Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

EFFECT OF AGGREGATE ON FRACTURE PROPERTIES OF HIGH-PERFORMANCE CONCRETE

T.P. Chang, K.L. Tsao and B.R. Lin
Department of Construction Engineering, National Taiwan University of Science and Technology, Taiwan, R.O.C.
B.R. Lin
Department of Civil Engineering, Tung Nan Junior College of Technology, Taiwan, R.O.C.

Abstract
The fracture properties of the high-performance concrete (HPC) having a slump of 260 mm, flowability of 680 mm, 28-day compressive strength of 64.7 MPa and modulus of elasticity of 25.1 GPa were studied. The size-effect law was used for examining the fracture properties. Experimental results show that the size of coarse aggregate and the amount of aggregate in the HPC have positive effects on the increase of its fracture properties. The value of fracture energy G_y of the HPC was found to be 68.3 N/m. When same volumetric amount of coarse aggregate in the HPC was replaced by the fine aggregate, the fracture energy G_y was dropped to the value of 22.5 N/m. The fracture energies of the hardened binder paste and cement paste range from 3.4 to 3.5 N/m.
Key words: Aggregate, fracture property, high-performance concrete.

1 Introduction

In addition to three major conventional ingredients used in the normal concrete, i.e., the Portland cement, fine and coarse aggregates and water, the making of high-performance concrete (HPC) needs to incorporate the supplementary mineral admixture such as silica fume, fly ash and blast-furnace slag, etc., and chemical admixture such as superplasticizer, etc., in order to have a high workability without segregation and high strength [Okamura 1997, Aitcin et al. 1993, Gutiérrez et al. 1996, Mehta et al. 1990]. There is no unique definition of HPC. The essence of HPC is emphasized on the performance requirement of the intended use of the concrete. In general, an HPC with an initial slump of more than 250 mm and a 28-day compressive strength of above 55 MPa can be regarded as the concrete having a high workability and high strength. Since the increasing demanding of applying the HPC to the various kinds of concrete constructions, the understanding of its fracture properties is useful for the designer to use the fracture criteria for the prediction of catastrophic crack propagation of the concrete structure under certain loading conditions. The purpose of this study is aiming at the effects of aggregate on the fracture properties of high-performance concrete based on the well-known size-effect model.

2. Calculation of fracture energy based on size-effect model

Three test methods have been recommended by the RILEM Technical Committee 50-FMC and TC89-FMT for measuring the fracture energy of concrete based on different fracture mechanics concepts, i.e., the fictitious crack model [Hillerborg et al. 1976], the two-parameter fracture model [Jenq and Shah, 1985], and the size-effect model [Bazant et al. 1987], respectively. The size-effect model was used in this study. According to this model, the geometry of the single-edge-notched three-point-bend (SEN-TPB) beam specimen used in this study is shown in Fig. 1. At least three sizes of specimens with a scale ratio of at least 4 must be used. Then the fracture energy G_f of the concrete can be calculated by the following equation [Bazant et al. 1987]:

$$G_f = \frac{B^2 (f_u)^2}{c_n^2 E'} d_0 g(\alpha_0) \tag{1}$$

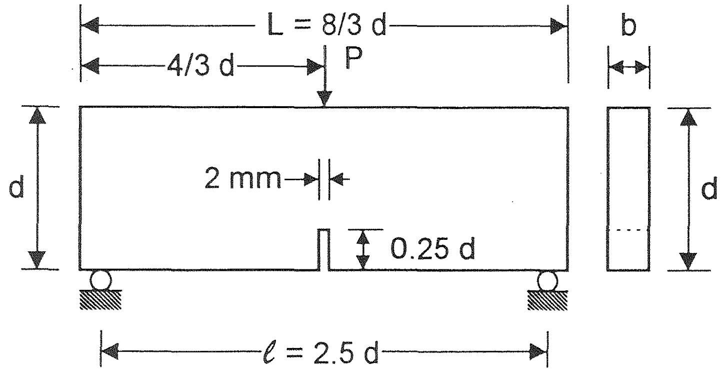

Fig. 1. Single-edge-notched three-point-bend (SEN-TPB) beam specimen

where E' = E for plane stress and E' = E/(1-v^2) for plane strain; E = modulus of elasticity; ν = Poisson's ratio; f_u = tensile strength of concrete; $c_n = 1.5\ell/[d(1-\alpha_0)^2]$; ℓ, d = span and height of the specimen, respectively; $\alpha_0 = a_0/d = 0.25$; a_0 = initial depth of the notch; $g(\alpha)$ is the geometric factor of the specimen and, for this case of $\ell/d = 2.5$, is given as

$$g(\alpha) = \left[\frac{6.647\sqrt{\alpha}\left(1-2.5\alpha+4.49\alpha^2-3.98\alpha^3+1.33\alpha^4\right)}{(1-\alpha)^{1.5}}\right]^2 \qquad (2)$$

Based on the size-effect law, the values of two constant B and d_0 in Eq. (1) can be determined from the test data of SEN-TPB beam directly through the following nonlinear regression:

$$\sigma_N = B\frac{f_u}{(1+d/d_0)^{0.5}} \qquad (3)$$

in which $\sigma_N = P_{max}/(bd)$; P_{max} = maximum failure load; b = thickness of the specimen. Or these two values can be simply calculated from the following linear regression:

$$Y = AX + C \qquad (4)$$

$$X = d; Y = \left(\frac{f_u}{\sigma_N}\right)^2; \sigma_N = c_n \frac{P_{\max}}{bd}; B = \frac{1}{\sqrt{C}}; d_0 = \frac{C}{A} \tag{5}$$

In general, the values of B and d_0 obtained from Eqs. (3) and (4) are different, but both sets can be legitimately used in the calculation of fracture energy. The linear regression approach was used in this study.

3. Materials

Portland Type I cement meeting the requirements of ASTM C150 was used for all the experiments. The coarse aggregate obtained from the crushed sandstone had its percents retained on the sieves of 4.7% (12.7 mm), 38% (9.5 mm) and 57.3% (4.75 mm), which led to a fineness modulus of 6.47. The specific gravity and absorption for coarse aggregate were 2.65 and 0.91%, respectively. The fine aggregate was a natural river sand, having a specific of 2.65, an absorption of 2.1 percent, and a fineness modulus of 2.89. A type F fly ash having a specific gravity of 2.21, a blast-furnace slag having a specific gravity of 2.87, and an ASTM Type G liquid superplasticizer were used in the test.

4. Experimental program

Four different types of specimen mixtures were used, i.e., the normal high-performance concrete (HPC), fine-aggregate concrete (HPCs), binder paste (HPCb), and cement paste (HPCp). The find-aggregate concrete (HPCs) was obtained by replacing all the coarse aggregate in the mixture of normal high-performance concrete (HPC) with a same volumetric amount of the fine aggregate. The binder paste was made purely by the paste in the HPC, which only contained water, cement, fly ash, blast-furnace slag and superplasticizer. Finally, the cement paste (HPCp) was composed of only same proportion of those water and cement that were used in casting the high-performance concrete (HPC). The proportioning of the four mixtures is summarized in Table 1.

Cylinders of $\phi 100 \times 200$ mm for compressive tests, splitting tensile test and test for modulus of elasticity were cast and tested using a 200 kN compression machine according to ASTM C469 and ASTM C496, respectively. Four different sizes of SEN-TPB beam specimens (40 × 40 × 110, 40 × 80 × 210, 40 × 160 × 430, 40 × 320 × 850 mm) with a notch width of 2 mm for the fracture energy test were cast and tested using a 100 kN MTS machine with a close-loop-controlled stroke system. There were three specimens tested for each set of experiment. All the specimens were stored in the saturated lime water under a temperature of 23±2 °C until one day before the test.

Table 1. Proportion of the concrete mixture (kg/m^3)

Item	Normal HPC	Fine aggregate HPCs	Binder HPCb	Cement HPCp
Coarse aggregate	1018	0	0	0
Fine aggregate	708	1726	0	0
Cement	382	382	1096	1342
fly ash + slag	145	145	416	0
Superplasticizer	21	21	15	3
Water	163	163	469	574
W/C	0.43	0.43	0.43	0.43

5. Test results and discussion

The compressive strength f_c, splitting tensile strength f_u, modulus of elasticity E_c, Poisson's ratio ν, slump, and flowability for four kinds of specimen mixtures tested in this study are shown in Table 2.

Table 2. Engineering properties of specimens

Item	HPC		HPCs		HPCb		HPCp	
age (day)	28	56	28	56	28	56	28	56
f_c (MPa)	64.7	67.2	40.7	50.7	71.0	75.2	52.7	54.4
f_u (MPa)	—	4.18	—	3.58	—	3.20	—	1.39
E_c (GPa)	25.1	26.3	21.0	22.9	18.7	19.8	12.6	15.2
ν	0.12	0.10	0.15	0.12	0.20	0.18	0.15	0.18
Slump (mm)	260		10		> 280		> 280	
Flowability (mm)	660		200		> 700		> 700	

Note: — data unavailable

With a careful and logical rule to make the concrete proportioning, the slump and flowability of the high-performance concrete (HPC) was found to be 260 mm and 660 mm, respectively. The compressive strength f_c and modulus of elasticity E_c at age of 28 days were 64.7 MPa and 25.1 GPa. Because of the increase of larger surface area of the replacing fine aggregate, the slump and flowability of fine-aggregate concrete HPCs reduced abruptly. The hardened binder paste has the highest compressive strength among four specimen mixtures, which indicates, in addition to the durability consideration, the positive gain of material strength by adding the mineral admixture in the mixture of high-performance concrete. Due to a better packing structure for the aggregate mixture of coarse and fine particles in the concrete, the compressive strength of high-performance concrete (HPC) is higher than that of the fine-aggregate concrete (HPCs).

The test data from the fracture experiments for all the SEN-TPB beam specimens are shown in Table 3. Typical point load-CMOD (Crack-mouth-opening-displacement) curves for the high-performance concrete HPC and the cement paste HPCp at the age of 56 days are shown in Fig. 2(a) and (b).

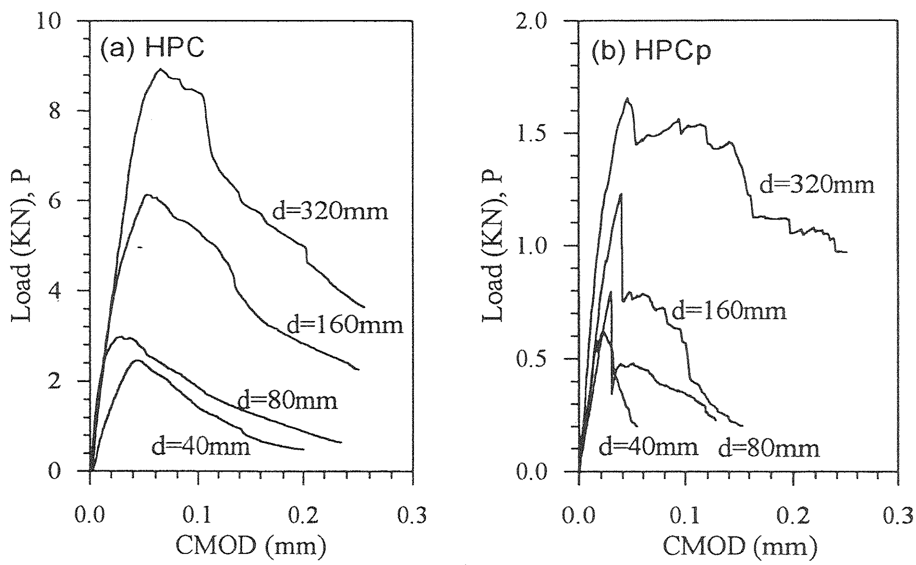

Fig. 2. Typical load-CMOD (crack-mouth-opening-displacement) curves for four different sizes of SEN-TPB beam specimen cast by (a) high-performance concrete (HPC) and (b) cement paste (HPCp)

Table 3 Maximum center loads P_{max} on four SEN-TPB specimens

Type	age (day)	d (mm)	P_{max} (N) #1	#2	#3	A (m^{-1})	C	B	d_0 (mm)	G_f (N/m)
HPC	56	40	1802	2389	2467	2.06	0.141	2.667	68.30	68.3
		80	2990	3714	—					
		160	5781	6852	6147					
		320	9025	8708	8892					
HPCs	56	40	1762	1925	2406	5.25	0.014	8.439	2.674	22.5
		80	2738	3248	—					
		160	3425	3525	—					
		320	4708	5632	5891					
HPCb	56	40	528	746	700	31.3	0.254	4.683	8.126	3.48
		80	—	1142	—					
		160	1655	1060	1296					
		320	1980	1911	—					
HPCp	56	40	694	606	592	6.75	0.046	4.683	6.756	3.40
		80	835	795	—					
		160	1228	1355	—					
		320	1654	1980	—					

Notes: —: unavailable due to bad specimen condition.

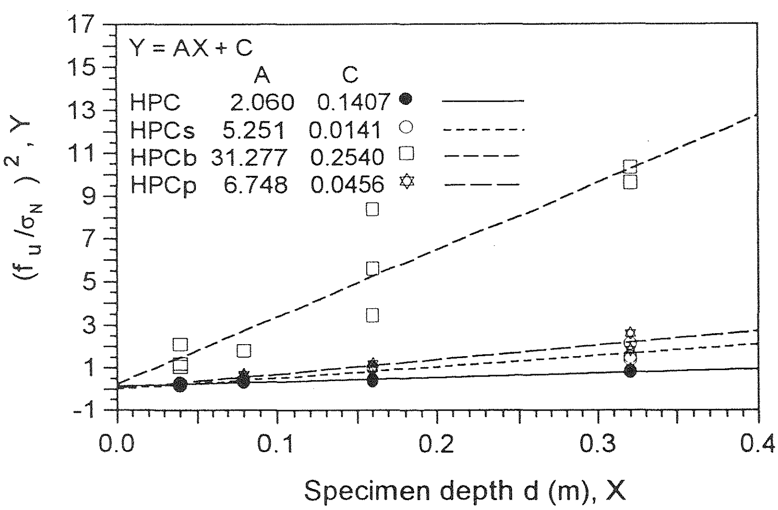

Fig. 3. Linear regression lines and values of constants

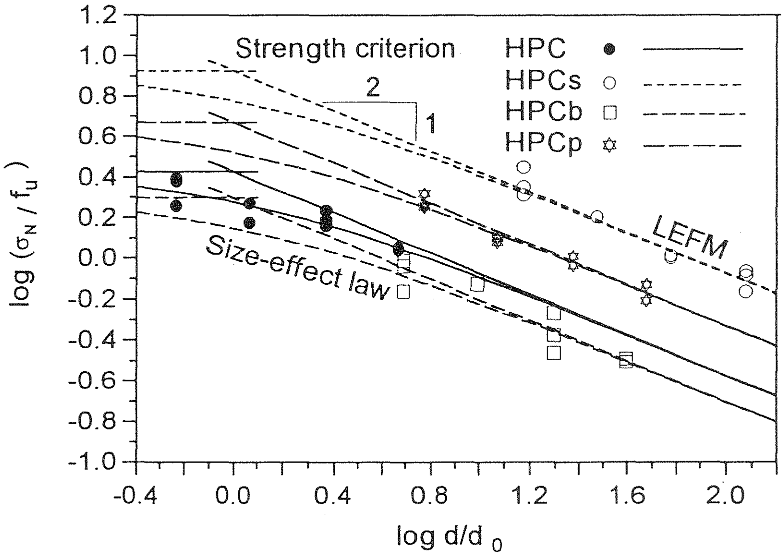

Fig. 4. Size-effect curves for four SEN-TPB beam specimens

Since the considerably brittle properties of the hardened cement paste (HPCp), the response after the peak load exhibits an unstable and abrupt up-and-down manner as shown in Fig. 2(b). Similar pattern was also found in the hardened binder paste (HPCb). By using Eqs. (4) and (5), the linear regression lines and the values of constants A and C for all the test data are shown in Fig. 3. Because of a relatively higher tensile strength of the hardened binder paste (HPCb), the slope of its linear regression line is much steeper than those of the other three mixtures as shown in Fig. 3. By using Eqs. (1), (2), (4) and (5), the fracture energies G_f for four mixtures are obtained and shown Table 3. The resulting size-effect curves based on these given values are illustrated in Fig. 4.

Although it has been well-known that the hardened concrete usually has a higher fracture energy than the hardened mortar and cement paste, it is quite surprised to note that, from the test results in this study, there is a tremendously higher fracture energy of 68.3 N/m for high-performance concrete (HPC), as comparing with those values of 22.5 N/m (HPCs), 3.48 N/m (HPCb) and 3.40 N/m (HPCp). For normal strength concrete, the value of G_f was about 24.1 N/m for f'_c = 36.9 MPa at age of 28 days ($G_f \cong$ 21.4 N/m for f'_c = 32.5 MPa at age of 14 days), and 85.5 MPa N/m for high-strength concrete (f'_c = 85.5 MPa at age of 14 days) [Gettu et al. 1990]. But the values of G_f seem to be rather scatter. Other paper reported that

G_f = 14.6 N/m for normal concrete with f'_c = 21 MPa, and G_f = 45.1 N/m for high-strength concrete with f'_c = 62.6 MPa [Perdikaris et al. 1995]. In current study, the pozzolanic reaction between the mineral admixture and calcium hydroxide in the product of cement hydration helps increase the strength of cement paste and interface strength on the aggregate surface of high-performance concrete. This is part of the reason that high-performance concrete has a better fracture energy. The test data confirms that the inclusion of a certain amount and size of coarse aggregate in the HPC is necessary and beneficial to both the concrete strength and fracture energy. On the other hand, the hardened binder paste (HPCb) has the highest compressive strength, but its fracture energy is also almost the lowest. Maintaining same volumetric amount of coarse aggregates but with the smaller size in the high-performance concrete (HPCs) will reduce the fracture energy substantially. The correlation between the strength and fracture energy varies considerably and randomly in the current study. This observation indicates that the strength of concrete seems not the only criterion to infer the value of its corresponding fracture energy. Other factors such as the characteristics of packing structure of aggregate mixture in the concrete, the sizes of aggregates, etc. need to be properly accounted for. Therefore, the relation between the strength and fracture energy of concrete seems not to be in a monotonic manner. Also note that a steeper slope in the regression line of the test data does not necessarily mean a higher fracture energy for the material.

6. Conclusions

The major conclusions of this study can be summarized as follows:

1) A certain amount and proper size of coarse aggregate in the HPC is beneficial to the concrete strength and fracture energy. Based on the size-effect law, the hardened high-performance concrete has a much higher fracture energy (68.3 N/m) than the comparable hardened mortar (22.5 N/m), binder paste (3.48 N/m) and cement paste (3.4 N/m).
2) In addition to the compressive strength, the packing structure of aggregate mixture and the sizes of aggregate particles, etc. also play a very important role in determining the fracture energy of high-performance concrete. Same volumetric amount of aggregate but with different size gradation used in the high-performance concrete will substantially alter the fracture properties of concrete.
3) The correlation between the strength and fracture energy of concrete is

not monotonic nor unique. There seems exist an optimal fracture energy for all kinds of the high-performance concrete.

7. Acknowledgments

The financial support of NSC86-2211-E-011-004 to this study from the National Science Council, Taiwan, R.O.C. is highly appreciated.

8. References

Aitcin, P.-C. and A. Neville (1993) High-Performance Concrete Demystified, **Concrete International**, Vol. 15, No. 1, Jan. 1993, 21-26.

Bazant, Z. P. and Pfeiffer, P. A. (1987) Determination of Fracture Energy from Size Effect and Brittleness Number, **ACI Materials Journal**, Vol. 84, No.6, 463-480.

Gettu, R., Bazant, Z.P., and Martha, E.K.(1990) Fracture Properties and Brittleness of High-Strength Concrete, **ACI Materials Journal**, Nov-Dec., pp. 608-618.

Gutiérrez, P. A. and Cánovas, M. F. (1996) High-Performance Concrete: Requirements for Constituent Materials and Mix Proportioning, **ACI Materials Journal**, Vol. 93, No. 3, 233-241.

Hillerborg, A., Modeer, M., Petersson, P.-E. (1976) Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements, **Cement and Concrete Research**, Vol. 6, No. 6, 773-782.

Jenq, Y. S. and Shah, S. P. (1985) A Two Parameter Fracture Model for Concrete, **Journal of Engineering Mechanics, ASCE**, Vol. 111, No. 4, 1227-1241.

Mehta, P.K. and P.-C. Aitcin (1990) Principles Underlying Production of High-Performance Concrete, **Cement, Concrete and Aggregate**, Vol. 12, No.. 2, Winter, 70-78.

Okamura, H, (1997) Self-compacting High-Performance Concrete, **Concrete International**, July, 50-54.

Perdikaris, P. C. and Romeo, A. (1995) Size Effect on Fracture Energy of concrete and Stability Issues in Three-Point Bending Fracture Toughness Testing, **ACI Materials Journal**, Vol. 92, No. 5, 483-496.