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Acoustic emission from gas-filled coal under triaxial compression

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ABSTRACT

Acoustic emission (AE) experiments have been performed on gas-saturated coal specimens under conventional triaxial compression. The AE characteristics were investigated for a methane gas flow through the coal specimen. One AE parameter, AE count, when normalized by the total count number was used to represent the damage evolution in the gassy coal. It is shown that this AE parameter is a reasonable indicator for damage occurring within the coal specimen since its envelope has almost the same shape as the complete stress–strain curve, except for a short time delay. In addition, the change in AE count is highly consistent with the change in coal permeability. Test results also show that methane containing coal emits a small number of AE events before entering the yield stage. AE activity gradually increases during the yield process up to the peak stress. The lowest permeability corresponds to the highest AE activity, implying failure will soon occur. An AE based constitutive model was constructed and the theoretical results agree well with those of experiments.

1. Introduction

Coal is the major energy source in China. The past 20 years have seen numerous deadly accidents associated with coal and gas outbursts due to enlarged coal mining operations that are stimulated by an increasing demand for coal. The occurrence of coal and gas outbursts is the result of dynamic instability of the underground coal rocks, frequently accompanied by the release of various kinds of energy such as elastic strain energy, acoustic energy, and electromagnetic energy.

Acoustic emission (AE) is becoming a common and effective means of studying stressed materials [1,2]. Acoustic emission is named for the elastic waves generated by sudden changes that occur locally in materials, including most rocks, due to deformation, cracking, or other transformation. Because the acoustic emission is directly related to the internal microscopic activity including crack initiation, development, and ultimate fracture of the rocks, it can be used to detect the evolution of damage in the rock. A great deal of research work has been devoted to investigating rock AE features. Significant advances have been achieved over the past several decades. These phenomena are seldom studied in stressed, gas-filled coal. A few studies were focused on rock or coal under conditions of uniaxial, or triaxial, cyclical loading [3–11]. This paper attempts to quantify AE data and correlate it with deformation and changes in permeability of gas-saturated coal. It describes a mechanism for coal and gas outbursts.

2. Experimental

2.1. Specimens and instrumentation

The testing system is illustrated schematically in Fig. 1. The dimensions of the cylindrical specimen are 50 (diameter) × 100 (height) mm. The patented loading apparatus was specially designed and fabricated to apply an axial load and confining pressure as well as a temperature field and methane flow through the coal [12]. The AE detection model PCI-2 of the DISP series manufactured by PAC was employed to detect AE signals from the gassy coal specimens. Two AE sensors were attached to the outer wall of the pressure cell with a matching medium for good signal detection. Data logging was computer controlled during testing.

2.2. Test procedure

Two ways were used to load the specimen. First, hydrostatic pressure was applied to a level of 2, 4, or 6 MPa. Then the coal specimen was exposed to methane gas to a state of saturation at a confining gas pressure of 1, 1.5, or 2 MPa. A stroke controlled loading was then applied at a loading rate of 0.1 mm/min. The valve for the gas pressure was opened and, simultaneously, the AE detection system was activated.

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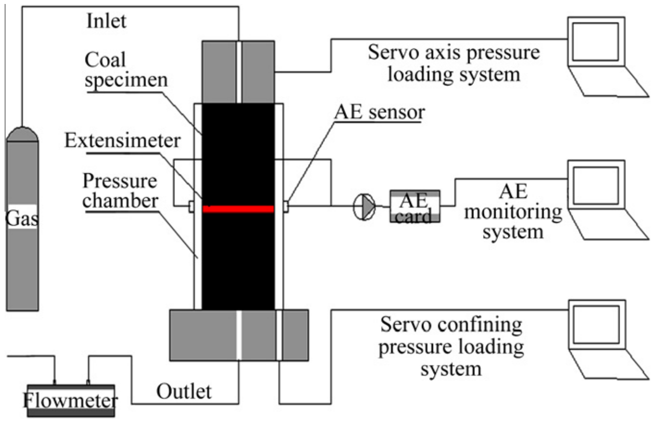

Fig. 1. A sketch of the test system.

3. Results and discussion

The recorded AE parameters include the AE event rate, an AE event count, the AE amplitude, and AE energy. Each parameter could be treated as a time series. The time series of AE rate, amplitude, and energy were correlated with strain, stress, and permeability at conditions of 1.5 MPa gas pressure and 6 MPa confining pressure. These correlations are illustrated in Fig. 2.

3.1. Correlation of stress and strain to permeability

The permeability of coal is controlled by various types of pores and cracks and their connectivity, which is ordinarily stress sensitive. The complete stress–strain curves in Fig. 2 can be roughly divided into four stages: compaction, elastic deformation, yield, and failure. The permeability decreases with increasing axial stress until the lowest permeability is achieved before the peak stress is reached. The highest permeability occurs almost at the same time as when the specimen fails. It then slowly rises to a stable value reflecting seepage properties post stress peak. In the compaction phase the decline in permeability and volume of the coal is attributed to the closure of cleats and the lack of new crack initiation as the axial stress increases. The compacted coal exhibits a linear elastic behavior that obeys Hook's law. This occurs after a nonlinear compacting process. In this elastic stage the permeability of the gassy coal varies inversely with stress.

Following that is the yield phase where strain does not change linearly with stress and plastic deformation dominates the total strain, cracks initiate, then develop, and the lowest permeability is seen.

At peak stress the specimen enters a failure stage featured by the appearance of faults through the specimen and a reduction in axial stress as the strain increases to a stable magnitude. The permeability fluctuates little with strain, staying at a high level.

3.2. AE activity and its correlation to stress and strain

Fig. 2 illustrates that AE activity lags behind stress and strain. In the compaction stage a few events appear suggesting that no damage to the coal happens and that the input energy is dissipated by compaction of the specimen. The elastic phase, corresponding to a linear variation of strain with stress, exhibits a rapid increase in AE activity. All AE parameters: rate, amplitude, and energy increase with rising axial stress.

As time passes the deformation enters the plastic strain stage where all AE parameters reach their peaks. At a certain time the energy accumulated in the elastic stage is suddenly released and a large number of cracks initiate and develop. After the stress peaks the failed coal specimen usually retains some load bearing capacity. AE signals are detected when loading is continued to a constant value.

3.3. Correlation of permeability and AE data

Fig. 2 illustrates the good correlation of the AE data to permeability. Permeability has four characteristic stages that correspond to a stably decreasing, a stably increasing, an unsteady, and a stable phase. Continuous decline in permeability represents the coal compacting and so AE activities are increasing then. A continuous permeability increase up to a peak value suggests a large number of cracks are initiating and developing. These ultimately coalesce to form continuous faults. At this stage AE activities peak. Subsequently, the stress and AE activity drop to a relatively stable level.

4. An AE based constitutive relation for gassy coal

Considering that gas-filled coal contains a great number of micro-pores and micro-cracks a reasonable failure mechanism for a basic element is random failure that is a function of both stress and strain.

Lemaitre's hypothesis for equivalent strain proposes a constitutive relation based on statistical damage that can be expressed as [13]:

$$\sigma^* = \sigma/(1 - D) \tag{1}$$

where σ^* is the effective stresses; σ the nominal stress; and D a damage variable.

Assume an element is randomly taken from gas-filled coal under triaxial compression. This element should have two features: on one hand, it should have a large enough size to include numerous micro-pores and micro-cracks and a measurable gas pressure; on the other, it should be small enough to be reasonably regarded as a particle in a continuum. These features are in opposition.

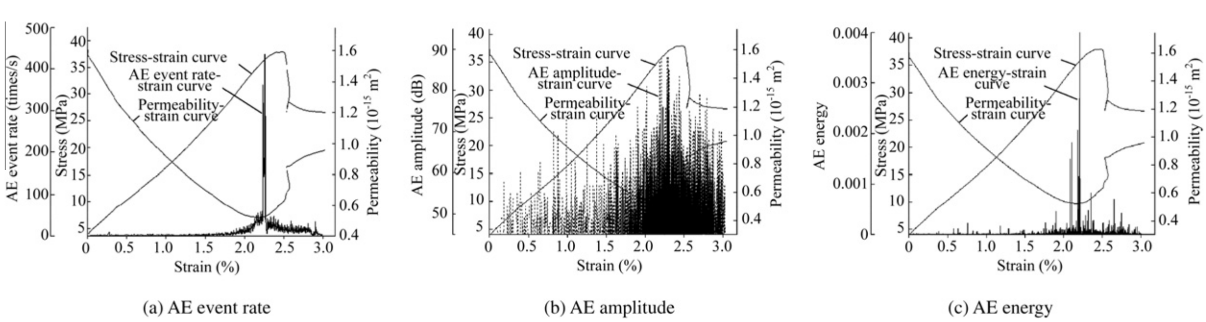

Fig. 2. Stress vs. strain, permeability vs. strain, and AE event rate, AE amplitude and AE energy vs. strain.