[2113] CT試験によるコンクリートの破壊エネルギー評価に関する研究

FRACTURE ENERGY EVALUATION OF CONCRETE WITH COMPACT TENSION TEST

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1. INTRODUCTION

While structural analysis techniques have been rapidly developed, the constitutive laws of concrete are still remained to be rather traditional. Although the tensile strength is not taken into consideration in general structural design calculations, the importance to study the cracking behaviour of concrete has been recently noticed. For example, shear failure and/or bond failure of reinforced concrete members are strongly influenced by the cracking behaviour. Demands of finite element analyses of concrete structures have been stimulating a great increase of investigations into rational failure criteria and rational constitutive laws (1).

Since concrete is an extremely heterogeneous composite material, cracks are arrested and deviate when they encounter aggregates. Such cracking process creates a rather large microcracking zone and crack tip is blunted by the development of the zone. That is one of the reasons why linear elastic fracture mechanics can not be applied to concrete, while fracture mechanics approaches have been employed to study tensile mechanical behaviour of concrete since around 1960. Ordinary nonlinear fracture mechanics approaches are also inapplicable to concrete because it is hardly possible to measure the real crack length (2).

One way to quantify the toughness is to introduce the 'fracture energy G_F', which is the energy absorbed in the unit area of fracture surface. In order to measure the real fracture energy G_F, the movement has to be stable and the deformation should be increased without any sudden jumps. RILEM Technical Committee 50 - Fracture Mechanics of Concrete (50FMC) has published a recommendation on the determination of the fracture energy G_F by means of three-point bend test on a notched beam. In that connection, totally about 700 beams were tested in 14 laboratories from 9 countries in order to collect information and experience regarding the proposed method (3). While it was proved that the proposed test method seemed to be suitable for a standard test used in normal testing laboratories, it was also recognized that the value of G_F was dependent on the size of the ligament, the composition of concrete, the maximum aggregate size, curing conditions, age and so on. However, it is so far not known in detail how and why those parameters influence the fracture energy. Before the concept

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of fracture energy can be applied to structural analysis, it must be studied how the fracture energy is influenced by such parameters as the specimen size, the composition of concrete and so on.

Horvath and Persson studied the influence of the specimen size on G_F of concrete by means of three-point bend tests and direct tensile tests (4). They found that G_F increased with specimen size for low water-cement ratio but such effect was not found for high water-cement ratio. Mindess did also three-point bend tests using notched beams with four times different sizes (5). He pointed out that the fracture energy of the largest beams tested was about 40% higher than that for the smaller ones.

Shortcomings of the three-point bend test to study the influence of specimen size and the maximum aggregate size might be following: 1). The influence of self-weight causes various kinds of vagueness. Consequently RILEM recommendation used to give rather large values of G_F (6). 2). Increasing the size causes too large influence of the weight of the beam. Beams with the span which is proportional to the square root of the depth suggested by Hillerborg (3) might have some different arch action effects.

The aim of this article is to present an idea to study the influences of specimen size, the composition of concrete, the maximum grain size and the rate of loading on G_F by means of compact-tension test method. In this method, the loading direction is horizontal and consequently the specimen weight have no influence on the fracture energy evaluation.

Another important information for numerical analyses is the constitutive law of the fracture process zone, which is the strain-softening diagram. Even though the value of the fracture energy G_F is the same, various load-displacement curves are drawn with different constitutive laws. It means that only the determination of G_F is not sufficient but also the identification of the constitutive law is essential for the application to computerized structural analysis. This is discussed in other articles (7,8).

2. EXPERIMENTAL PROCEDURES

2.1 TEST SERIES AND PREPARATION OF SPECIMENS

The dimensions of CT (compact tension) specimens are shown in Fig. 1. Fourteen series of CT-specimens were tested. Test conditions for each series are given in Table I. More than three specimens were tested for each condition. The test series are classified in the following three groups:
1). Tests on the effect of specimen size;
2). Tests on the effect of loading rate;
3). Tests on the effect of concrete composion. The mixproportions of concrete are given in Table II together with the 28 days compressive strength. Normal portland cement and rounded river gravel from the Rhone valley graded according to Swiss standards were used (SIA 162). All CT-specimens were cast with their largest side being horizontal. The direction of crack propagation is then perpendicular to the direction of casting. The notch was cast using a 8 mm thick greased steel plate. After demoulding, they were cured in water until the test age of 28 days.
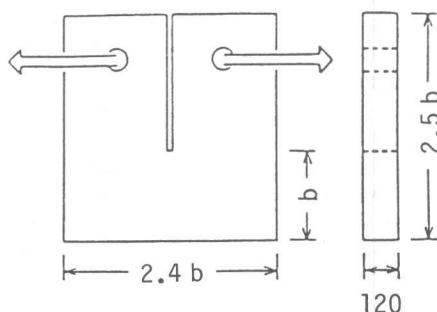

Fig. 1 Dimensions of specimens

Table I. Characteristics of the different test series

Test Group	Series		Specimen Size * (mm)	Ligament Length (mm)	Loading Rate (mm/min)	Composition d_{max} (mm)	W/C	Number of Specimens
	Reference		750x720x120	300	0.2	16	0.43	6
1	Small Size		375x360x120	150	0.2	16	0.43	6
	Large Size		1500x1440x120	600	0.2			
2	v (mm/min)							
	0.002		750x720x120	300	0.002	16	0.43	3
	0.02				0.02			3
	2.0				2.0			3
3	d_{max}	W/C						
	8	0.43	750x720x120	300	0.2	8	0.43	6
	8	0.50				8	0.50	4
	8	0.60				8	0.60	3
	16	0.50				16	0.50	5
	16	0.60				16	0.60	3
	32	0.43				32	0.43	4
	32	0.50				32	0.50	4
	32	0.63				32	0.60	3

* height, width and thickness.

Table II. Concrete compositions and 28 days compressive strength

Max. grain size d_{max}		8 mm			16 mm			32 mm		
Water-cement ratio W/C		0.43	0.50	0.60	0.43	0.50	0.60	0.43	0.50	0.60
Unit weight (kg/m^3)	Cement	375	350	330	350	332	306	320	310	288
	Aggregate									
	0/3	740	735	725	608	597	598	595	592	581
	3/8	1105	1100	1086	635	634	626	395	395	389
	8/16	--	--	--	676	670	658	395	395	389
	16/32	--	--	--	--	--	--	595	592	581
	Water	160	175	199	150	166	184	138	155	173
	Admixture*	5.4	2.3	--	4.6	2.3	--	4.3	2.0	--
Compressive strength (MPa)		40.6	39.0	30.2	42.9	37.7	24.4	42.2	39.2	28.7

* super plasticizer

2.2 TESTING PROCEDURES

A servo-controlled hydraulic jack was used onto the CT-specimen hung on steel beams. Besides the load, both the displacement in the plane of the loading points and the crack mouth opening displacement were measured and recorded for all specimens except for small size specimens, where only the crack mouth opening displacement was measured because the specimen size was too small to attach a displacement meter between loading points. The crack mouth opening displacement was used to control the rate of loading. The concrete surface around the ligament was covered with a wet cloth during the test in order to avoid drying.

3. TEST RESULTS AND DISCUSSION

For each series, a mean curve was obtained from the individual load-displacement curves measured in the plane of the acting load. The specific fracture energy value G_F was calculated as the area under the load-displacement curve divided by the ligament area. The tail of the curve was cut off at the position of 10 per cent of the peak load to consider the 'hinge mechanism' due to interlocking of aggregates, which did not work for the fracture energy. Although this treatment was introduced from a rather engineering point of view, the error might be about 3 per cent. Another possible way may be to use the information of the differential of the curve.

Tests to study size effect on G_F have been performed on specimens of different size where the height and the width have been changed proportionally and the thickness was kept constant. In the critical section, the ratio between the tensile stresses due to pure tension and the tensile stresses due to pure bending is the same for all specimens.

In Fig. 2, the effect of specimen size on G_F is shown. The fracture energy of smaller specimens was evaluated exceptionally using the ratio between the LVDT-displacement and the clip-gauge displacement as determined on the medium and the large size specimen. It seems that the specific fracture energy increases with increasing ligament length up to a limit value which is 300 mm in this case. For specimens with larger ligaments, G_F may turn out to be constant. Open circles are average values of the fracture energy evaluated for each curve by using the criterion to cut off the tail at the point where the differential normalized by the initial slope has become almost zero (greater than -0.003). The standard deviation of the obtained values is indicated by the length of the solid lines. The
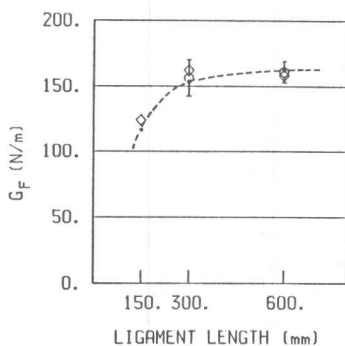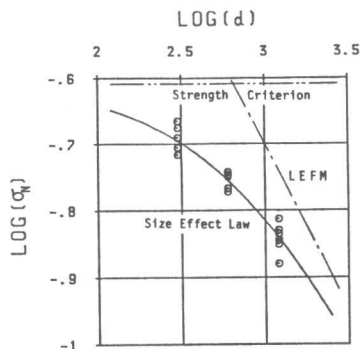

Fig. 2 Size effect on G_F

Fig. 3 Size effect law

dashed line with dots shows the calculated values using the fictitious crack model determined from load-crack mouth opening displacement curves (9).

Fig. 3 shows the size effect law proposed by Bazant (10). The fracture energy obtained from his approach is 117 N/m which is about 30 per cent less than that estimated from Fig. 2.

Fig. 4 shows the influence of the rate of loading on G_F. The fracture energy increases by about 45% while the maximum load increases by about 25%. This tendency is about the same as that in three-point bend test (6).
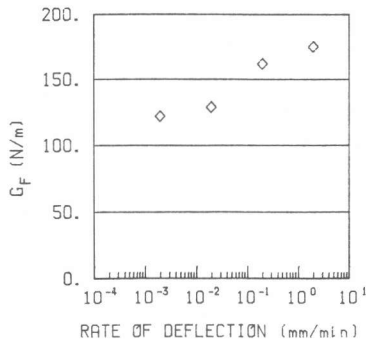

Fig. 4 Loading rate effect on G_F

Table III.
Influence of concrete
composition on G_F(%)

		W/C		
		.43	.50	.60
mm d_{max}	8	77	74	70
	16	100	88	77
	32	108	105	99

The influence of concrete composition on the fracture energy is shown in Table III. The reference value is 162 N/m. The values of G_F for concrete with different water-cement ratio and different maximum grain size are presented in Figs. 5 and 6, respectively. Generally speaking, increasing water-cement ratio decrease the fracture energy while increasing the maximum grain size increases the specific value G_F.

In the case of the maximum grain size 16 mm, the influence of w/c is relatively large but still 20% less than the corresponding value of three-point bend test (6). In other cases, the influence of w/c is rather little.

The influence of the maximum grain size is quite obvious and making the maximum grain size four times from 8 mm to 32 mm increased G_F by 40% for each water-cement ratio. However, the decreasing ratios in the case of d_{max} = 16 mm was dependent on the water-cement ratio. Similar test results have been reported by Kleinschrodt and Winkler (11), while Petersson found only a slight increase of G_F with increasing the maximum grain size (12). It might
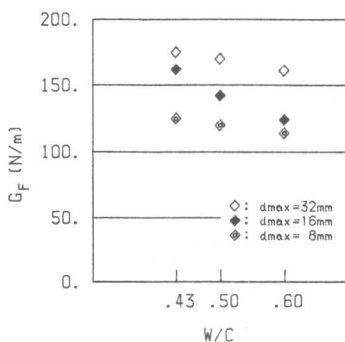

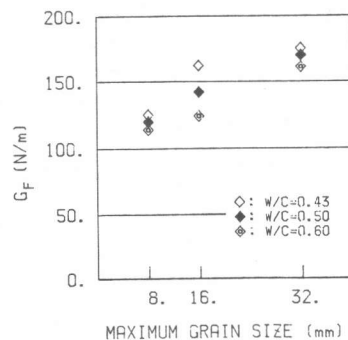Fig. 5 Effect of w/c on G_F Fig. 6 Effect of maximum grain size on G_F

not be so simple to describe the fracture energy as a function only of the maximum grain size but also the volume and the grading of aggregates might affect the development of the fracture process zone.

4. CONCLUSIONS

The fracture energy of concrete is influenced by the ligament length, the rate of loading, the water-cement ratio and the maximum grain size. The specific fracture energy increases with increasing ligament length up to a limit, then G_F seems to remain constant. The fracture energy increases at higher rates. The value of G_F decreases slightly with increasing w/c ratio. Furthermore G_F is considerably influenced by the maximum grain size. Concrete with the maximum grain size of 32 mm has a higher value of G_F by about 40 % than the value of concrete with the maximum grain size of 8 mm.

REFERENCES

(1) IABSE-AIPC-IVBH, "Advanced Mechanics of Reinforced Concrete," IABSE Colloquium, Delft, 1981.
(2) Wittmann, F. H. (Ed.), "Fracture Mechanics of Concrete," Elsevier, 1983.
(3) Hillerborg, A., "Results of Three Comparative Test Series for Determining the Fracture Energy G_F of Concrete," Materials and Structures, Vol. 18, No. 107, Sept.-Oct. 1985, pp. 33-39.
(4) Horvath, R. and Persson, T., "The Influence of the Size of the Specimen on the Fracture Energy of Concrete," Report TVBM-5005, Lund Institute of Technology, Lund, Sweden, 1984.
(5) Mindess, S., "The Effect of Specimen Size on the Fracture Energy of Concrete," Cement and Concrete Research, Vol. 14, 1984, pp. 431-436.
(6) Wittmann, F. H. et al., "Influence of Age of Loading, Water-Cement Ratio and Rate of Loading on Fracture Energy of Concrete," Materials and Structures, 1987 (to be published).
(7) Wittmann, F.H. et al., "Fracture Energy and Strain Softening of Concrete as Determined by Means of Compact Tension Specimens," Materials and Structures, (submitted).
(8) Rokugo, K. et al., "Different Methods to Determine Fracture Energy and Strain Softening of Concrete," Contribution to this volume.
(9) Kinoshita, Y., "Constitutive Law of Strain Softening for Concrete on the Basis of Fracture Mechanics ," M.S. Thesis of Tohoku University, 1987.
(10) Bazant, Z. P., "Nonlinear Fracture Properties from Size Effect Tests," J. of Structural Div., ASCE, Vol. 112, Feb. 1984, pp. 289-307.
(11) Kleinschrodt, H. D. and Winkler, H., "The Influence of the Maximum Aggregate Size and the Size of Specimen on Fracture Mechanics Parameters," Fracture Toughness and Fracture Energy of Concrete, Wittmann, F. H. Ed., Elsevier Science Publisher, 1986, pp. 391-402.
(12) Petersson, P. E., "Fracture Energy of Concrete: Practical Performance and Experimental Results," Cement and Concrete Research, Vol. 10, 1980, pp. 91-101.