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Fractal characteristics and acoustic emission of anisotropic shale in Brazilian tests

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ABSTRACT

The strata of shale contain structural weak planes such as laminations and joints, which do not have the same mechanical properties as intact rock masses. Tensile strength is a critical parameter that determines the capacity of a rock and its resistance to deformation and failure. Focusing on tensile strength and acoustic emission (AE), the characteristics of shale were investigated at various orientations of the laminations with respect to the loading direction. By coupling Brazilian test and the AE technique, the mechanical properties and damage patterns of shale can be explored. The shale exhibits clear laminations and contains a high proportion of brittle minerals by XRD and SEM analysis. The stress–time curve of the Brazilian test can be divided into three stages with distinct brittleness characteristics, and the tensile strength exhibited undulatory trend as bedding angles increases. At low bedding angles, the compaction of fissures and pores within the shale is not significant, and the cumulative AE count–time curves exhibited a flat-to-sharply rising trend. By contrast, the curves showed a gradually increasing "stepped" tendency at high bedding angles. Analysis of the AE time sequence based on fractal theory reveals that fractal dimension values fluctuate with increase of the stress, signifying the initiation of complex microcracks within the shale. The fractal dimension values sharply dropped when approaching the limit of tensile strength, signifying the occurrence of major cracks. The sudden drop of AE time sequence correlation dimension values can serve as an early warning for the coming failures. The research findings could be instrumental in the monitoring of rock mass instability, microcrack mechanisms, and earthquake sequences.

1. Introduction

Unstable rock failure is always a concern in rock mechanics and rock engineering, and it is closely associated with numerous rock engineering hazards. Therefore, investigations of the development of internal cracks during unstable rock failure, rigorous research tools and methodologies, are essential to understand the mechanisms of rock failures. With the advance of technology, new and improved methods have been introduced, such as the use of scanning electron microscopes (SEM), computerized tomography (Sun et al., 2016; Yang et al., 2017), micro-seismic monitoring (Ma et al., 2015; Feng et al., 2016), acoustic emission (Lockner, 1993; Agioutantis et al., 2016), and numerical simulation (Erarslan and Williams, 2012; Yang et al., 2016).

The failure of a rock is the process by which internal microcracks are initiated, expanded, and eventually developed into macrocracks. The process is usually accompanied by the generating of acoustic emission (AE). The phenomenon of AE, also called stress-wave emission, is the release of strain energy as elastic waves in the deformation process of a material or structure (Lockner, 1993). AE is a common physical phenomenon of which wave signals can be detected, recorded, and analyzed by acoustic monitoring devices and data processing systems. The primary feature AE parameters include AE rate, AE counts, and cumulative AE counts, all of those parameters vary with the internal structure of specimens (Shkuratnik et al., 2004; Prasad and Sagar, 2008; Yin et al., 2012; Xiao et al., 2016). AE rate refers to the number of AE observed within a unit of duration, and it reflects the change in the intensity of AE events. Cumulative AE counts refer to the number of cumulative AE events in a certain time period, and this parameter reflects the number of burst AE signals in rocks.

The technique of locating the source of AE from its signals is commonly called the AE technique. As a highly sensitive nondestructive testing method, AE technique can monitor in real time the initiation and growth of internal microcracks in rocks, which is an advantage characteristic not shared by other testing methods (Xu et al., 2012; Vidya Sagar and Rao, 2014; Guo et al., 2015; Zhang et al., 2015; Kong et al., 2016). Each AE signal contains information on the development

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of internal damage in the rock, and through analyzing and studying such signals, the pattern of the initiation, growth, and fracturing of internal microcracks can be identified. AE technique was often used for the basic research of rock mechanics from a variety of viewpoints (Wasantha et al., 2014; Hou et al., 2016), e.g., AE three-dimensional positioning technology, by using several inductive probes, can simulate the development of cracks in the process of hydraulic fracturing and study the complex crack patterns generated in fracturing rocks (Wang et al., 2016). In addition, as a nondestructive examination method, the AE technique has been widespread used in measuring rock stress, stress measurement, earthquake sequences, and rock mass instability (Fijii et al., 1997; Shiotant et al., 2001; Cai et al., 2007; He et al., 2010; Ishida et al., 2010; Xu et al., 2010; Liu et al., 2012a,b; Lisjak et al., 2014), as well as providing early warnings with regard to coal and rock dynamic disasters (Chang and Lee, 2004; Ganne et al., 2007; Lei and Akashi, 2007; Li and Wong, 2013, 2015).

The change in AE parameters reflects the degree of damage a rock has sustained to some extent, and the degree of damage is directly related with the growth of defects within the rock. Through the AE technique, changes in properties and conditions of a rock can be detected from AE wave signals, furthermore, the fractal analysis can be used to predict failures in rock mass. Kusunose et al. (1991) discussed fractal dimension of spatial distribution with granodiorites, and concluded that the texture of rock may affect the growth of microcracks inside and distribution of AE events. Feng and Seto (1999) applied fractal theory to AE data collected from a torsion test, and found the time series distribution of the initiation of microcracks exhibit fractal and multifractal characteristics, which enables the prediction of rock failures from changes in the fractal dimension. Bagde et al. (2002) studied the fractal of the rock rough surface and the rock mass fracture network using the covering method. Biancolinia et al. (2006) presented a good description about the evolution process of the rock cracks by box fractal dimension. Xie et al. (2011) concluded that damages and fractures in rocks could be predicted from stress reduction, energy release, and the fractal dimension in spatial distribution of AE. Zhang et al. (2015) employed AE positioning technique to examine, from a fractal perspective, the change in fractal dimension with stress levels in uniaxial and triaxial compression tests; they concluded that the fractal dimension exhibited a “rise–drop” pattern with the increase in stress levels. However, not many studies involved with the tensile tests in combination with AE technique in anisotropic rocks.

Tensile strength is a primary indicator of bearing capacity, deformability and strength of a rock (Li and Wong, 2013). The tensile strength was related to water saturation, temperature, loading rate, anisotropic degree and the included angle between loading direction and the bedding planes in Brazilian test (Dinh et al., 2013; Kodama et al., 2013; Ma et al., 2017a). Khanlari et al. (2015) concluded that the relationship curves of tensile strengths and bedding angles can be categorized into U-type, undulatory type and shoulder type. However, Ma et al. (2017b) reviewed and compared the main anisotropic tensile failure criteria, and recommended Nova-Zaninetti criterion for the characterization of anisotropic tensile strength from the viewpoint of theoretical studies. As for the fracture patterns of tested sample after failure in Brazilian test, in general, the isotropic rocks including granite and sandstone failed mainly with central or central multiple types of fracturing over the entire range of determined Brazilian test, while the anisotropic rocks principally failed by layer activation in combination with either central or non-central fractures under Brazilian test (Basu et al., 2013). In addition, Vervoort et al. (2014) classified the fracture patterns into central and non-central fractures, as well as fractures parallel to the weak planes in Brazilian test.

Tensile strength is vital for tunnel engineering and plays a highly important role in the processes of excavation, and tensile failure is deemed to be the main failure mode in many underground excavations. However, the past studies mostly focus on tensile strength and failure patterns of anisotropic rocks from laboratory results and numerical analyses. Rarely did studies combine AE technique with fractal theory in an attempt to investigate the tensile strength of anisotropic materials and monitor the rock mass instability in the underground excavations. Study coupled the AE technique and Brazilian test to investigate the tensile strength and failure patterns of anisotropic shale at multiple bedding angles. This study also analyzed the relationships between spatial distribution patterns of AE, characteristics of the fractal dimension, and the influence of rock anisotropy on the Brazilian test results.

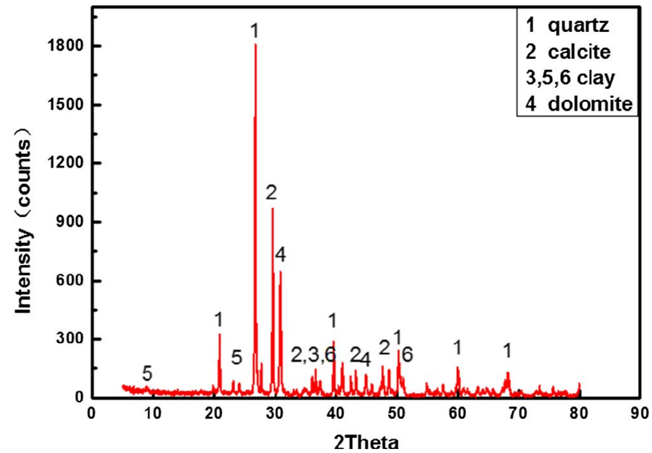

Fig. 1. The results of X-ray diffraction analysis.

2. Methodology

2.1. Preparation of specimens

The specimens used in this study were collected from a black shale outcrop in the Longmaxi Formation in the Yibin County of Sichuan Province, China. The shale in this area are well stratified and have clear laminations. The powders of the specimens were examined by X-ray diffraction to identify their mineral composition (Fig. 1), and the results suggest the existence of quartz, calcite, dolomite, and clay minerals such as chlorites. The contents of the constituent minerals are as listed in Table 1, which indicates that brittle minerals such as quartz and calcite were the primary constituents of the specimens. Mineral composition is a critical factor for the mechanical properties of rocks, as the brittleness index of a rock increases the more brittle minerals it contains (Zhang et al., 2016).

In order to observe the microstructure of the shale specimens, the TESCAN MIRA3 scanning electron microscope (SEM) with magnification settings of 3000×, 6000×, and 9000× was used. The constituent minerals as viewed from angles parallel and vertical to the bedding plane of the shale are shown in Figs. 2 and 3, respectively. These images demonstrate that in views vertical to the bedding plane, the pores and fissures are visibly well developed and neatly arrayed, but that there are relatively fewer pores. The overlapping slices of the shale are laid out in a stepped fashion with relatively weaker degree of cementation among laminations but well-filled matrix space, and the laminations is not very well defined on the surface. By contrast, in views parallel to the bedding plane, the mineral grains are arbitrarily arrayed in significantly richer concentrations, and individual grains are loosely embedding in porous black organic matter that exhibits conspicuous laminations. The

Table 1
The mineral content of the rock sample.

Mineral	Quartz	Calcite	Dolomite	Clay	Other
%	57.37	15.64	13.17	8.50	5.22