

Two types of coal samples' dynamic mechanical properties under impact loading

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Abstract. This study presents a kinetic experiment process of briquette and raw coal samples in detail by means of Φ 75mm split Hopkinson pressure bar test system and dynamic stress-strain relations and mechanical properties of this two different coal samples. According to the experimental results, this two coal samples both have strain rate effect. The DIF (dynamic stress increasing factor) and DEIF (dynamic strain increasing factor) of the two coal samples have different trends. There is a turning phenomenon of DIF as the strain rate is around 100s^{-1} , and the DIF of the hard coal increases rapidly over 100s^{-1} , but the DIF increasing rate of soft coal has little change before or after the turning point. The DEIF of the two types of coal all increases with the increase of strain rate, but the turning strain rate of ordinary coal is 120s^{-1} , while a platform of turning strain rate exists for outburst coal with strain rate ranging from 100s^{-1} to 210s^{-1} . It represents the discrepancy in their strain rate hardening effect and dynamic toughening effect.

1. Introduction

Coal or rock dynamic disasters have been increasingly serious, such as rock burst, coal and gas outburst with the growth of mining depth. Thus, it is urgent to prevent and cut down its occurrence for ensuring the safety, rationality and efficiency of coal mining. Besides, the research of coal's dynamic mechanical properties receives more attention. It is indicated by the research results of dynamic mechanical properties of rock-like material that strain rate serves as one of the important factors that influence rock property. In other words, dynamic mechanical parameters of rock-like materials are evidently dependant on strain rate. In the fields of mining engineering in the deep, the dynamic properties of a strain rate from 10s^{-1} to 100s^{-1} are the key to analyzing the causes of rock burst and gas outburst. In recent years, with the frequent occurrence of coal's dynamic disasters more and more attention has been paid to coal dynamic mechanical properties because of its unique failure forms and strength properties from that of the statics. Shan et al. [1] established the relation of yield strength, ultimate strength and strain rate of anthracite by utilizing SHPB equipment. Gao et al. [2] established the theoretic equation of dynamic fracture strength of its impacting, compression and expansion. Li et al. [3] analyzed the softening effect of coal body under impact loading. Liu and Zhang [4] explored its splitting forms under a high strain rate. Fu et al. [5] analyzed the mechanical properties of its dynamic stress-strain curve separated by three stages. Liu et al. [6] researched on the relation of dynamic strength, fractal dimensions of fragment s and stress wave energy of compound coal-rock. At present, the mechanical properties of concrete, rocks under impact loading have been studied intensively. However, research of coal's mechanical properties is just at the beginning.



With a large quantity of experiments on dynamic mechanical properties of briquette and raw coal samples carried out by $\Phi 75\text{mm}$ SHPB, this paper focuses on their stress-strain relations, properties of dynamic strength and growth mechanism of dynamic stress and strain under various strain rates conditions. The study results can provide reference for the further research on the mechanical mechanism of coal under impact loading.

2. Experiment preparations

The coal samples of this experiment were taken from C13-1 coal seam in Zhangji mine of Huainan Mining Bureau. And the sampling location is in the 1133(3) workplace of 1st eastern 13-1(3) mining district, which is -454.3m in elevation.

2.1. Preparation of raw coal samples

First, the lump coal is taken out that is right exposed in the mining face at the scene. Next, it is vacuum-packed by closed-bags. Later, as shown in fig.1, the cylindrical coals with diameter 50mm are acquired by using the rock drill, and then the required raw coal samples of dynamic experiment are got after incised and polished.

2.2. Preparation of briquette coal samples

First, after the coal is crushed into pulverized coal with a fineness of 40~80 meshes, the pulverized coal is compacted into a homemade coal compacting vessel on a large-scale stiffness compressor with a pressure of 100MPa. Then, the briquette coal samples are got. With a strict control of the quality and forming pressure of pulverized coal, the size of briquette coal sample can be controlled within a certain range that meets the requirement of this dynamic experiment.

According to the research results of the other scholars, the static compressive strength of briquette coal is lower than that of raw coal. Also, the mechanical mechanism of briquette coal is much similar to that of soft layer in outburst coal seam. Hence, the briquette coal is defined as the outburst coal in this paper. By contrast, the raw coal is defined as the ordinary coal due to its high strength, which is drilled out from lump coal in the field. The coal samples are shown in Fig.1.

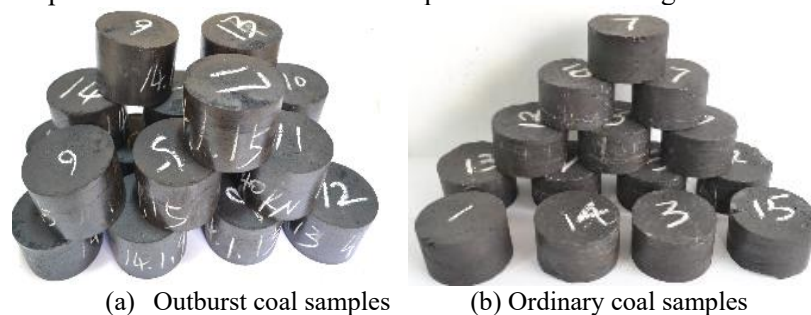


Fig.1 Pictures of coal samples

3. Mechanical properties of coal under impact loading

In order to facilitate the comparison of their change law of the stress-strain curves under various strain rates conditions in the experiment, the stress-strain curves of the two types of coal samples are drawn respectively in the same coordinate, which is shown in Fig.2 (a) and Fig.2 (b).

Under the static loading, the coal appears a linear deformation in the initial stage. By contrast, it appears evidently none-linear at the beginning while impact loading with various strain rates is applied. Then, with the loading going on, the curve starts to bend down, which means that the slope of tangent decreases gradually until it reaches the yield point of stress. This is mainly due to the cracks extending little by little inside the sample, as making its tangent modulus decrease gradually. After reaching the yield point, the stress of coal continues to grow until the peak stress with the increase of loading, which presents the strain hardening property. Then, as the growth of strain, the tiny cracks inside get well propagated and run through. In the end, it results in macro cracks and that's when the sample

begins failure. Owing to coal's rapid failure after the peak stress, the stress-strain curve is all post-peak unloading of a negative slope after the peak stress. Besides, there have been controversies over the measurement of post-peak unloading curve by SHPB experimental technique. Overall, the deformation process of coal under impact loading can be summarized as follows: initial none-linear stage, yield stage, strain strengthened stage, unloading failure stage.

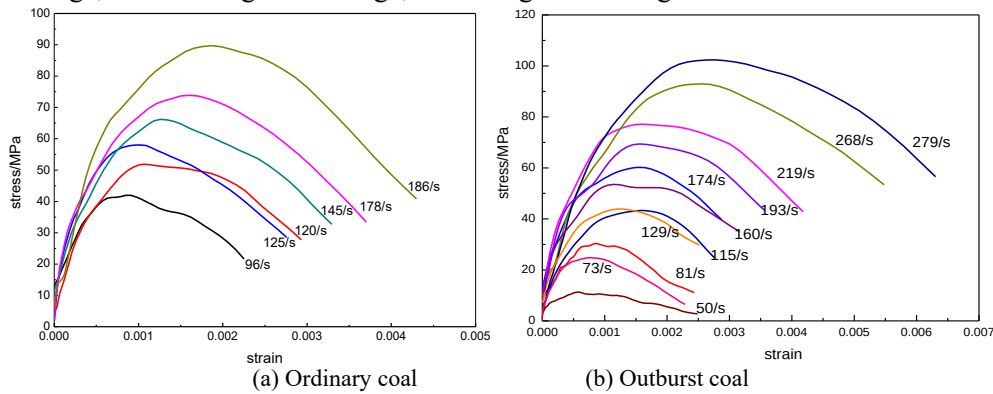


Fig.2 Dynamic stress-strain curve of coal under different strain rate

The experiment results show that the dynamic compressive strength of these two kinds of coal both increases compared to their static compressive strength. Moreover, along with the increase of strain rate in the experiment, the improved range augments. Within the strain rate range of this experiment, the strength of ordinary coal raises 2.03 times more than its static strength at least and 4.35 times at most; By contrast, the strength of outburst coal raises 15 times more than its static strength at least and 50 times at most. It indicates that these two types of coal are all sensitive material to strain rate and have the property of strain rate hardening. This is because that the coal failure is caused by crack generation and propagation and the energy of crack generating is much higher than that of crack propagating. When the loading rate is higher, the number of crack generating is much more. And as the loading applied on sample is in a short time, the material hasn't enough time to accumulate energy, so it has to raise its stress to boost energy levels. Therefore, the failure strength of material increases along with strain rate.

4. Relation of strain rate and DIF, DIF

4.1. Relation of dynamic stress increasing factor (DIF) and strain rate

To compare the improved range of coal's dynamic strength with the static strength under a certain strain rate, the ratio of dynamic strength to the static strength is defined as the dynamic stress increasing factor, as shown below:

$$DIF = \sigma_f / \sigma_{fs} \quad (1)$$

Where, σ_f is the dynamic compressive strength under conditions of various strain rates, *MPa*; σ_{fs} is the static compressive strength of coal, *MPa*. As shown in Fig.3, the variable relation of strain rates and DIF of two types of coal are drawn, with the ratio $\dot{\epsilon}/\dot{\epsilon}_s$ of average strain rate to quasi-static strain rate in the experiments as X-axis and DIF as Y-axis.

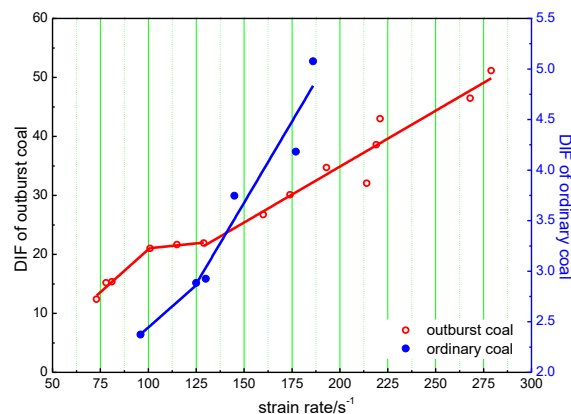


Fig.3 Relation of DIF and strain rate

What can be found from the figure is that there exists a phenomenon that DIF of the two types of coal all increases with the increase of strain rate. In addition, the strain rate sensitivity of DIF is different when it's under a high or a low strain rate respectively. In other words, there exists a turning strain rate. From Fig.3, a platform of turning strain rate exists for outburst coal whose $\dot{\epsilon} = 100 \sim 130 \text{ s}^{-1}$. Furthermore, the value of DIF all follows a linear change with $\dot{\epsilon}/\dot{\epsilon}_s$ before or after the platform and the increase of DIF is much faster under a low strain rate, which indicates that the improved range of relative strength of outburst coal slows down with the increase of strain rate. The turning strain rate of ordinary coal is around 120 s^{-1} and its DIF also follows a linear change with $\dot{\epsilon}/\dot{\epsilon}_s$ before or after the turning point. Moreover, the change of DIF is bigger under a high strain rate, which indicates that the strain rate effect of ordinary coal under conditions of high strain rate is much more obvious. Additionally, within strain rate of the experiments, the DIF of outburst coal is much bigger, and the increasing rate of DIF has a tendency to decline following the growth of coal strength (i.e. coal hardening) under a constant strain rate. It shows that coal's strength is of great influence on DIF.

The studies on concrete by Rose and other scholars [7-8] show that there exists a turning phenomenon of DIF as the strain rate is around 100 s^{-1} and it has a rapid increase when the rate exceeds this strain rate. Li and Meng [9] also found the similar phenomenon while analysing the strain rate effect of concrete. To the brittle materials such as the concrete and coal, it is found that there equally exists a turning phenomenon of DIF as the strain rate is around 100 s^{-1} . In addition, DIF of the hard coal and concrete increases rapidly as the rate is over 100 s^{-1} . By contrast, the increasing rate of DIF of soft coal has little change before or after the turning point. This is mainly resulted from the transverse inertial effect of this kind of material and it adds lateral restraint on the sample and thus leads to an effect of lateral restraint. To explain, the soft coal has a lower strength and smaller density than hard coal, and so its lateral inertial effect is not obvious.

There is a turning platform in the relation of DIF and strain rate whether it is hard coal or a soft coal, and the relation varies before and after the turning point. This is mainly because that the master control mechanism of strength and deformation of coal is different under the different strain rate. Under the conditions of a low strain rate, the strength and deformation of coal is mainly controlled by thermal activation mechanism which was proposed by Zhurkov [10]. Hence, under the condition of little difference in thermal activation energy, DIF increasing rate of coal with different strengths is almost identical under a low strain rate. As shown in Fig.3, the two curves are almost parallel before the turning point. Along with the increase of strain rate, the coal's macroviscosity becomes evident. Therefore, a turning platform of DIF shows up near 100 s^{-1} . Besides, the softer the coal is, the more evident the macroviscosity phenomenon is. Following a further increase of strain rate, the coal's inertial effect starts showing. And the harder the coal is, the more apparent the lateral restraint phenomenon of inertial effect is. Moreover, with the increase of strain rate, the improving strength rate becomes higher, and the improving strength rate of hard coal is much higher than that of soft coal.

under a high strain rate. Therefore, the hard coal has a higher ability of strain hardening under a high strain rate.

As shown in Fig.4, the relation of strain rate and DIF of coal and other rock materials are obtained by comparing the research results of materials such as quartzite, sandstone, and granite, concrete and marble. The strain rate hardening effect is ubiquitous in rock materials, and the lower the strength, the bigger the DIF. And so the strength of coal has a significant impact on DIF.

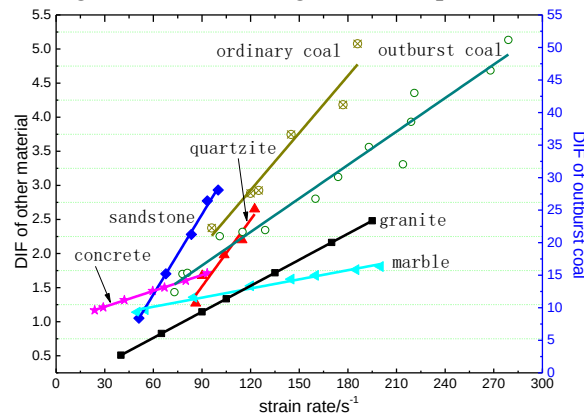


Fig.4 Relation of DIF and strain rate of different rock materials

4.2. Relation of dynamic strain increasing factor (DEIF) and strain rate

To study the improved range of peak strain under various strain rates compared to that of static loading, the dynamic strain increasing factor is defined as shown below:

$$DEIF = \varepsilon_p / \varepsilon_{ps} \quad (2)$$

Where, ε_p is peak strain of material under various strain rates conditions; ε_{ps} is peak strain of material under static loading. It is obvious that DEIF is a dimensionless parameter and thus the ratio of strain rate under impact loading to static loading $\dot{\varepsilon}/\dot{\varepsilon}_s$ is applied to represent the change of strain rate. The mean peak strains of outburst coal and ordinary coal in this experiment are 118.65×10^{-4} and 63.94×10^{-4} respectively.

As shown in Fig.5, the DEIF of the two types of coal all increases with the increase of strain rate and there are two different kinds of change trend. And yet, there both exists the turning point of strain rate. In addition, the turning strain rate of hard coal (i.e. ordinary coal) is 120 s^{-1} , while a platform of turning strain rate exists for soft coal (i.e. outburst coal) with strain rate ranging from 100 s^{-1} to 210 s^{-1} .

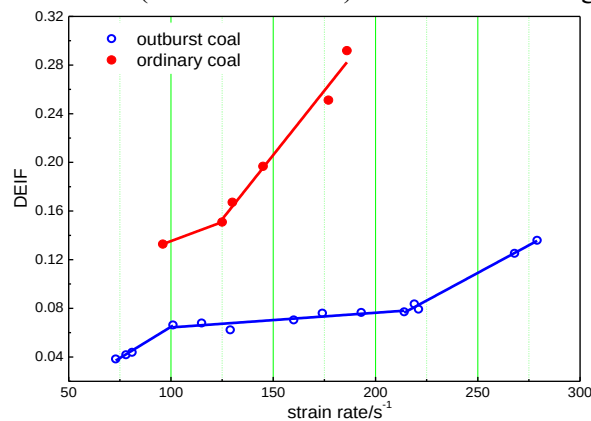


Fig.5 Relation of DEIF and strain rate

DEIF of hard coal is bigger than that of soft coal under the same strain rate, and the increasing rate of hard coal increases much faster after the platform. It is mainly because that the lateral restraint of

inertial effect is much more evident when the hard coal is under a high strain rate condition while a stronger deformation ability in axial direction existing. By contrast, the macroviscosity effect of soft coal is much more evident. To sum up, Both hard coal and soft coal have the tendency of strain rate hardening under a high strain rate condition, but only the hard coal's performance is more obvious.

The absorbed energy of material from loading to its failure is defined as its toughness, and that the dynamic toughness of hard coal is higher than that of soft coal. It means that the absorbed energy of hard coal from intactness to failure is bigger than that of soft coal under conditions of the same strain rate. And this is the reason why it is easier for the soft coal to fail under impact loading.

5. Conclusions

(1) The stress-strain curve of coal under impact loading which is obtained in the experiment is evidently different from that under static loading or that of other rock materials, which is none-linear in the initial stage. When the experimental strain rate is low, the coal body has some plastic deformation, and as it exceeds a certain value, coal's deformation shows an obvious property of strain hardening and the sample reaches the ultimate stress soon.

(2) For the two types of coal, the strain rate hardening property of ordinary coal is much more obvious and the improved range is much bigger along with the increase of strain rate, which indicates that the ordinary coal is capable to resist impact loading better than the outburst coal.

(3) The change trends of DIF and DEIF with strain rate of the two types of coal are different. Before and after the turning strain rate, their DIF and DEIF meet a linear increasing relation, which shows the strain rate hardening effect and the dynamic toughening effect. Furthermore, in the different stages of strain rate, the influence and contribution of thermal activation mechanism, macroviscosity and inertial effect on coal materials are different from each other.

Acknowledgments

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