THE ENERGY EVOLUTION CHARACTERISTICS OF COAL UNDER DIFFERENT DYNAMIC STRAIN RATES AND CONFINING PRESSURES

by

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Coal specimens from baijiao coal mine were impacted by a split Hopkinson pressure bar to study its dynamic mechanical behavior under different confining pressures (0-12 MPa) and different strain rates (20-250 s^{-1}). The performances and the energy evolution characteristics of the coal specimens were analyzed. The results show that the strengthening effect and toughening effect of rock are gradually enhanced with the increase of confining pressure. At the same time, the coal failure gradually transitions and develops from tensile failure to compression-shear failure under the action of confining pressure. The peak strength and peak strain of coal rock show significant strain rate correlation and strong confining pressure effect with the change of confining pressures and strain rates. The dynamic strength growth factor of coal is approximately linear with the increasing of strain rates. The energy density and energy absorption density increase linearly with the increase of strain rates, and the energy consumption ratio has a logarithmic growth relationship with the strain rates.

Key words: coal, split Hopkinson pressure bar, confining pressure, strain rate

Introduction

In the process of solid mineral resources mining, the mine dynamic disasters in coal mines are prone to occur, such as rock burst, coal and gas outburst, *etc.* Coals are destroyed under dynamic loads [1, 2]. Especially in the deep coal mining process, the mined coal is in a high geostress environment, and the deep coal rock is more prone to dynamic disasters such as impact and ground pressure [3].

It is well known that there is a significant strain rates effect on the dynamic response of rocks [4]. The uniaxial compressive test of the tuffs was performed in [5]. The results were showed that the compressive strength of the tuff specimens was increased with the increasing of strain rate when the strain rate was greater than 76 s^{-1}. The uniaxial compression test on Bukit Timal granites were performed in [6]. It was found that the compressive strength of granite was increased as the strain rate increased. Dolomite, limestone, granite and basalt were studied in [7] in the range of loading strain rate, $1\cdot10^{-4}$, $1\cdot10^{8}$ s^{-1}. The results were showed that the

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mechanism of damage of rocks were very different between low strain rate and high strain rate. The stain rate effect characteristics of salt rock strength of layered salt rock were comprehensively explored [8]. It was found out there was a positive correlation between uniaxial compressive strength and strain rate. The vibration and damage effects of engineering rock mass were studied [9]. The results were showed that the dynamic failure process of rock was inextricably linked with its energy evolution process.

The earliest research of strength characteristics of coal at high strain rates was studied in the 20th century [10]. The mechanical properties of coal were analyzed in [11] under impact load and determined the sensitivity of coal mechanical parameters to variability in the range of strain rates, 0, 2000 s^{-1}. The results were indicated that the elastic properties of coal are not sensitive to changes within a certain range of strain rates. When the strain rates were exceeded the certain range, the elastic modulus and crack initiation stress of coal had almost linearly increase relationship. The impact characteristics of coal specimens were studied in [12]. It was found that the uniaxial compressive strength and impact energy index of coal was increased first and then decreased with the increase of loading rate.

In view of this result, the main aim of the paper is to present that the Φ = 50 mm split Hopkinson pressure bar (SHPB) test device with active confining pressure is used to synthetically study and analyze the dynamic mechanical properties of coal under different confining pressure levels and different impact loads.

Experimental preparation

Specimen preparation

The coal used in this test is an ash-rich and sulfur-rich anthracite from Baijiao Coal Mine in Sichuan Province, China. There are a large number of randomly distributed inherent defects such as bedding, joints and cracks. The structure is extremely uneven and the layer structure is obvious. In order to eliminate the influence of the specimen layer structure on the experimental results, the specimens tested in this paper are all vertical bedding direction. In the dynamic test, the diameter of the coal rock specimen is 50 mm in diameter and 1:1 in length to diameter ratio. The uniaxial compressive strength was 7.72 MPa, and the compressive strength at the confining pressure of 4 MPa, 8 MPa, and 12 MPa were 26.93 MPa, 35.47 MPa, and 56.79 MPa, respectively. The main physical and mechanical properties were shown in tab. 1.

Table 1. Basic physical and mechanical parameters of coal

Elastic modulus E [GPa]	Poisson's ratio	Density [kgm^{-3}]	Longitudinal wave velocity [ms^{-1}]
1.62	0.36	1 594.34	988.38

Loading system

The dynamic load was applied by the SHPB loading system of Central South University. The test system generates different impact velocities by setting different gas pressures and obtaining different strain rate history, [13, 14]. The test system corresponds to a strain rate in the range of 1~10^3 s^{-1}. The incident bar was impacted by a *shuttle* projectile, which was able to accurately obtain a half sine wave and reduce the transverse dispersion effect, [15], as shown in fig. 1.

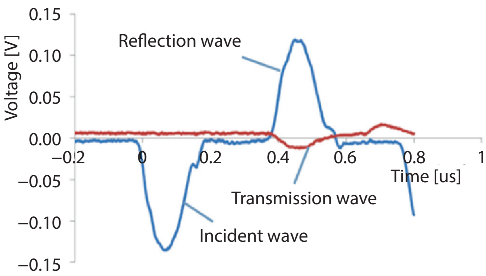

Figure 1. Wave diagram of typical dynamic impact test of coal

Analysis of experimental results

The dynamic stress-strain curves of vertical layered coals under different confining pressures, 0-12 MPa, and different strain rates, 20-250 s^{-1}, are shown in fig. 2.

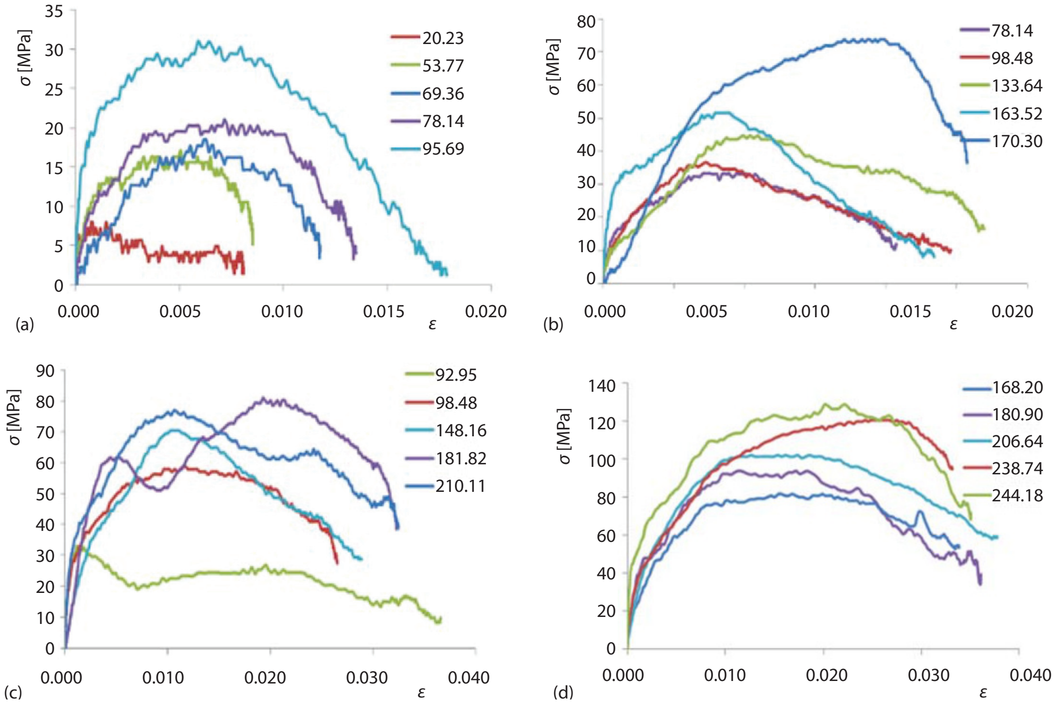

Figure 2. Coal rock stress-strain curve under dynamic impact load; (a) 0 MPa, (b) 4 MPa, (c) 8 MPa, and (d) 12 MPa

It can be seen from fig. 2 that the stress peak of the stress-strain curve is generally low and the peak strain is small under the uniaxial dynamic load. At the same time, the post-peak stress level decreases rapidly. In the three-direction stress state, the rock stress peak is mostly higher. The effect of confining pressure leads to the increase of peak strain, residual stress and ductility. Because a large amount of elastic energy is carried in the entire impact loading process, the original cracks of the coal expand rapidly and new cracks are generated. Due to the development and extension of these micro cracks, the coal quickly enters the yielding stage. After the peak stress, the mechanical property of coal decreases. Comparing the dynamic stress-strain curves of coal under different strain rates. Results show the strength of coal increases with the increase of strain rate. At the same time, it is not difficult to see that the confining pressure has a significant impact on the mechanical behavior characteristics of coal and rock. With the increase of confining pressure, the stiffness and ductility of coal specimens are improved, and the impact resistance is greatly increased.

According to the dynamic stress-strain curves of coal under different strain rates, the variation of peak stress of coals can be obtained, as shown in fig. 3. It can be seen from fig. 3 that the strength of coal increases with the increase of confining pressure in the range of confining pressure from 0-12 MPa, which means that the strength of coal is affected by the confining pressure not only in the static strain rate, but also in the dynamic strain rates.

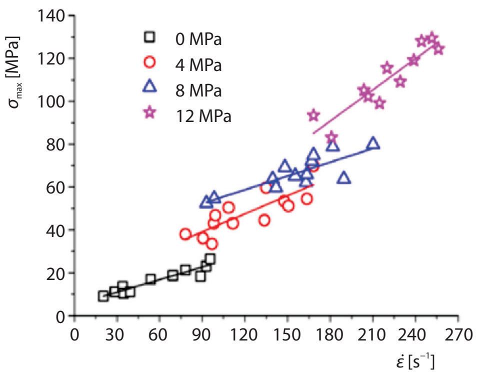

Figure 3. Peak stress variation curve of dynamic impact compression coal (vertical layering)

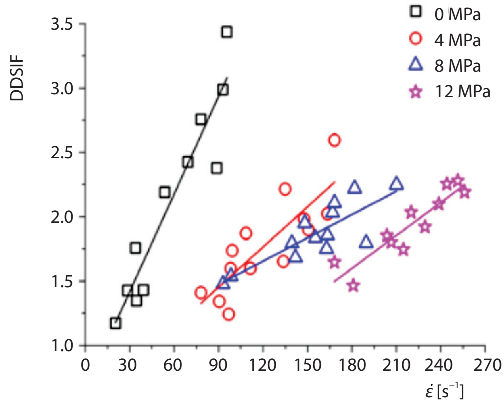

Figure 4. Variation of DDSIF with strain rate under different confining pressure

In order to quantitatively study the influence of strain rate and confining pressure on coal strength, we define the dimensionless dynamic strength increase factor (DDSIF) as the ratio of the dynamic compressive strength and the static compressive strength of the specimen under the same confining pressure condition. The equation of DDSIF is expressed:

$$\text{DDSIF} = \frac{\sigma_{\text{max,d}}}{\sigma_{\text{max,s}}} \tag{1}$$

where $\sigma_{\text{max,d}}$, $\sigma_{\text{max,s}}$ are the dynamic compressive strength and static compressive strength of coal under the same confining pressure condition, respectively.

The variation of DDSIF with the increase of strain rates obtained according to eq. (1) is shown in fig. 4. The linear fitting formula for DDSIF under different confining pressures.

It can be seen from fig. 4 that DDSIF exhibits a significant linear correlation with the increase of strain rate. However, as the confining pressure increases, the growth slope of DDSIF gradually decreases (there is an abnormal point at a confining pressure of 8 MPa). It is shown that the sensitivity of DDSIF to variability decreases with the increase of confining pressure. This is because as the confining pressure increases, the plasticity of the coal becomes more prominent, and coal deformation gradually increases, resulting in a decrease in brittleness and a decrease in sensitivity of strength. Therefore, as the confining pressure increases, the slope decreases.

Energy evolution analysis of coal under dynamic impact loading

Energy composition during dynamic testing

As it is known, the damages of the coal specimens are the result of energy evolution, which is a non-equilibrium irreversible state. We analyze the damage process of the specimen from the point of view of energy in this section. In the SHPB dynamic test, the energy carried by the incident wave $\sigma_i(t)$, the reflection wave $\sigma_r(t)$, and the transmission wave $\sigma_t(t)$ can be given [13]:

$$\left.\begin{aligned} W_\mathrm{i} &= \frac{A_\mathrm{b} C_\mathrm{b}}{E_\mathrm{b}} \int_0^t \sigma_i^2(t)\mathrm{d}t \\ W_\mathrm{r} &= \frac{A_\mathrm{b} C_\mathrm{b}}{E_\mathrm{b}} \int_0^t \sigma_r^2(t)\mathrm{d}t \\ W_\mathrm{t} &= \frac{A_\mathrm{b} C_\mathrm{b}}{E_\mathrm{b}} \int_0^t \sigma_t^2(t)\mathrm{d}t \end{aligned}\right\} \tag{2}$$

where $W_\mathrm{i}(t)$, $W_\mathrm{r}(t)$ and $W_\mathrm{t}(t)$ are incident energy, reflection energy and transmission energy, respectively, and E_b, $A_\mathrm{b}(t)$, and $C_\mathrm{b}(t)$ are the elastic modulus, cross-sectional area, and longitudinal wave velocity of the SHPB, respectively.

The dissipative energy of the rock specimen W_s(t) can be suggested [13]:

$$W_\mathrm{s}(t) = W_\mathrm{i}(t) - W_\mathrm{r}(t) - W_\mathrm{t}(t) \tag{3}$$

where $W_\mathrm{s}(t)$ mainly includes crushing energy, ejection kinetic energy and other energy consumption, such as acoustic energy, thermal energy, radiant energy and other forms of dissipation energy.

It is generally believed that at medium or low loading rates, other energy consumption can be ignored. Therefore, the coal energy $W_\mathrm{s}(t)$ can be used to replace the coal energy consumption, which will not have a great impact on the research conclusion. In the dynamic experiments, the total absorbed energy density μ can be written, [16]:

$$\mu = \int \sigma \mathrm{d}\varepsilon \tag{4}$$

where μ represents the absorbed energy per unit volume of the specimen.

The total dissipation energy density absorbed by a unit volume of coal specimen as e_d can be presented:

$$e_\mathrm{d} = \frac{W_\mathrm{d}}{V} \tag{5}$$

where V is the volume of the coal specimen. According to the conservation of energy, the energy absorption density is equal to the sum of the dissipative energy density and the releasable elastic energy density.

The energy consumption ratio as the ratio of the dissipation energy density to the energy absorption density can be written:

$$\eta = \frac{e_\mathrm{d}}{\mu} \tag{6}$$

Coal dynamic impact compression and failure energy analysis

The characteristics of incident energy, reflection energy, transmission energy, dissipation energy, dissipation energy density and energy absorption density in the dynamic impact failure process under four confining pressures calculated according to eqs. (2)-(6) are plotted in the fig. 5.

It can be seen from figs 5(a)-5(d) that the incident energy, reflection energy, transmission energy and dissipation energy of coal increase with the increase of strain rates. From the ratio of the transmission energy of coal to the total input energy, the value of coal transmission energy does not exceed 10%, which indicated that a large amount of energy is used for reflec-

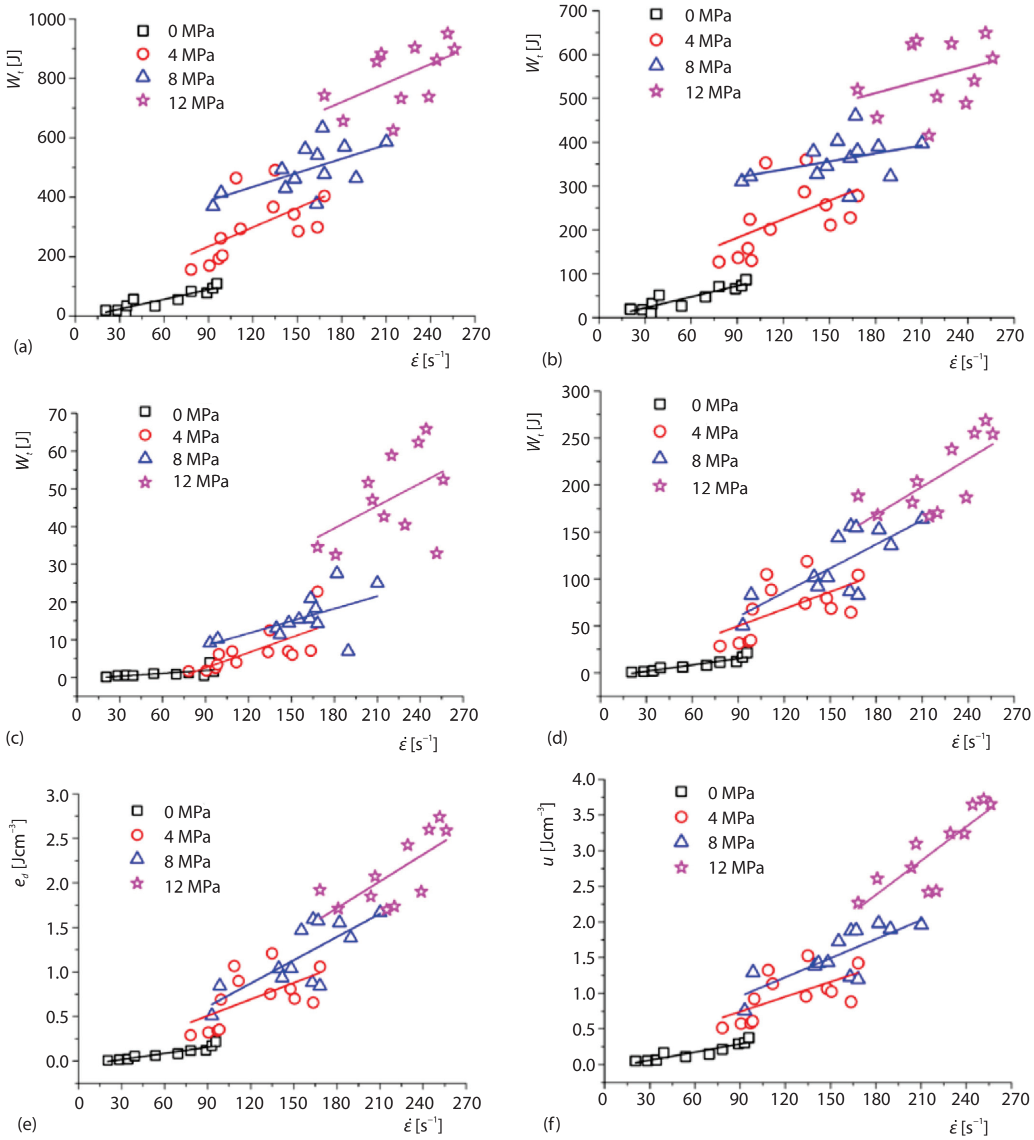

Figure 5. Energy evolution of coal under dynamic loads (vertical bedding); (a) incident energy, (b) reflective energy, (c) transmission energy, (d) dissipative energy, (e) dissipation energy density, and (f) energy absorption density

tion and absorption by the specimens. The greater the energy absorbed by coal, the greater the dissipative energy of coal under dynamic impact. It can be seen from the fig. 5 that the coal dissipation energy increases with the increase of strain rates and confining pressures. The minimum energy dissipation of coal rock under uniaxial conditions. It can be seen from figures 5(e)-5(f) that the specimen dissipation energy increases with the increase of confining pressure at the same strain rate range. This is because the higher the confining pressure, the larger the shape of the coal, the greater the energy required for the friction inside the rock, the slip work and the cracking of the crack, so the more energy is used to damage the dissipation energy.

In order to study the distribution of coal energy dissipation under the dynamic load of coal, the variation trend of energy consumption ratio with strain rates is given:

$$\eta = -0.895\mathrm{e}^{-\frac{\dot{\varepsilon}}{45.27}} + 0.755 \tag{7}$$

It can be seen from fig. 6 that under the uniaxial dynamic load, the energy consumption ratio of the specimen increases obviously with the increase of confining pressure. The energy consumption ratio fluctuates within the range of, 0.55, 0.9. It shows that under the action of confining pressure, the energy consumption ratio of the specimen tends to be stable. Confining pressure has a good redistribution effect on energy.

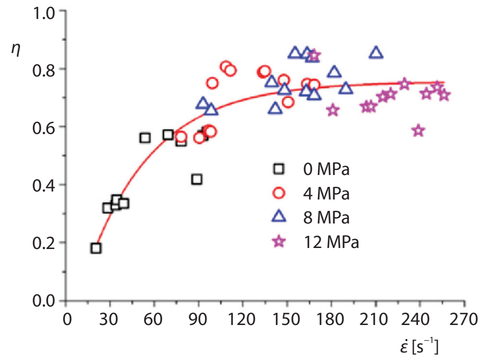

Figure 6. Curve of energy density of coal under dynamic strain rates

Conclusion

The performances and the energy evolution characteristics of the coal specimens were analyzed. The test results show that the stress peak of the stress-strain curve of coal is higher than that of the uniaxial dynamic load. The effect of confining pressure makes the peak strain value increase, the residual stress increases and the ductility characteristic development trend.

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Nomenclature

$A_b(t)$ – cross-sectional area of SHPB, [cm^{-2}]
$C_b(t)$ – longitudinal wave velocity of SHPB, [ms^{-1}]
E_b – elastic modulus of SHPB, [GPa]
e_d – total dissipation energy density, [Jcm^{-3}]
$W_i(t)$ – incident energy, [J]
$W_t(t)$ – transmission energy, [J]
$W_r(t)$ – reflection energy, [J]
$W_s(t)$ – dissipative energy, [J]

Greek symbols

η – energy consumption ratio, [–]
μ – total absorbed energy density, [Jcm^{-3}]
$\sigma_{max,d}$ – dynamic compressive strength, [MPa]
$\sigma_{max,s}$ – static compressive strength, [MPa]

Acronym

DDSIF – dimensionless dynamic strength increase factor

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