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Fragmentation Characteristic and Energy Dissipation of Coal under Impact Load

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Abstract

The catastrophic failure of coal under super-critical stresses and mining-induced disturbance is becoming one of major safety risks of underground mining. Research of the failure pattern of coal under impact load is helpful for understanding its burst behavior in order to mitigate the burst risk. To investigate the fragmentation characteristic and burst behavior of coal under impact load, drop weight tests of coal samples were conducted. This paper found that coal samples have high peak stress, pulverized fragmentation, and intensive burst energy under impact load. The fragments induced by the impact load have a relatively consistent distribution mode, which can be characterized by a fractal model. The burst energy accounts for more than 99% of the impact energy input while fragmentation energy only accounts for no more than 1%.

Keywords

Coal burst, Drop weight, Energy dissipation, Fragmentation characteristics, Impact load

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Keywords

Fragmentation Characteristics; Coal Burst; Impact Load; Drop Weight; Energy Dissipation

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Introduction

As the fourth largest producer and second largest exporter of coal resource, Australia owns a big underground mining industry which consists of tens underground coalmines and thousands mining workers (Geoscience Australia and ABARE 2010). With the increases of mining depth, the catastrophic failure of coal under super-critical stresses, complicated geological conditions and mining-induced disturbance is becoming one of major safety risks of underground mining. It has been well-documented that the catastrophic failure of coal can cause severe damage to mining workers and equipment (Zhang, Canbulat et al. 2017). However, the failure of brittle or quasi-brittle materials including coal has not been adequately understood at current stage (Grady 2008). Previous research has shown that coal tend to have more violent and instantaneous failure under impact or dynamic load as the strength of coal is positively related with loading rate (Okubo, Fukui et al. 2006, Zhao, Wang et al. 2014). Research of the failure pattern of coal under impact load is helpful to understand its burst behaviour hence to mitigate the associated safety hazards by addressing sufficient mitigative measures and protective equipment.

Fragmentation is a common physical and mechanical phenomenon exists in the failure process of geo-materials under static, impact and dynamic loads (Li, Li et al. 2018, Li, Zhang et al. 2018). It has been pointed out by many researchers that the study of fragment size distribution (FSD) is important for the understanding of energy dissipation and failure mechanism of geo-materials. Grady analysed the experimental and theoretical size distribution of solid materials resulting from dynamic fragmentation based on the power-law character (Grady 2008). Liu et al. compared the FSD of sandstone samples subject to impact load and static load and found the crushing degree of fragments generated by impact load is higher, accompanied with blocky characteristics (Liu, Li et al. 2014). Deng et al. conducted dynamic uniaxial compression tests of rock samples with the application of SHPB system and proposed energy consumption model of rock fragmentation based on fractal rock mechanics and fracture mechanics theory (Deng, Chen et al. 2016). Chen et al. found that the energy dissipation of fragments declines linearly with increase in loading rate from 0.5 to 4.0 MPa/s (Chen, Su et al. 2019). It has been well proved by these research that the fragmentation characteristic of rock subject to impact load is obviously different with it subject to quasi-static load. Based on previous research of rock fragmentation, Yang et al. proposed the energy calculation model of coal fragmentation subject to quasi-static load based on Rittingers's theory and fractal model (Yang, Ren et al. 2020). The experimental study conducted by Yang et al. demonstrated that this model can be used to study the fragmentation characteristic and energy dissipation during catastrophic failure of coal. However, the research of coal fragmentation subject to impact load has not been well-developed.

Drop weight system has been adopted by many researchers to study the dynamic fragmentation features of different materials including concrete (Rahmani, Kiani et al. 2012), rock (Whittles, Kingman et al. 2006), glass (Sam, Joren et al. 2014) and other materials (Rajput, Burman et al. 2018). Through the drop weight tests of granite, Hogan et al. offered insight into the catastrophic dynamic fragmentation of rock under low-energy impact and provided useful data for the numerical modelling of rock fragmentation (Hogan, Rogers et al. 2012). The drop weight tests done by Reddish et al. indicated that the degree of fragmentation formed a non-linear relation with impact energy (Reddish, Stace et al. 2005). Alex et al. investigated the impact energy absorption capacity of concrete through drop weight tests (Remennikov and Kaewunruen 2007). Hence, drop wight test is a widely used method to apply impact load on materials and to investigate the corresponding dynamic fragmentation characteristic. In a drop weight test system, a hammer with known height and weight will be given impact velocity and energy by gravitational acceleration to impact the samples placed underneath. The impact energy can be calculated based on measuring the dropped weight and calculating the resultant velocity. The FSD generated by drop weight tests can be determined by manual sieving and image processing technique. Then the energy dissipation can be analysed based on impact energy input and fragmentation energy consumption (Yang, Ren et al. 2020).

This paper aims to investigate the fragmentation characteristic and energy dissipation of coal under impact load. The impact load tests of coal samples were conducted in laboratory by the application of an innovatively modified drop weight test system. The fragmentations generated by impact load were analysed by a novel combination method of manual sieving and image processing. Six coal samples taken from local coal seam were tested by a 0.72 kN drop weight with 0.5 m height. The test results demonstrated that the FSD of coal generated by impact load can be characterised by Fractal Model. Experimental results are compared with the fragmentation characteristic and energy dissipation of coal samples subject to quasi-static load.

Material and Methods

Experimental Setup

Coal blocks were taken from local coal seam and delivered to our laboratory. To maintain the original state of the coal, all blocks were fully wrapped with aluminium and polymer membranes during delivery. As shown in Figure 1, coal blocks were processed into 50 mm * 50 mm * 100 mm cuboid samples through the process of cutting and grinding.

In this study, steel incident plate was used to distribute impact load to coal sample through transmission bar. The impact load was achieved by a free-fall drop weight that can be dropped from a maximum height of 2.5 m, or equivalent to the maximum drop velocity of 7 m/s. The drop height in this paper was selected as 0.5 m based on a series of pre-test experiments, which can achieve 3 m/s impact velocity. This impact velocity can achieve complete fragmentation and intermediate strain rate of coal samples (Zhu, Niu et al. 2015). The impact load was monitored by a force sensor and then recorded by the connected computer. A transmission bar was placed above the sample to transfer the impact load. Coal sample was placed between the transmission bar and the base. To guide the descent of the transmission bar and maintain the direction of impact load, bolts were installed between transmission bar and base. The apparatus setup is shown in Figure 2.

The drop weight adopted has the weight of 73.35 kg, which is equivalent to 0.72 kN. It was found that due to the friction of guiding runner that the incident plate's experimental velocity averagely reduces to 98 % of the theoretical value (Remennikov and Kaewunruen 2007). Therefore, test system efficiency needs to be considered during the impact energy calculation process based on energy conservation theory.

Fragment Size Distribution

FSD is important for the understanding of failure process and fragmentation characteristic of material. As mentioned in introduction part, it has been found by many researchers that the FSD of rock generated by super-critical quasi-static, impact or dynamic loads can be characterised by typical functions. Experiments done by Li et al. found that fractal model is appropriate for FSD of coal samples resulting from uniaxial compression loading. Uniaxial compression tests of coal samples done by our previous research has verified that fractal model can be used to describe the FSD of coal samples under quasi-static load (Yang, Ren et al. 2020). However, the statistical and exponential FSD of coal subject to impact load have not been well understood.

In this paper, FSD analysis was carried by a combination of manual sieving method and image processing technique. Coal fragments generated by impact load test were sieved into several regimes and then digital analysed through image processing in MATLAB software (Yang, Ren et al. 2020). The selected meshes have different sizes including d = 2.5, 5 and 10 mm. The sieving and image analyse process are shown in Figure 3. The cumulative mass distribution curve of each sample could be plotted based on sieved and image processed data.

Energy Dissipation

During the brittle failure of coal samples subject to quasi-static load, most of the energy will be dissipated in the form of fragmentation energy as shown in Figure 4. The energy conservation of this process can be written as (Yang, Ren et al. 2020):

$$E_{dissipation} = E_{burst} + E_{fragmentation} \tag{1}$$

where $E_{dissipation}$ is energy stored in coal samples during loading process, $E_{fragmentation}$ is energy consumed by coal fragmentation and E_{burst} is the kinetic energy carried by burst coal.

During the impact load test, energy was inputted by impact load and then dissipated in the forms of fragmentation and burst. Refer to equation (1), the energy conservation of this process can be written as (Zhang, Kou et al. 2000, Feng, Wang et al. 2016):

$$E_{impact} = E_{burst} + E_{fragmentation} \tag{2}$$

where E_{impact} is the energy input resulting from impact load.

According to the calculation equation of gravitational potential energy, the impact energy can be acquired as follow:

$$E_{impact} = m \times g \times h \times \varphi \quad (3)$$

where m is the weight of dropped hammer, g is gravitational acceleration, h is dropping height and φ is the energy efficiency of test system (As mentioned above, φ = 0.98).

The fragmentation energy can be calculated based on FSD function and Rittinger's theory (Yang, Ren et al. 2020). Then the burst energy is the difference between impact energy and fragmentation energy. Generally, burst energy only accounts no more than 1 % of the total energy dissipation during brittle failure of coal samples subject to quasi-static load (Su, Jiang et al. 2016). Based on the test results, the energy dissipation of coal samples subject to impact load can be analysed.

Results and Discussions

As shown in Figure 2, a force sensor mounted to incident plate was adopted to record the impact load during the test process. The recorded load wave of each sample is shown in Figure 5. The arrival time of impact load wave for each sample was different as data sampling and weight dropping were triggered by recording button of software and releasing button of test apparatus, respectively. The peak impact load of each sample is marked by red arrow in Figure 5. It can be seen that 2-3 main impact load waves were captured by force sensor for each sample. The lower impact waves 0.2 s after of test initiation are caused by impact between drop weight and transmission bar as coal samples have been completely damaged by high impact load wave. The peak load is contained by the first impact load wave. Although the dropping height is the same, the peak impact load of each sample is different as coal is inhomogeneous. The average peak stress of coal samples subject to impact load is 39.88 MPa according to the peak impact load data in Figure 5. According to our previous research (Yang, Ren et al. 2020), the average peak stress of coal sample subject to quasi-static load is 16.82 MPa. It is obvious that impact load increases the peak stress of coal samples.

The cumulative FSD of coal samples acquired by manual sieving and image processing is shown in

Figure 6. It has been proved by previous research that the cumulative FSD of coal samples subject to uniaxial compression load (quasi-static load) can be characterised by fractal model (Peng, Ju et al. 2015, Yang, Ren et al. 2020) :

$$F(d) = (\frac{d}{d_{max}})^{3-n} \quad (4)$$

Where $F(d)$ is the cumulative mass fraction of the fragments smaller than size d, d_{max} is the maximum size of coal fragment and n is the fractal dimension of particle size distribution, which is related to coal properties.

The maximum fragment size of each sample can be determined based on image processed data. Then the fractal dimension can be determined based on fitting of manual sieving and image processing data. As shown in Figure 6, the fractal model also can be adopted to describe the FSD of coal samples subject to impact load as the fitting curve is highly correlated to manual sieving and image processing data. The FSD of coal samples subject to impact load has a relatively consistent distribution mode as the distribution curves of these 6 samples are pretty similar, which can also be seen from Figure 7. Figure 7 shows the comparison of cumulative FSD of coal samples subject to impact and quasi-static loads. UCS1 and UCS2 are FSD curves of two coal samples tested by uniaxial compression load (quasi-static load). It is obvious that fragmentation of coal under impact load is more pulverized. The maximum fragment size of coal under quasi-static load is over half sample length while it under impact load is only around 1/5 of the sample length. This finding will be important for understanding the driving force of coal burst in underground coal mines according to its FSD data, hence, to adopt proper measures to maintain the stability of underground structure. Generally, the stress concentration induced by quasi-static load can be mitigated by water infusion (Frid 2000), de-stress drilling (Justine and Ian 2016) and de-stress blasting (Dou, Lu et al. 2004). However, the mitigation of coal burst induced by impact needs innovatively designed roadways (Dou, Mu et al. 2014) or specific solving techniques.

The dropping height of all impact tests is 0.5 m and the dropping weight is 73.35 kg. Based on equation (3), the energy inputted by impact load is 352.23 J. According to fragmentation energy calculation equation proposed by Yang et al. (Yang, Ren et al. 2020), the energy consumed by fragmentation can be calculated based on fractal FSD function of each samples. Then the burst energy can be calculated based on equation 2. The values of burst and fragmentation energy for each coal sample are shown in Figure 8. It has been proved by uniaxial compression tests of coal samples that only no more than 1% of stored energy is dissipated in the form of burst energy for coal samples subject to quasi-static load (Su, Jiang et al. 2016). However, for coal samples subject to impact load, the burst energy accounts for more than 99 % of the impact energy input while fragmentation energy only accounts for no more than 1 %, which is distinctly different with quasi-static load tests. The burst severity and hazard are positively related to burst energy scale (Rezaei, Hossaini et al. 2015, Yang, Ting et al. 2018). Hence, the burst of coal under impact load will be more severe and instantaneous as more kinetic energy will be carried by burst coal. The dynamic loading tests of coal/rock achieved by Split-Hopkinson Bar (SHPB) System also found that the kinetic energy increases with impact speed of striker bar (Zhang, Kou et al. 2000). However, fragmentation energy still accounts for 87 % of the dissipated energy for gabbro samples when the impact velocity is 20 m/s according to the equation proposed by Zhang et al (Zhang, Kou et al. 2000). This may be caused by the material property as gabbro is denser and can consume more fragmentation energy. However, the percentage of fragmentation energy and kinetic energy of coal samples subject to different impact velocities still need to be further studied by more tests with the application of drop weight and SHPB test systems.

Concluding Remarks

The stability of coal is essential to main the safety and efficiency of underground mining as catastrophic failure of coal can cause personal casualties and economic losses. Coal body in mine site is always under static, impact or dynamic loads induced by mining disturbance and original stress. Research of the coal failure subject to impact load will contribute to understand the fragmentation characteristic and burst behaviour of coal burst caused by impact load. In this paper, the drop weight tests of coal samples were conducted in laboratory to investigate the fragmentation characteristic and energy dissipation of coal under impact load. 6 coal samples taken from local coal seam were tested by a 0.72 kN drop weight with 0.5 m height. The main findings of this paper include：

1. It is obvious that impact load increases the peak stress of coal samples. The average peak stress of coal samples subject to impact load is 39.88 MPa, which is twice of the average peak stress of coal sample subject to quasi-static load (16.82 MPa).
2. The FSD of coal samples subject to impact load has a relatively consistent distribution mode, which can be characterised by fractal model. It is obvious that fragmentation of coal under impact load is more pulverized.
3. For coal samples subject to impact load, the burst energy accounts for more than 99 % of the impact energy input while fragmentation energy only accounts for no more than 1 %, which is distinctly different with quasi-static load tests. That is, the burst of coal under impact load will be more severe and instantaneous as more kinetic energy will be carried by burst coal.

Data Availability

All data, models, or code generated or used during the study are available from the corresponding author by request.

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Declarations

Authors declare no conflict interests.

Authorship Contribution Statement

Xiaohan Yang: Methodology; Formal analysis; Writing – original draft. **Ting Ren:** Supervision; Funding acquisition. **Lihai Tan:** Validation; Experimental. **Alex Remennikov:** Supervision; Writing – review & editing.

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Figure Captions

Figure 1 Coal Samples Preparation

Figure 2 Impact Test Setup

Figure 3 Image Processing Technique

Figure 4 Energy Dissipation of Coal Samples under Impact and Static Load

Figure 5 Impact Load of Coal Samples

Figure 6 Cumulative FSD of Coal Samples

Figure 7 Comparison of Cumulative FSD of Coal Samples subject Impact and Quasi-static Load

Figure 8 Burst and Fragmentation Energy of Coal Samples under Impact Load