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Effect of specimen size on fracture energy and softening curve of concrete: Part I. Experiments and fracture energy

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ABSTRACT

The fracture energy of concrete G_F is a fundamental fracture parameter, presenting the concrete's cracking resistance. However, because of the experimentally observed size dependency, it remains controversial as to whether the fracture energy can be considered as a material property. In this study, a three-point bend test for a notched beam and a wedge splitting test were performed with different size specimens for ten different concrete mixes in order to investigate the effect of specimen size and geometry on the fracture energy. A data processing method was proposed for averaging the test results of companion specimens, and the fracture energy was calculated from the averaged results. From a comparison of the fracture energies, it was found that the fracture energy increases with an increase in specimen size in both the beam and wedge splitting tests.

1. Introduction

Fracture energy is a fundamental fracture parameter, representing cracking resistance and fracture toughness of concrete, and is generally considered as a material property in concrete fracture mechanics and cracking analyses. However, it remains controversial as to whether or not the fracture energy is size dependent. Existing studies [1–5] have shown that the experimentally determined fracture energy increases with increased specimen size. Some researchers have argued that the fracture energy is a material property, and the observed size effect is caused by several sources of experimental error, the testing procedure or limitations of the three-point bend test in finding the fracture energy [6–10]. In practice, three-point bend tests are performed in most studies on size effect of fracture energy; however, this testing method could entail considerable experimental error, as noted in the literature [7–9]. Hu and Wittmann [11] here stated that the size effect is caused by variation in the width of the fracture process zone according to the ligament length of the specimen.

In order to more clearly verify the effect of specimen size and geometry on the fracture energy, three-point bend tests for a notched beam and wedge splitting tests were performed simultaneously for thirty-four specimens comprised of ten different concrete mixes, where the maximum size of coarse aggregate and the water to binder ratio were varied. The load-deflection and the load-CMOD measured from the companion specimens were averaged by a data processing method suggested in this study, and the fracture energy for each specimen was calculated from the averaged data. From the calculated fracture energy for every specimen, the effects of specimen size, geometry, aggregate size, and water to binder ratio on the fracture energy are analyzed and discussed.

2. Experiments

2.1. Materials

Table 1 shows the concrete mix proportions. There are three groups of concrete mixes; SG group is concrete made of small size gravel, LG group is dam concrete, and WG group is wet-screening concrete where the gravel of more than 40 mm is removed through screening the fresh mixes, LG1 and LG2, respectively. Type IV cement, fly ash, crushed gravel, and river sand were used in all the mixes. The water to binder ratio was ranged from 0.30 to 0.50, and the gravel size from 10 mm to 80 mm. The substitution rate of fly ash was 10–30% for the total binder content.

2.2. Test program

Table 2 shows the test program. Both three-point bend tests for a notched beam and wedge splitting tests were performed for the six

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Table 1
Mix proportions

Concrete mix		w/b	Maximum gravel size	Unit weight(kg/m^3)						
				c	w	F.A	S	G	W.R.	A.E.
SG	1	0.50	10 mm(0.4 in.)	196	140	84	869	1090	1.68	0.0196
	2	0.50	20 mm(0.8 in.)	185	132	79	846	1152	1.58	0.0185
	3	0.45	20 mm(0.8 in.)	240	135	60	814	1154	1.80	0.0195
	4	0.35	20 mm(0.8 in.)	309	135	77	744	1145	2.32	0.0251
	5	0.30	20 mm(0.8 in.)	420	140	47	698	1121	2.80	0.0280
	6	0.50	40 mm(1.6 in.)	168	120	72	769	1287	1.44	0.0168
LG	1	0.45	80 mm(3.1 in.)	159	102	68	625	1496	1.36	0.0159
	2	0.50	80 mm(3.1 in.)	143	102	61	653	1491	1.22	0.0143
WG	1	0.45	40 mm(1.5 in.)	159	102	68	625	1496	1.36	0.0159
	2	0.50	40 mm(1.5 in.)	143	102	61	653	1491	1.22	0.0143

SG; small gravel concrete, LG; large gravel concrete, WG; wet-screening concrete.

mixes, SG1 to SG6. The beam tests were carried out for LG1 and WG1, and the wedge splitting tests for LG2 and WG2. The mixes SG1, SG2, LG1, LG2, WG1, and WG2 have from two to five different size specimens for the beam and wedge splitting tests. The tests were designed so as to allow for comparison of the test results according to the specimen size, maximum aggregate size, water to binder ratio, and testing method for ten different concrete mixes.

2.3. Specimen and test set-up

Fig. 1 shows the geometry of the beam and wedge specimens, and the dimensions are listed in Tables 3 and 4. In addition to the fracture tests, tests for compressive strength and secant modulus were performed following the ASTM C 469-94 [12] at an age of 1 year. Compressive strength and elastic modulus were determined based on an averaged result of three identical 150×150×150 mm cubes and Φ150×300 mm cylinders, respectively. The mold for each specimen was removed 1 day after casting, and each specimen was cured by spraying water on the surface to prevent drying during a period of 28 days. All the mixes were designed for an actual dam built in China, and the specimens were kept in the same environmental condition as the dam for 1 year after curing. The characterization specimens were also stored together with the fracture specimens.

Every test was performed at the age of 1 year. Four companion specimens were manufactured for each test variable, but some specimens were broken in handling and moving and reliable test results could not be obtained for some specimens. The numbers of companion specimens that were employed in the beam and wedge splitting tests and provided reliable data are also listed in Tables 3 and 4.

Fig. 2(a) shows the set-up for the three-point bend beam test. The tests were conducted in a very stiff servo-hydraulic closed-loop testing machine. A 100 kN capacity load cell was used to measure the applied load, and the accuracy was ±2% of the maximum applied load. The crack mouth opening displacement (CMOD) was measured with a displacement sensor having a capacity and accuracy of 5 mm and ±0.0005 mm, respectively. The vertical deflection was also measured at the loading point. The loading actuator was controlled by a constant CMOD rate of 0.15 mm/min.

Some wedge splitting specimens were much larger than ordinary size, because large size coarse aggregate was used. One line support is generally located in the center of the wedge specimen [13–15]. In contrast with an ordinary wedge splitting test, two line supports located in the center of the half section of the specimen were used in order to circumvent difficulties in handling the very large size specimen and to prevent unexpected failure of the specimen while preparing the test. As shown in Fig. 2(b), two massive steel loading devices equipped with roller bearings on each side were placed on top of the specimen. A steel profile with two identical wedges was fixed at the upper plate of the testing machine. The wedges enter between the bearings, which apply a horizontal splitting force (P_S). The displacement sensor and load cell were identical to those used in the beam test. The axis of the roller was aligned with the displacement sensor, that is, the displacement was measured at the horizontal loading axis. The wedge splitting test was also controlled by a constant CMOD rate of 0.15 mm/min. Fig. 3 shows the real test set-up.

To make the notch in every specimen, steel plate with the thickness of 2 mm was fixed in the molds before casting, and the surfaces facing concrete were painted with lubricating oil to prevent friction between the plate and concrete. When demolding, the steel plate was carefully removed.

3. Data processing for companion specimens

3.1. Averaging the data for companion specimens

There were two to four companion specimens for each test. In order to find the fracture characteristics for each test, it is necessary to average the test results for the companions. However, the averaged results may depend on the method used to average the data. The method used to process the test results for the companion specimens is described below.

In Fig. 4, the data processing procedure for three companion specimens of LG2-W1 is illustrated as an example for beam and wedge splitting specimens. Fig. 4(a) shows the raw test data for three companion specimens, where the total number of raw data for each specimen was about 50,000. The data scattered far from the load-CMOD curve are first filtered and then one point is taken every 20 points in the load-CMOD curve. Around a given point, an average was taken of five points consisting of the given point, and two points above and below the given point. By averaging the five adjacent points, the effect of fluctuation in the measurement can be removed. Fig. 4(b) shows the results after filtering and averaging for each companion. The peak load point of each specimen are taken from the results given

Table 2
Test program

Concrete mixes	Test method	
	Beam	Wedge
SG1	○	○
SG2	○	○
SG3	○	○
SG4	○	○
SG5	○	○
SG6	○	○
LG1	○	X
LG2	X	○
WG1	○	X
WG2	X	○