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Fracture process zone in notched concrete beam under three-point bending by acoustic emission

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HIGHLIGHTS

- Investigation of fracture process zone in concrete by AE-SiGMA.
- Fracture energy varies with two parameters of notch depth and maximum size of aggregate.
- The opening crack (mode I crack) mostly generates when the notch depth becomes higher.
- Fracture energy correlates with the width of AE cluster.

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ABSTRACT

Investigation on fracture process zones in notched concrete beams under three-point bending is performed by applying acoustic emission (AE). The tests were conducted on beam specimens with different notch depths and the maximum sizes of aggregate in concrete to clarify the generation mechanisms of micro-cracks in the fracture process zone. SiGMA (simplified Green's functions for moment tensor analysis) procedure was applied to analyze AE signals. The experimental results show the fracture energy increases with increase in the maximum size of aggregate. It is found that dominant motions of micro-cracks vary with the notch depth, regardless of the maximum size of aggregate. The widths of the fracture process zone were estimated from results of AE source location. It is confirmed that the fracture energy correlates with the width of AE cluster, as the energy increase when the width of fracture process zone expands.

1. Introduction

Nucleation of the fracture process zone is a key issue for determining of the fracture energy. The fracture process zone is known to be created in front of an existing crack in concrete. The fracture energy in concrete is normally obtained by a three-point bending on a notched concrete beam as defined by RILEM and JCI (Japan Concrete Institute) [1]. It is well known that the fracture energy varies with specimen size and geometry. In addition, development and size of the fracture process zone play an important role in fracture energy in concrete [2,3]. Therefore, it is important to investigate development process of the fracture process zone and generation mechanisms of micro-cracks in the zone.

Formation and growth of micro-cracks are associated with the release of strain energy in the form of acoustic emission (AE) signals. AE technique has been applied to investigate the fracture process zone in notched concrete beams under three-point bending [4–7]. The zone elsewhere was visualized by X-ray diffraction analysis [7]. These results imply that the area of AE cluster with higher energy could be referred to as the fracture process zone [7]. In addition, two zones of an inner zone with interacting micro-cracking zone and a surrounding isolated micro-cracking zone are classified [7,8], although it is limited by specimen boundary [8,9].

In this study, three-point bending tests are conducted in notched concrete beams which have different notch depths and different maximum sizes of aggregate. The generation mechanisms of micro-cracks in the fracture process zone are discussed based on results of AE measurement. SiGMA (simplified Green's functions for moment tensor analysis) procedure is applied to identify AE sources because the technique is applicable to classify micro-crack into three modes of tensile, mixed-mode and shear cracks [10,11].

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Table 1
Physical properties of aggregates.

Type	Density		Absorption (%)	F.M.
	S.S.D.[a] (g/cm^3)	O.D.[b] (g/cm^3)		
Natural sand	2.61	2.53	3.32	1.54
Crushed sand	2.61	2.57	1.49	2.83
Crushed stone	2.63	2.60	1.02	6.68

[a] S.S.D. is density in saturated surface-dry condition of aggregate.
[b] O.D. is density in oven-dry condition of aggregate.

In addition, the relation between the fracture energy and the width of the fracture process zone is discussed.

2. Experimental procedure

2.1. Specimens

Ordinary Portland cement of 3.16 g/cm^3 density was used as binder. Natural sand and crushed sand were used for fine aggregate in concrete specimens, they were mixed as the proportion of two to eight by weight. Table 1 shows physical properties of aggregates. In the experiment, three types of concrete were cast to investigate the effects of the maximum size of aggregate. The maximum sizes of aggregate were 5, 10 and 20 mm. Table 2 shows mixture proportions of concrete. Actually concrete specimens of the maximum size 5 mm was mortar. All specimens were cured in 20 °C water for 28 days. Mechanical properties of hardened concrete are summarized in Table 3.

2.2. Experimental setup

The three-point bending tests were conducted in accordance with the code of JCI [1]. The specimens are of dimensions: length = 400 mm, width = 100 mm and height = 100 mm with the notch depths 'a' as shown in Fig. 1. The notch depths (a) were 30, 50, 70 and 80 mm. The notches were created by setting T shaped plastics in the molds before fresh concrete was cast into them. The load was measured by a load cell and the crack mouth opening displacement (CMOD) was measured by three transducers attached at bottom of the notch. The specimens were tested under CMOD control at a rate of 0.001 mm/s. Teflon sheets were inserted between specimen and supports to avoid noise signals.

The fracture energy (G_f) can be obtained by following equations [1].

$$G_f = \frac{0.75W_0 + W_1}{A_{lig}} \quad (1)$$

$$W_1 = 0.75\left(\frac{S}{L}m_1 + 2m_2\right)g \cdot CMOD_c \quad (2)$$

where, G_f is fracture energy [N/mm], W_0 is area of under load-CMOD curve [N mm], W_1 is specimen weight [N mm], A_{lig} is area of ligament, m_1 is specimen weight [kg], S is span [mm], L is specimen length [mm], m_2 is weight of jig on the specimen [kg], $CMOD_c$ is crack mouth opening displacement at fracture [mm].

2.3. AE measurement and SiGMA analysis

Six AE sensors of 150 kHz resonance were attached to the surface of the specimen as shown in Fig. 1. AE signals were amplified with 40 dB gain by pre-amplifier, and then they were recorded by AE measurement system (μSAMOS, PAC). AE waveform was recorded at 1 MHz sampling frequency. The threshold level was 35 dB.

The detected AE signals in the test were applied by SiGMA (simplified Green's functions for moment tensor analysis) procedure to investigate AE source mechanisms in the fracture process zone. The SiGMA analysis consists of three-dimensional AE source location procedure and moment tensor analysis of AE source. From the SiGMA analysis, AE source is classified into three types of tensile mode, mixed-mode and shear mode [10]. Visualization of SiGMA results on cracking progress in fracture tests of reinforced concrete specimens under four-point

Table 3
Mechanical properties of hardened concrete.

Age (days)	Maximum aggregate size (mm)	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (kN/mm^2)
28	5	40.0	3.98	28.2
	10	45.4	4.00	25.9
	20	40.5	3.35	24.8

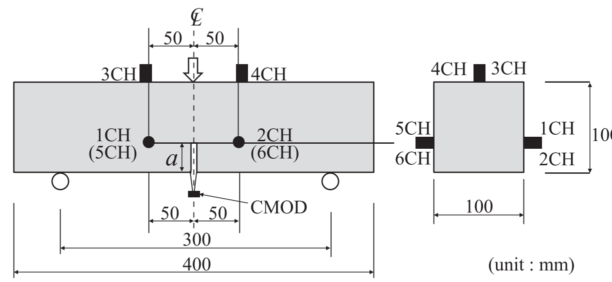

Fig. 1. Geometry of specimen and position of transducers.

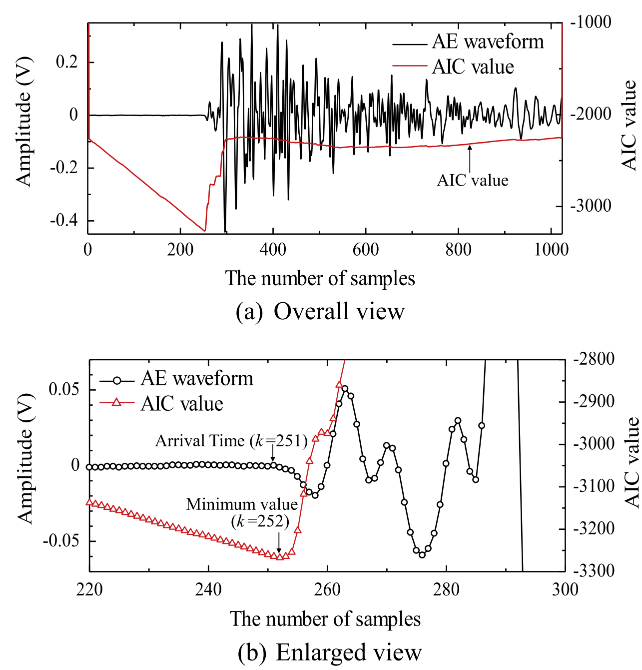

Fig. 2. The relation between an AE waveform and AIC value.

Table 2
Mixture proportions of concrete.

Maximum aggregate size (mm)	Slump (cm)	Air content (%)	Water to cement ratio (W/C) (%)	Sand aggregates ratio of volume (s/a) (%)	Unit content (kg/m^3)				
					Water	Cement	Fine aggregate	Coarse aggregate	Water-reducing admixture
20	8.0	4.5	58	45.9	172	297	826	981	1.20
10	8.0	4.5	58	45.9	172	297	826	981	1.20
5	–	–	58	–	172	297	826	–	–