Modes of Failure and Acoustic Emission of Rock Samples under Uniaxial Compression

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Summary A number of acoustic emission (AE) tests of rock samples in eight rock types were carried out in the laboratory under uniaxial compression. The correlation between pre- and post-failure behaviour of rock samples, modes of failure and AE patterns was investigated. The results showed that the AE patterns for different modes of failure were different while for the same type of failure modes, they shared certain types of similarities. It was anticipated that modes of failure could be predicted by the AE patterns.

1. INTRODUCTION

Mechanical properties of rocks are important parameters in mining engineering; they largely affect mine design, stability of mining workings, mine safety and production efficiency. Since the complexity of mining geomechanics comes from the unique condition that geological materials deposit, its corresponding measuring techniques are fraught with difficulties. The most effective approach in solving mechanical problems in mining geomechanics is to adopt a method that combines theoretical analysis, experimental research and field work in an integral model.

As a new method to study the behaviour of stressed rocks, the acoustic emission (AE) technique has been introduced and developed very quickly in rock mechanics in recent decades. Scholz [1] studied the cracking that occurred during the deformation of rock in compression by detecting and analysing the radiated elastic waves; Alheid et al [2] tested the acoustic emission of rock samples subjected to a stable sliding or stick-slip motions along the shear planes; Mansurov [3] performed rock AE tests and tried to define the failure process characteristics; Zou et al [4] simulated the microseismic emission during rock failure; Cox et al [5] investigated the microformation and material softening in rocks by monitoring acoustic emission; and Fonseka et al [6] carried out research on the crack development in rocks by means of scanning electron microscope and acoustic emission.

Nevertheless, there is little systematic work on the interrelations between modes of failure and AE patterns in the literature. The research that is to be carried out comprehensively in this area is in a high demand. It may contribute significantly to a better understanding of the role of factors affecting the way that rock fails and thus reveal the mechanism of rock failure. Furthermore, it will set up a theoretical basis for the wide application of the AE technique in the safety monitoring of rock engineering.

2. FAILURE MODES OF ROCK SAMPLES

The failure modes of rock samples can be simplified into three categories; shear failure, multiple fracture and vertical splitting as illustrated in Fig. 1.

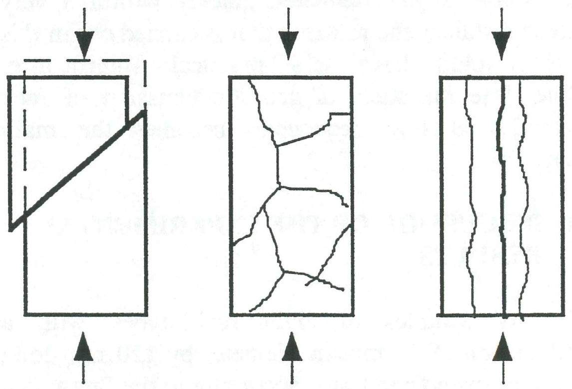


Fig.1 Modes of failure of rock samples

Generally, shear failure occurs by sliding along planes of weakness that are oriented at an acute angle to the loading axis. If planes of weakness are oriented parallel or sub-parallel to the loading axis, vertical splitting would be the case. More often, rock samples fail in both modes where shear and tensile failures appear to be present simultaneously. In such cases, the modes of failure can be classified as shear-dominated failure, multiple fracture or tensile-dominated failure. Since the shear failure, multiple fracture and vertical splitting result from distinct mechanisms, it is anticipated that the corresponding acoustic emission may exhibit different features.

3. EXPERIMENTAL SETUP

The experimental system used at the Western Australian School of Mines comprises three major parts: loading system, stress-strain measurement system, and AE monitoring system.

Loading system: The load was applied by the stiff servo-controlled electro-hydraulic INSTRON machine with a maximum capacity of 4500 KN.

Stress-strain measurement system: Load cell and LVDT (Linear Variable Displacement Transducer) were utilised to measure load and displacement respectively which were logged by a computer. The strain rate was controlled at about 10^{-5} /sec during the whole loading process.

AE monitoring system: The entire acoustic emission system [7] consists of a detector, a event counter, a data-logger and a computer.

The detector used in the experiment is 308B accelerometer with a nominal acceleration sensitivity of 100 mv/g. The signal output from the detector is passed through a selectable (in/out) filter and then fed into the event counting system which counts the number of times when the output signal exceeds a prescribed level, namely pre-set threshold. The present work is mainly to investigate the rock noise occurring in the frequency range of 1.5 KHz to 8 KHz and with a trigger-free period of 50 ms. As it is well known that the high frequency signals are liable to be attenuated quickly within a very short distance, the research that is carried out in this area would have less practical significance. Therefore the study of acoustic emission of rock samples at low frequencies becomes the main concern.

4. DISCUSSION OF THE EXPERIMENTAL RESULTS

Twenty samples in eight rock types with a dimension of 50 mm in diameter by 120 mm long were prepared and tested according to the Suggested Method by the International Society of Rock Mechanics. Selected results (Fig.2 to Fig.6), obtained from experiments, were taken for analyses, where Fig.(a) shows the photos of sample in failure and for Fig.(b), the horizontal axis is the axial strain (micro-strain), the left-hand vertical axis stress (MPa) and the right-hand vertical axis AE event rate (events/min.).

4.1 Acoustic Emission during Shear Failure

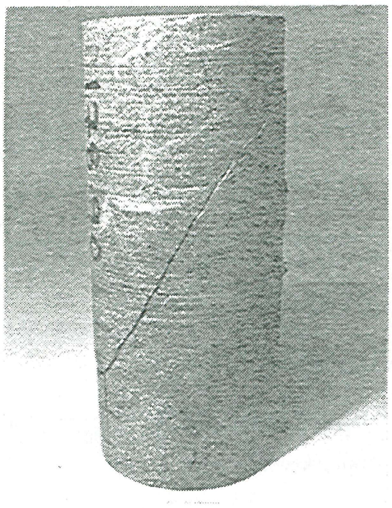
Acoustic emission, generally produced by a rapid microcrack growth, is an ubiquitous phenomenon associated with brittle fractures and can provide information on the failure process in rocks. The sudden release of energy in the form of an elastic wave that travels from the origin within the material to a boundary is called as AE signal or a discrete AE event. The testing result for a basalt sample which failed in a pure shear mode is shown in Fig.2. Shear failure took place by shearing along a single oriented discontinuity or plane of weakness. The shearing process normally emitted noticeable noises, manifested by the relatively high concentration of AE events (or rate) as shown in the figure. Most of the AE events occurred at a stress level of 24.4% to 55.8% uniaxial compressive strength (UCS). For shear failure, the major energy release was closely associated with the shearing or sliding along the shear planes, generally observed at a stress level around 30% to 50% UCS.

4.2 Acoustic Emission during Vertical Splitting

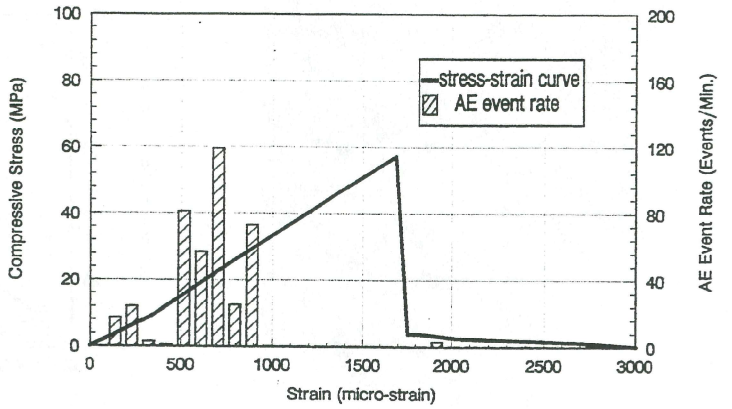
The testing result for a felsic-porphyry sample which failed in a tensile mode is illustrated in Fig.3. Vertical splitting was observed when the imperfections were invisible or planes of weakness were oriented parallel or sub parallel to the loading axis. It was expected that the initiation, propagation and development of major tensile cracks occurred on the late portion of stress-strain curve just prior to failure, which contributed to the generation of noticeable AE events and accompanied by the high concentration of AE event at a stress level of 67.3% to 100% UCS. The AE events observed at a low stress level of 15.7% to 22.4% UCS were more likely caused by the initial adjustment and movement between platen and rock sample or local shearing. After the peak stress, the stress exhibited some kinds of oscillations in the stress-strain curve which is termed as the stick-slip. It was found that whenever there was a stress drop, there accompanied by an increase in the AE event rate. This result agrees well with the Alheid's observations [2].

4.3 Acoustic Emission during Multiple Failure

The testing result for a meta-basalt sample where it failed in a shear-dominated mode is shown in Fig.4. The AE events were recorded at two distinct stress ranges. The first range occurred at a stress level of 18.8% to 30.6% UCS, presumably associated with the movements along the shear planes. The second stress range was observed around peak stress, closely related to the tensile failure at the upper end of the sample. If the AE events prior to failure were

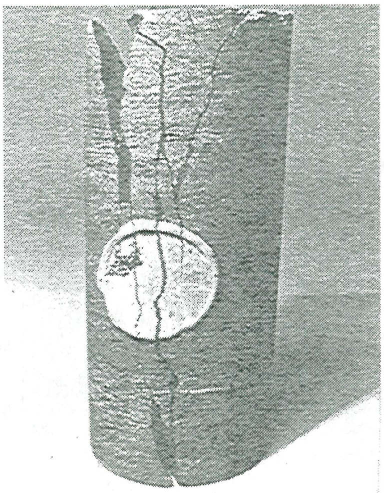


(a) Shear failure of a sample

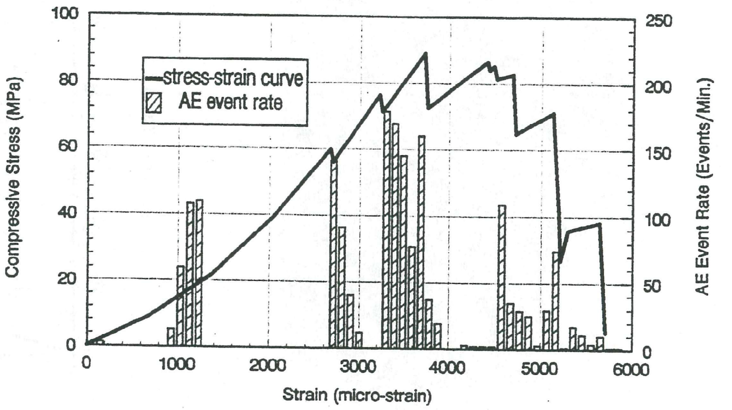


(b) The stress-strain curve and AE event rate versus strain

Fig.2 Shear failure and acoustic emission for a basalt sample

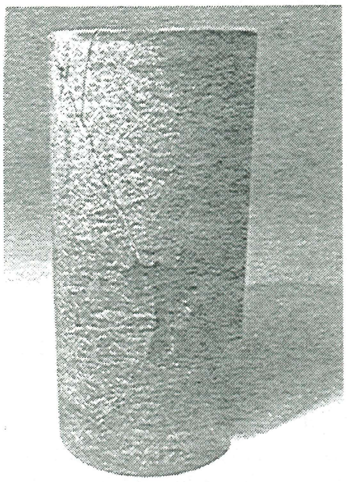


(a) Vertical splitting of a sample

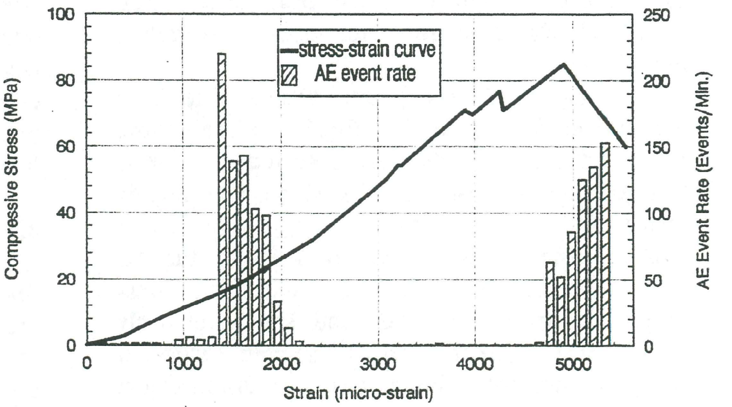


(b) The stress-strain curve and AE event rate versus strain

Fig.3 Tensile failure and acoustic emission for a felsic-porphyry sample

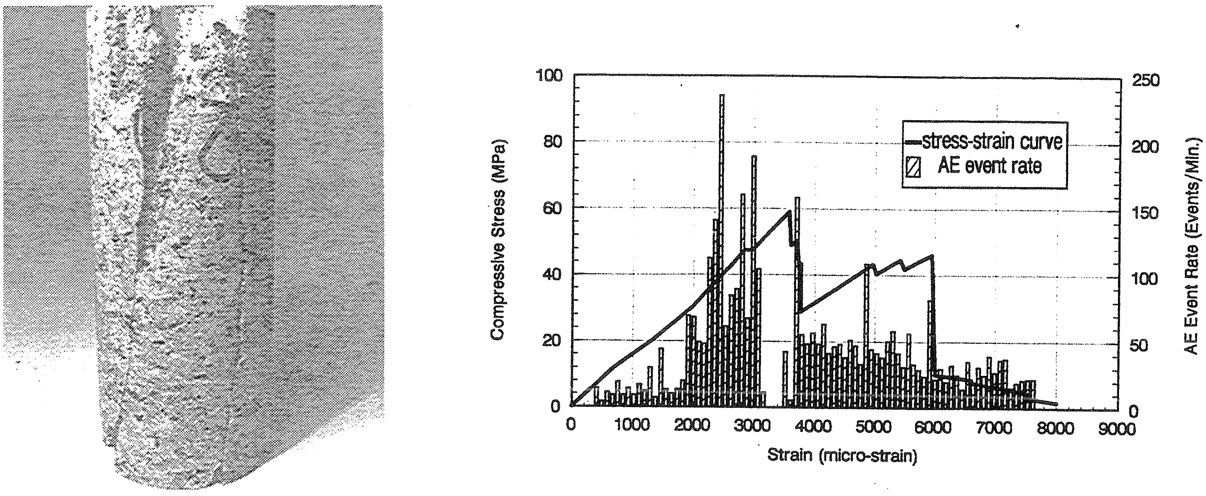


(a) Shear-dominated failure of a sample



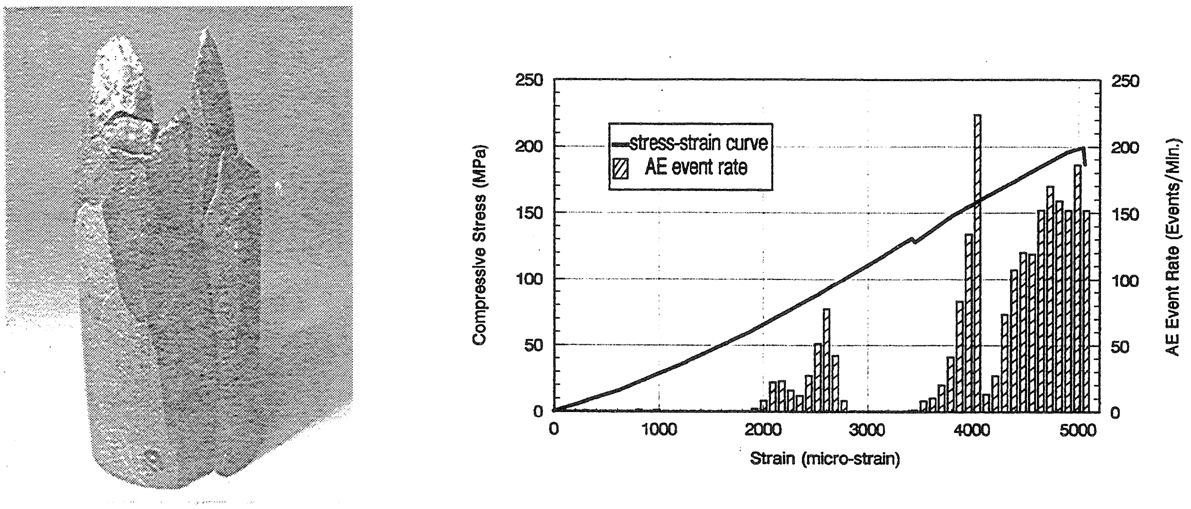
(b) The stress-strain curve and AE event rate versus strain

Fig.4 Shear-dominated failure and acoustic emission for a meta-basalt sample



(a) Multiple failure of a sample (b) The stress-strain curve and AE event rate versus strain

Fig.5 Multiple failure and acoustic emission for a granite sample



(a) Tensile-dominated failure of a sample (b) The stress-strain curve and AE event rate versus strain

Fig.6 Tensile-dominated failure and acoustic emission for a meta-basalt sample

taken into consideration, it was found that most of the AE events occurred at a medium stress level, which correlated to the shear-dominated failure mode.

The testing result for a granite sample, failed in a multiple mode, is plotted in Fig.5. Before failure, most of the AE events were observed at a stress level of 50.8% to 84.6% UCS which were largely associated with the initiation and propagation of major tensile cracks. At the peak stress, the AE event rate became to be null. When the stress dropped down, the AE event rate kept a relatively high value. From then on, the sample underwent stable-sliding, interrelated with the displacement along the shear planes and manifested in a way of continuous generated relatively high AE event rate.

The testing result for another meta-basalt sample, where the tensile-dominated failure mode was observed, is shown in Fig.6. It was obvious from the figure that most of the AE events occurred at a stress level of 75.3% to 100% UCS, largely attributed to the initiation, propagation and development of major tensile cracks. The AE events around a stress level of 50% UCS could be due to the shear-dominated multiple fracture or local shearing.

4.4 Analysis of Results

Shear failure, multiple failure and vertical splitting are the three typical modes of failure for rock samples, which are largely dependant on the distributions of imperfections, discontinuities and planes of weakness within rock samples besides the sample preparation. In order to have a better understanding of the correlations between modes of failure and AE patterns, the summary of acoustic emission tests for rock samples was listed in Table 1

Table 1 Summary of acoustic emission tests in rock samples

Test No.	Rock Type	Dimension (dia×length)	Modes of Failure (%) SF	MF	VS	Factor of Failure Mode	UCS (MPa)	Normalised Stress (%)
1	meta-gabbro	50.0×102.0	70	10	20	0.25	270.4	3.7-7.4
2	meta-dolerite	47.8×105.3	80	20		0.10	175.5	2.3-10.3
3	meta-basalt	47.7×99.0	70	20	10	0.20	50.4	35.7-59.5
4	meta-basalt	47.7×105.7		10	90	0.95	148.3	95.8-100.0
5	meta-basalt	47.8×103.5	80	10	10	0.15	85.0	18.8-30.6
6	meta-basalt	47.8×126.2		30	70	0.85	199.2	75.3-100.0
7	meta-basalt	47.7×117.6		30	70	0.85	166.5	96.1-100.0
8	basalt	50.0×118.5	95		5	0.05	57.3	24.4-55.8
9	talc-carbonate	47.8×116.4	95		5	0.05	26.5	49.1-64.2
10	talc-carbonate	47.7×121.4	100			0.00	37.8	34.4-45.0
11	talc-carbonate	47.6×123.6	90		10	0.10	26.7	22.5-63.7
12	talc-carbonate	47.6×109.5	100			0.00	23.9	54.4-66.9
13	granite	47.0×121.0	50		50	0.50	59.1	50.8-84.6
14	granite	47.5×106.0	40		60	0.60	31.7	59.9-100.0
15	granite	47.8×115.6	100			0.00	161.6	6.2-12.4
16	granite	47.9×122.7			100	1.00	69.4	63.4-100.0
17	quartz-felspar-porphyry	47.0×112.0	20	80		0.40	187.9	19.2-24.5
18	quartz-felspar-porphyry	47.7×124.1	30	30	40	0.55	218.2	6.9-11.5
19	felsic-porphyry	50.0×117.0	10		90	0.90	89.1	67.3-100.0
20	felsic-porphyry	50.0×128.0	40	20	40	0.50	113.3	21.2-33.5

and the relation between the modes of failure and normalised stress that was closely associated with the acoustic emission was drawn in Fig.7. The modes of failure were classified into three categories: shear failure (SF), multiple fracture (MF) and vertical splitting (VS). The values for factor of failure mode were obtained through observing and analysing the percentage of failure planes resulted from different mechanisms by assigning weight value to each mode of failure, for example 0 for SF, 0.5 for MF and 1 for VS and then accumulating them. The normalised stress was defined as a ratio of stress range corresponding to the major AE event rate (greater than 50 events/min.) before failure divided by UCS. It demonstrates in Fig.7 that for pure shear or shear-dominated failure, most of AE events occurred at a stress level of 30% to 60% UCS while for tensile or tensile-dominated failure most of AE events were observed at a stress level over 70% UCS. For the multiple modes of failure, the AE events generally exhibited two ranges of concentration prior to failure. If more events occurred around 50% UCS, the dominant mode of failure was shear whereas if more events were observed right prior to failure, then the dominant mode of failure was vertical splitting. It should be noted that in the tests, some samples had some AE rate at a stress level less than 20%. It was believed that the observed AE rates at these low stress levels were closely associated with the initial adjustment and movement between the platen and rock samples or local uneven loading, thus these points were discarded from the Fig. 7.

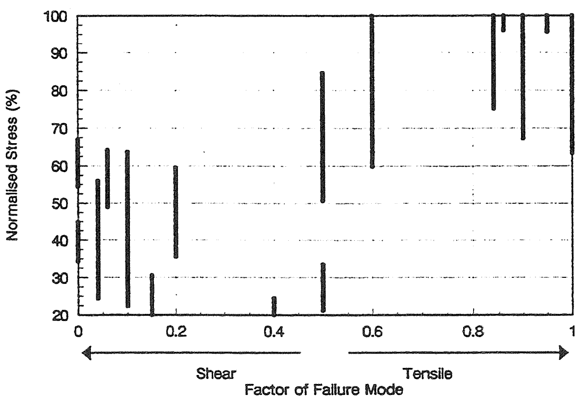


Fig.7 Modes of failure versus normalised stress

5. CONCLUSIONS

Twenty samples in eight rock types were tested by the acoustic emission (AE) technique under uniaxial compression. The interrelations between modes of failure and the AE patterns were investigated. Based on the presented results, the following conclusions are drawn:

- For the shear failure, most of AE events occurred at a stress level of 30% to 60%

uniaxial compressive strength (UCS) while for the vertical splitting, most of AE events were observed at a stress level over 70% UCS.

- For the multiple modes of failure, the AE events generally exhibited two ranges of concentration prior to failure. If more events occurred below a stress level of 50% UCS, the dominant mode of failure would be shear whereas if more events were observed right prior to failure, then the dominant mode of failure would be vertical splitting.
- For the case of stress oscillation in the post failure region, there always has an increase in the AE event rate with the stress drop; and for the stable-sliding, there always accompanied by a continuously high AE event rate.

The study shows that shear failure, multiple failure and vertical splitting result from distinct mechanisms and exhibit different AE patterns. It is feasible to classify the modes of failure by applying the AE technique, which has an engineering significance.

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