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Study of the influence of aggregate size distribution on mechanical properties of concrete by acoustic emission technique

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Abstract

Acoustic emission (AE) has been widely used in concrete research as a dynamic nondestructive test method. In this study, the AE characteristics of concrete with different aggregate size distributions under uniaxial compression and three-point-bending were studied. Parameters such as maximum aggregate size, compressive strain and fracture energies of different concretes were also measured and discussed. The test results show that the characteristics of AE signals from concrete can illustrate the failure process in both compression and three-point-bending. The fracture energy increases with increment of the maximum aggregate size. Moreover, there is a good relationship between AE hits and fracture energy.

Keywords: Concrete; Aggregate; Mechanical properties; Acoustic emission

1. Introduction

Concrete is a composite material, consisting of aggregates and hardened cement paste. Generally, since aggregates occupy about 70% of the volume of a concrete mix, they exercise an important influence on the properties of the composite material. Thus, there has been a recent focus [1,2] on the influence of aggregate on the mechanical properties of concrete. For example, many studies have been carried out concerning the influence of the maximum aggregate size (d_{max}) on the fracture energy (G_f) of concrete. Kleinschrodt and Winkler [3] reported that the influence of d_{max} seemed to be insensitive to G_f, while Mihashi et al. [4] showed that the influence was significant. Since the real structure of the fracture process zone is not clarified yet, the influence of these factors has not yet been sufficiently discussed.

The acoustic emission (AE) technique, a tool for the nondestructive evaluation of metal and nonmetallic material, and for the detection of instability in engineering structures, has been applied to the studies of concrete mechanics, which focused on the properties of cracks extending during the fracture process [5–7]. The purpose of the present study is to investigate the influence of the aggregate size on the mechanical properties of concrete under uniaxial compression and three-point-bending using AE technique.

2. Experimental details

2.1. Raw materials

2.1.1. Cement

Chinese standard 525# ordinary portland cement, made by the Wusong cement factory, with a 28-day compressive strength of 63.5 MPa.

2.1.2. Ultrafine slag powder

The slag was provided by the Shaofeng cement factory of Hunan, and had specific surface of 6000 cm^2/g.

2.1.3. Aggregate

The fine aggregate used was natural sand, whose fineness modulus was 2.85 and the maximum size was less than 5 mm. The coarse aggregates are defined as the crushed particles with maximum size 10, 15 and 20 mm, respectively.

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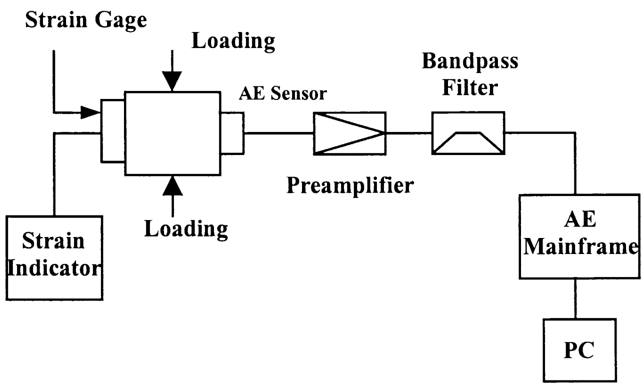


Fig. 1. Block diagram of AE setup for uniaxial compression test of concrete.

2.1.4. Superplasticizer

A sulfonated naphthalene formaldehyde superplasticizer was used.

2.2. Testing equipment

A schematic diagram of the loading equipment for compression tests and the AE setup is shown in Fig. 1. A SPARTAN-AT2000 AE system manufactured by Physical Acoustic was used for AE data acquisition; the emitted AE signals during tests were detected using a sensor with a resonant frequency at 150 kHz. The AE signals were amplified with a 40-dB gain in a preamplifier and a 20-dB gain in the system. The threshold was set at 40 dB to eliminate a high signal/noise ratio. The full details of the three-point loading flexural tests were given in a previous study [8].

2.3. Sample preparation

Mix proportions of the concretes are given in Table 1. The dimensions of specimens for compression tests were $100 \times 100 \times 100$ mm and for the three-point-bending tests were $100 \times 100 \times 515$ mm. Each bending specimen had a single edge notch with a depth of 50.0 mm. The specimens were demolded after 24 h, and then cured in a moist room (relative humility $>90\%$) for 28 days.

3. Test results and discussion

3.1. Relationship between AE total hits and compressive strength

Fig. 2a shows the relationship between the compressive strength and the maximum aggregate size. It may be observed that when the maximum aggregate size was less than 15 mm, the compressive strength of the concrete increased with an increase in maximum aggregate size. However, when the maximum aggregate size was greater than 15 mm, the strength began to decrease as d_{max} of aggregate increased. On the other hand, Fig. 2b shows the relationship between the detected AE total hits and the maximum aggregate size. It can be seen that the AE total hits increased with increasing maximum aggregate size. Especially when coarse aggregate was introduced into concrete, the AE total hits increased rapidly. The main reasons for this case are the following.

(1) The increasing strength of concrete with increase in maximum size of coarse aggregate is attributed to its improved "skeleton" effect. But the strength of the concrete may be reduced when the size of coarse aggregate exceeds a certain size (in this case 15 mm) due to the weak ITZ between the aggregate and the cement paste.

(2) Large defects may more easily exist in concrete containing large size aggregate, which is the main cause that microcracks propagate and develop under compression. Therefore, the AE total hits increase with the increasing aggregate size. The mortar, which is more homogeneous, causes few AE hits.

3.2. Correlation between AE signals and measured compressive strains

Fig. 3 shows the typical relationships between the AE total hits and the measured compressive strains of concrete specimens as a function of time. It may be seen that during the first two-thirds of the compression process both the AE total hits and the measured compressive strains increased approximately linearly and at a relatively low level. However, when the specimens were approaching failure, both the AE total hits and the measured compressive strains were found to increase rapidly and nonlinearly. The results

Table 1
Mix proportions of concrete

Series	Unit mass (kg m^{-3})							W[a] (Superplasticizer), %
					Gravel			
	Water	Cement	Slag	Sand	5–10 mm	10–16 mm	16–20 mm	
M00	175	472	202	1580				2.00
C10	175	472	202	632	948			1.25
C15	175	472	202	632		948		1.25
C20	175	472	202	632			948	1.25

[a] Percentage by mass of binder.

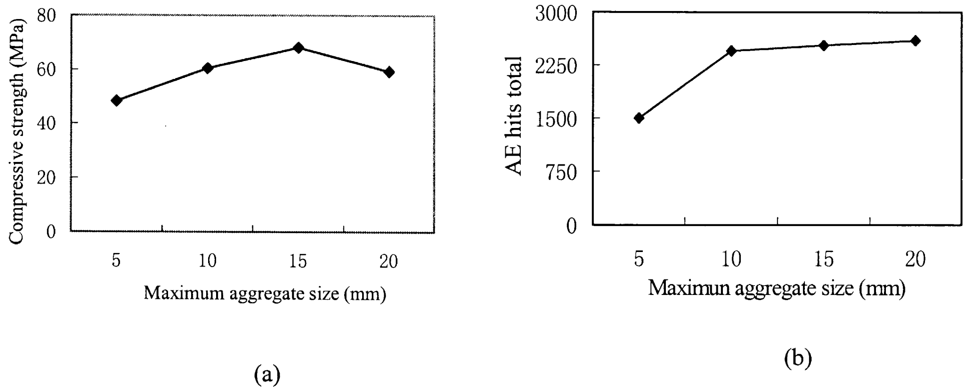


Fig. 2. Variation of (a) compressive strength and (b) AE total hits with different maximum aggregate.

showed that the AE total hits correlate well with the measured compressive strains.

It was also found that for the specimens in this study, there existed a significant common trend in the variation of the AE total hits during the entire compression process. The AE phenomenon can be divided into three stages:

(1) Stage 1 (Initial stage): At the beginning of the test, many AE hits were detected within a short period. It is believed that when the head of the universal testing machine came into contact with the specimen, cracks grew and propagated rapidly between the weak boundaries of the particles within the concrete specimen. Thus, many AE signals were emitted from the specimen and were detected.

(2) Stage 2 (Stable stage): As the compression process continued, the cracks within the specimen grew steadily, and the AE hits increased correspondingly.

(3) Stage 3 (Unstable stage): When the specimen approached its ultimate strength, unstable cracking occurred. Correspondingly, the AE hits increased abruptly, as shown in Fig. 3.

From the above descriptions, it is noted that the rapid increase in the AE hits from Stage 2 to Stage 3 may provide potentially useful information for judging the stability of a concrete specimen under uniaxial compression. This phenomenon could be treated as an indicator that the specimen is approaching failure.

3.3. Correlation between the distribution of AE hit peak amplitude and d_{max} of the aggregate

To establish the AE hit peak amplitude distribution curves for each stage, a new term called "AE hit ratio" is introduced. The AE hit ratio is defined as the number of AE hits for a certain peak amplitude divided by the total number of AE hits within a certain stage. By calculating the hit ratio for each different peak amplitude, the curve for each stage of the compression process can be established. Fig. 4 shows a typical diagram of AE hit ratio vs. hit peak amplitude for the concrete specimen with a maximum aggregate size of 15 mm. From Fig. 4 it may be observed that the proportions of the high peak amplitude AE hits (higher than 70 dB) in unstable stages are much higher than that in the initial and stable stage. In addition, it was found that the proportion of the lower peak amplitude AE hits (from 50 to 60 dB) in the stable stage were generally higher that in the unstable stage. It can be seen that there exists a good correlation between the

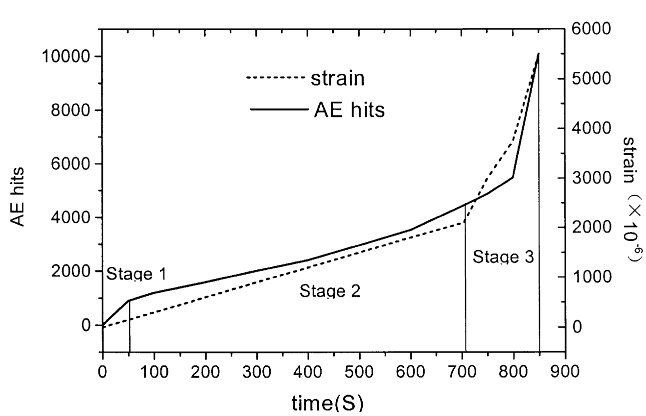


Fig. 3. A typical correlation between AE total hits and compressive strain of concrete.

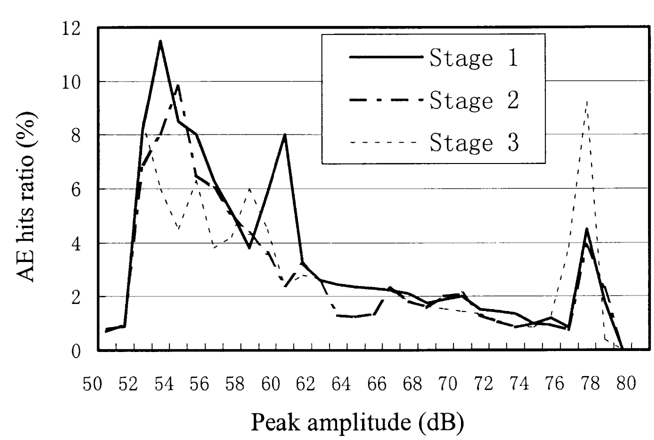


Fig. 4. AE peak amplitude distribution pattern for the three stages of the compression process, $d_{max} = 15$ mm.

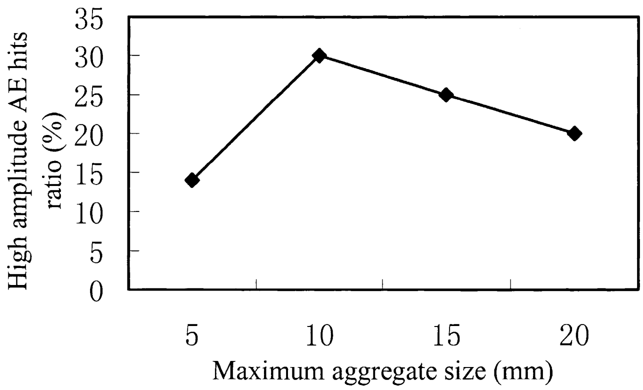


Fig. 5. Correlation between high amplitude AE hits ratio and the maximum aggregate size.

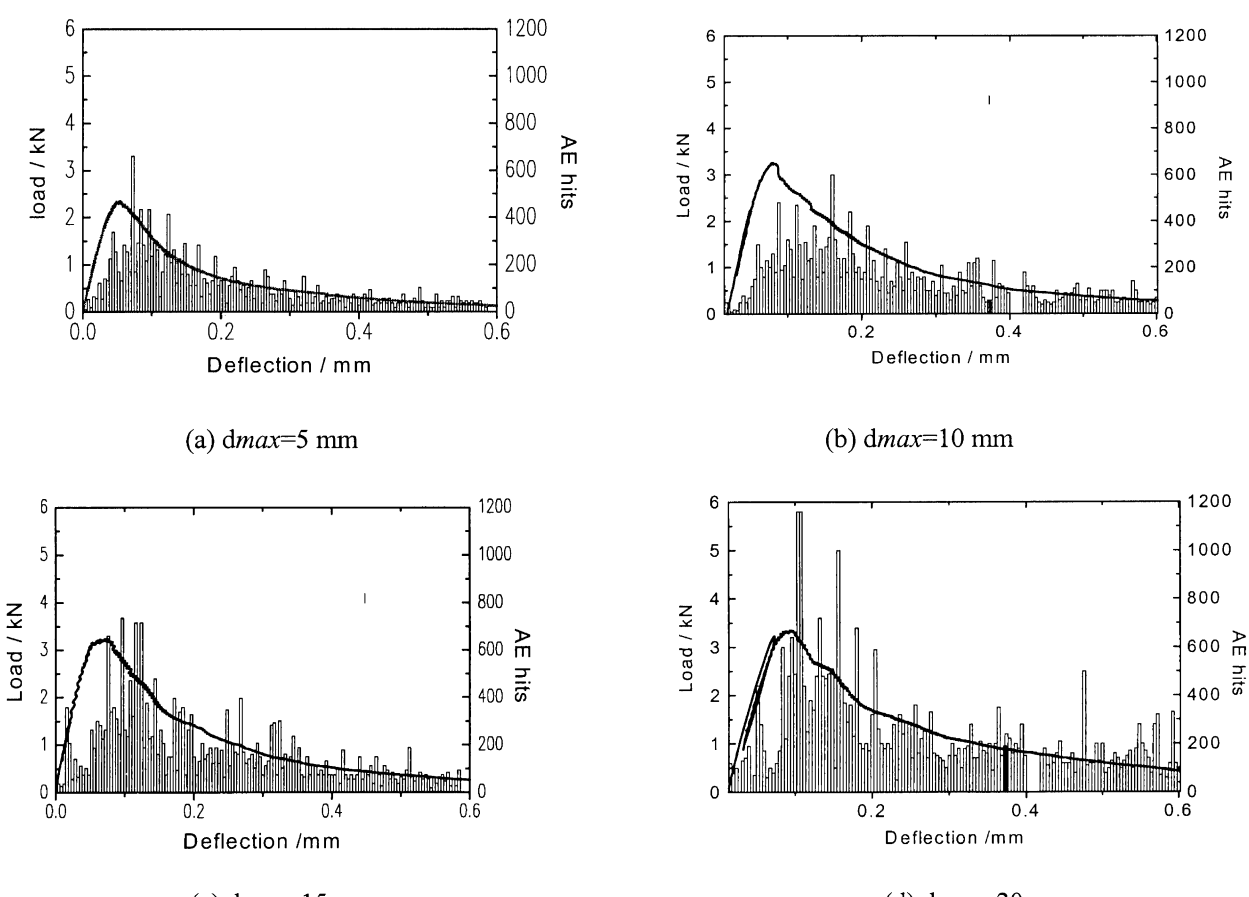
high peak amplitude AE hits and the growth of unstable cracks in concrete specimens. Therefore, a study was made to correlate the variations of the high amplitude AE hits and the concrete with different max size aggregates.

Fig. 5 shows the correlation between concrete with different maximum size aggregates and the high amplitude AE hit ratio. The "high amplitude AE hit ratio" is defined as the number of high peak amplitude AE hits (higher than 70 dB) divided by the number of detected AE total hits. From this figure, it may be seen that the high amplitude hit ratio reached maximum when the maximum aggregate size was 10 mm.

3.4. Correlation between AE signals and the P–δ curves

Concrete beams will also suffer damage under loading, resulting in unstable failure finally. AE, a tool for detecting the changes occurring in materials under load, can provide useful information regarding material properties.

The correlation between AE signals and the P–δ curves of concrete beams with different max size aggregate are shown in Fig. 6. It was found that the occurrence of AE has a good correlation with the load vs. deflection curve. In the ascending branch of the P–δ curves, the AE characteristics of concrete beams of different maximum aggregate size are similar, as follows: (1) During the initial loading stage, there is little AE occurring; (2) As the load reaches about 80% of the failure load, the AE activity becomes more intense; (3) When the external load exceeds the ultimate strength, the AE activity increases rapidly. In the descending branch of the P–δ curves, the maximum size of aggregate has a great effect on the AE



(a) d*max*=5 mm

(b) d*max*=10 mm

(c) d*max*=15 mm

(d) d*max*=20 mm

Fig. 6. The relationship between AE and the f–δ curve.

Table 2
Influence of aggregate size on the total number of hits and G_f

Series	M00	C10	C15	C20
G_f (N/m)	111.9	172.2	193.9	237.4
Hits	20733	25000	33187	43195

characteristics, represented by a change in the position of the peak of the hits occurring with different maximum size aggregate. The position of peak shifts to the later with decreasing maximum aggregate size.

The influence of the aggregate size on G_f and the total number of AE hits are shown in Table 2. As the aggregate size became larger, the values of G_f and AE hits significantly increased. From the fracture surfaces of the specimens, it is seen that when d_{max} is small, especially for mortar, the fracture surface is smooth; when d_{max} is large, the surface becomes rough and complex, and sometimes the coarse aggregates were broken.

4. Conclusions

(1) The AE technique can be applied to the study of the mechanical properties of concrete. The variation of the AE total hits was found to have a close correlation with the measured compressive strains and the compressive strength, which indicates that AE technology can be used as a helpful tool for monitoring the strain history and strength of concrete. It can also reflect the influence of the aggregate on the mechanical properties of concrete.

(2) The results of the study on the AE peak amplitude distribution showed that a good correlation existed between the high peak amplitude AE hits and the growth of the unstable cracks in concrete specimens.

(3) The results of the study on the three-point-bending beams showed that the total number of AE hits reflected the cracks propagating in the concrete. As the aggregates become large, the propagating crack path becomes complex.

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