Test Methods for Concrete**, eds. S.P. Shah and A. Carpinteri, Chapman and Hall. London, pp. 1-86.

RILEM, 50-FMC (1985) Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. **Mat. and Stru**. 18, 106.

RILEM, 89-FMT (1990) Determination of fracture parameters (K^S_{IC}) and $CTOD_c$) of plain concrete using three-point bend tests. **Mat. and Stru**., 23, 138, 457-60.

Swartz, S.E. and Refai, T. (1989) Cracked surface revealed by dye and its utility in determining fracture parameters. In **Fracture Toughness and Fracture Energy - Test Methods for Concrete and Rock**, eds. H. Mihashi, H. Takahashi and F.A. Wittmann, A.A. Balkema, Rotterdam, pp. 509-20.

Swartz, S.E. and Kan, Y.-C. (1991) On the validity of indirect measurement of the LPD for SEN concrete beams. In **Fracture Processes in Concrete, Rock and Ceramics**, eds. J.G.M. vanMier, J.G. Rots, A. Bakker, E&FN SPON, London, pp. 771-778.