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Energy dissipation rate: An indicator of coal deformation and failure under static and dynamic compressive loads

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ABSTRACT

Dynamic disasters in Chinese coal mines pose a significant threat to coal productivity. Thus, a thorough understanding of the deformation and failure processes of coal is necessary. In this study, the energy dissipation rate is proposed as a novel indicator of coal deformation and failure under static and dynamic compressive loads. The relationship between stress-strain, uniaxial compressive strength, displacement rate, loading rate, fractal dimension, and energy dissipation rate was investigated through experiments conducted using the MTS C60 tests (static loads) and split Hopkinson pressure bar system (dynamic loads). The results show that the energy dissipation rate peaks are associated with stress drop during coal deformation, and also positively related to the uniaxial compressive strength. A higher displacement rate of quasi-static loads leads to an initial increase and then a decrease in energy dissipation rate, whereas a higher loading rate of dynamic loads results in larger energy dissipation rate. Theoretical analysis indicates that a sudden increase in energy dissipation rate suggests partial fracture occurring within coal under both quasi-static and dynamic loads. Hence, the energy dissipation rate is an essential indicator of partial fracture and final failure within coal, as well as a prospective precursor for catastrophic failure in coal mine.

1. Introduction

China, the world's largest producer and consumer of coal, produced about 3.41 billion tons of coal and consumed nearly 2.70 billion tons coal in 2016. However, dynamic disasters, such as rockburst and coal and gas outburst, present a serious threat to coal productivity in Chinese coal mines. With the increase in mining depth in recent years, the number of accidents in Chinese coal mines has been on the rise and this has drawn extensive attention from both government and research institutes. Consequently, substantial efforts have been carried out to investigate the mechanism underlying these accidents to implement effective measures for their prevention and control [1,2]. In general, dynamic disasters involve an abrupt failure of coal under external loads generated by various mining-induced activities, such as roof fall, fault slip, and blasting. It is therefore of utmost importance to understand the deformation and failure process of coal under different types of external loads.

Theoretical and experimental studies have already indicated that the energy concepts play a significant role in describing the deformation and failure process of rock materials. For example, the energy concept "specific energy", defined as the energy required to excavate a unit volume of rock, was considered as a useful index to identify the critical failure mode transition depth in rock cutting [3]. The energy concept "dissipated energy" was closely related to the fatigue deformation of rock under cyclic loading [4]. In addition, other types of energy involved in rock engineering have also been extensively investigated. The seismic energy released during brittle rock failure and rock blasting results in strong tremor, eventually causing serious destruction to the underground tunnel [5]. The fragmentation energy is intrinsically associated with the breakage and the creation of new surfaces of rock blocks [6].

Researches in recent years have demonstrated that the deformation and failure of coal are irreversible processes involving energy dissipation, which eventually cause continuous damage and material deterioration during the loading process [7]. The mechanism of these processes has already been proven in many experimental studies on energy dissipation of coal under different loads. Quasi-static experimental studies of coal under uniaxial

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compression conditions evaluate the positive relationship between dissipated energy and electromagnetic/acoustic energy emitted during coal fracture and failure [8]. Additionally, the results of these studies also confirm the link between energy dissipation and coal deformation and failure under conventional triaxial compression conditions [9].

The deformation and failure of coal under dynamic loads are usually conducted using the split Hopkinson pressure bar (SHPB) system, which is an innovative technique for achieving high-strain-rate loads in dynamic compressive tests [10]. Significant progress has been made in rock dynamic tests over the past few years, a series of key loading techniques has been reported in the literature, including the pulse shaping, momentum-trap [11], strain controlling, coupled static-dynamic loading, and axial-radial confining loading techniques [12]. Various measurement techniques have also been introduced to modify the SHPB system, such as the X-ray micro- computed tomography [13], laser gap gauge, and digital image correlation [14]. Moreover, many dynamic properties of rock materials have been studied using the modified SHPB system, including the dynamic deformation and energy dissipation, the dynamic fracture toughness [15], and the dynamic crack propagation [16]. The experimental studies of coal dynamic properties demonstrate that the energy dissipation is closely related to coal fragmentation caused by the dynamic loads [17].

However, the aforementioned energy dissipation refers to the total energy dissipated during the whole loading process, rather than the instantaneous energy consumed at any time during the loading. Thus, the traditional energy concepts are not appropriate for quantitatively describing the instantaneous energy dissipation of coal. Besides, the energy dissipation of coal in quasi-static tests and in dynamic tests has not yet been compared in previous studies.

In this study, experiments of coal under quasi-static loads and dynamic loads were conducted using the MTS C60 tests and SHPB systems, respectively, and the energy dissipation rate was proposed to quantitatively describe the energy dissipation process and the deformation process of coal. The relationship between stress-strain, uniaxial compressive strength, displacement rate, loading rate, fractal dimension, and energy dissipation rate under both quasi-static and dynamic loads were experimentally investigated and theoretically discussed.

2. Experimental method

2.1. Specimen preparation

Raw coal materials were obtained directly from the same working face at a depth of over 550 m in Sanhejian coal mine located in Jiangsu Province, and then processed uniformly by subjecting them to drilling, slicing, and polishing to obtain cylindrical specimens. The dimensions of the specimens are Ø50 × 50 mm for dynamic tests and Ø50 × 100 mm for quasi-static tests according to the ISRM suggested methods [18]. Both ends of the specimens were lubricated with vacuum grease to eliminate the inertial effects (i.e., the axial inertial effect and the radial inertial effect) and the interfacial friction effect, which affect the homogeneity of the sample deformation [18]. In addition, physical properties (true density and apparent density), thermal property (volatile matter), proximate analysis result (moisture and ash content), and wave velocities (dilatational wave and shear wave) of the coal specimens are obtained through laboratory tests, and the results are listed in Table 1.

2.2. Experimental system

The quasi-static tests were conducted using an MTS C60 tests system (Fig. 1). The entire load and displacement histories in the quasi-static tests are measured using linear variable displacement transducers, and the following displacement rates were chosen for

Table 1
Physical properties, thermal property, proximate analysis result, and wave velocities of coal specimens.

True density (kg/m^3)	Apparent density (kg/m^3)	Moisture (%)	Ash (%)	Volatile matter (%)	Calorific value (MJ/kg)	Dilatational wave speed (m/s)	Shear wave speed (m/s)
1446	1541	2.10	26.27	37.53	23.15	2126.89	1074.24

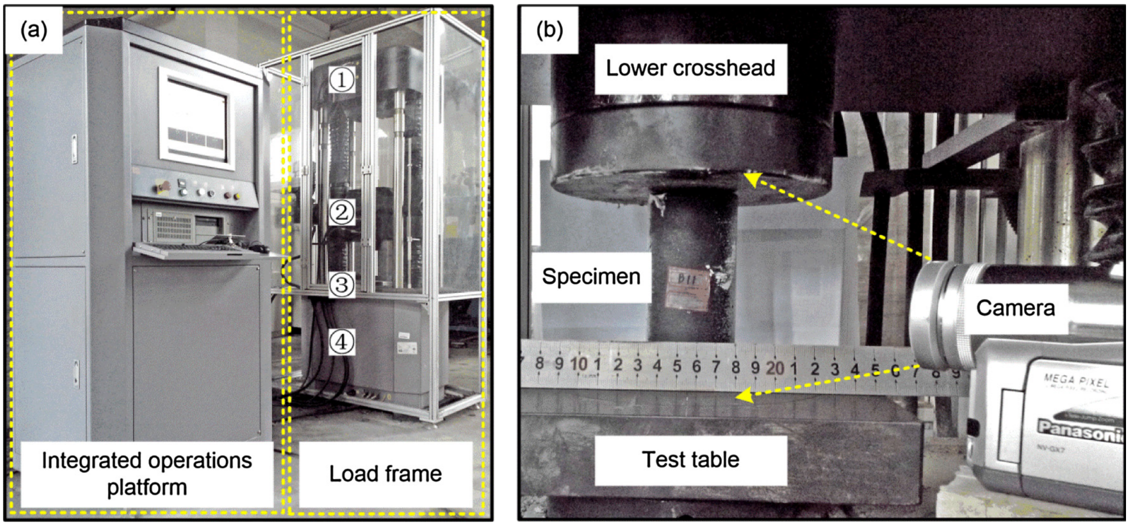

Fig. 1. Photographs of MTS C60 tests system. (a) Operation platform and load frame; (b) Compression space in load frame. ① Upper crosshead, ② Lower crosshead, ③ Test table, ④ Actuator.

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