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Research Article

An Experimental Research on Surrounding Rock Unloading during Solid Coal Roadway Excavation

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In order to further explore the deformation and failure essence of the deep coal body, based on the characteristics of surrounding rock stress adjustment before and after solid coal roadway excavation, an experiment of unloading confining pressure and loading axial pressure of the coal body was designed and conducted in this study. Based on test results, the failure mechanics and energy characteristics of the coal body were analyzed through experiments. Rapid unloading is considered a key factor contributing to lateral deformation and expansion failure, which exacerbates the deterioration of coal body and reduces the deformation energy storage capacity of coal. On the other hand, the larger loading rate tends to shorten the accumulation time of microcracks and cause damage to the coal body, resulting in strengthening the coal body and improving energy storage. Under the circumstance that the coal body is destroyed, the conversion rates of the internal deformation energy and dissipated energy are more significantly affected by unloading rate. The increasing unloading rate and rapid decreases in the conversion rate of deformation energy make the coal body more vulnerable to damage. Under the same stress conditions, the excavation unloading is more likely to deform, destroy, or even throw the coal than the experiment unloading. In order to reduce or avoid the occurrence of deep roadway excavation accidents, the understanding of the excavation unloading including possible influencing factors and the monitoring of the surrounding rock stress and energy during the excavation disturbance should be strengthened. It can be used as the basis for studying the mechanism of deformation and failure of coal and rock and dynamic disasters in deep mines, as well as the prediction, early warning, prevention, and control of related dynamic disasters.

1. Introduction

With the depletion of coal resources and the deterioration of mining environment, the mine rockburst accidents occurred more frequently than before, posing as a threat to the safe and efficient mining. According to the incomplete statistics of rockburst cases, a total of 85% of the rockburst accidents occurred in the roadway which makes the roadway the main occurrence area of rockburst. In addition, 49% out of roadway rockburst accidents were identified as excavation rockburst with 51% mining rockburst [1–3]. At present, the research on rockburst is mainly focused on mining, centering around the stress environment of large space, high static load, and big disturbance. Comparatively, roadway excavation is a construction process in the environment of small space, featured with low static load and small disturbance. The research on the mechanism of large deformation or rockburst has been limited.

Roadway excavation is defined as an unloading process, which is essentially different from continuous loading failure in mechanical response, action mechanism, and deformation failure characteristics [4–6]. Recently, researchers have done a considerate amount of work on engineering excavation unloading [7–9]. Academician Qian Qihu [10] considered that the zone failure of roadway surrounding rock was led by dynamic unloading caused by excavation, and the practice also confirmed this conclusion. Roadway engineering and even underground engineering are unloading in one direction, and the balance state of triaxial compression is broken, resulting in the deformation and failure of coal and rock. The mechanical and energy characteristics of coal and rock serve as the foundation for studying the system interaction between roadway and surrounding rock. Combined with the specific cases or actual engineering requirements, scholars domestically and abroad have designed a variety of loading and unloading stress paths aiming to explore their mechanical characteristics and energy efficiency mechanism in practical application in a more accurate manner [11].

Wei [2] studied the stress path and failure characteristics of surrounding rock in solid coal roadway excavation by an unloading experiment and numerical simulation method and proposed the excavation rockburst mechanism of high static load+"loading and unloading" stress path transformation of surrounding rock. Feng [12] investigated the deformation and failure characteristics of coal under different stress paths through experiments and established the failure mechanical model for the sides of coal roadway based on the effect of unloading stress. Yao [13] researched the failure mode and law of unloading surrounding rock by theoretical analysis and numerical simulation and carried out on-site monitoring and quality evaluation on the broken range of unloading surrounding rock. Zhu [14] considered that unloading rockburst and creep rockburst are two typical impact forms of extra thick coal seam and explained their occurrence mechanism. Qin et al. [15] discussed the influence of excavation speed on the stress, displacement, and stability of roadway surrounding rock by using numerical software.

Based on the previously conducted research, this study firstly investigated the roadway excavation and surrounding rock stress adjustment and explored the suitable stress paths of loading and unloading for actual engineering. In addition, a number of experimental methods were adopted to investigate the mechanical and energy characteristics of unloading surrounding rock, which lay a foundation for further understanding of deformation, failure, and rockburst of unloading surrounding rock during excavation.

2. An Experimental Analysis on Surrounding Rock Unloading in Roadway Excavation

2.1. Experiment Preparation. The coal sample was selected from the #8 coal seam in the third mining area located in the Xianyang mining zone. The buried depth of the coal seam is nearly 800 m with an average density of 1.4 g/cm^3 and the average uniaxial compressive strength of 22.3 MPa. According to the requirements and standards of the rock mechanics experiment, the sample was processed into a cylinder of Φ 50 mm × H100 mm (Figure 1). In the experiment, multiple systems were adopted including a MTS815.02 electro-hydraulic servo rock mechanics experiment system borrowed from China University of Mining and Technology (as shown in Figure 2).

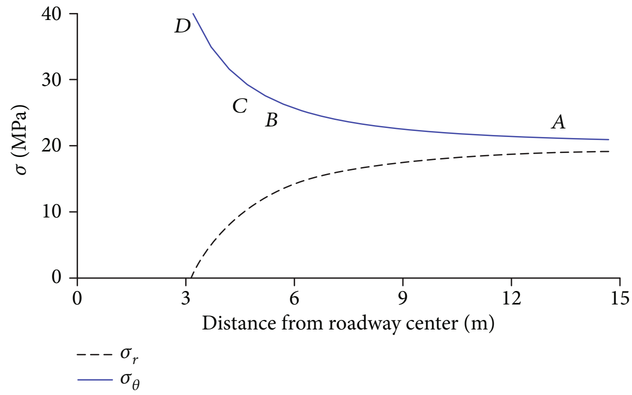
Figure 1: The typical sample specimen.

Figure 2: The MTS 815.02 testing system.

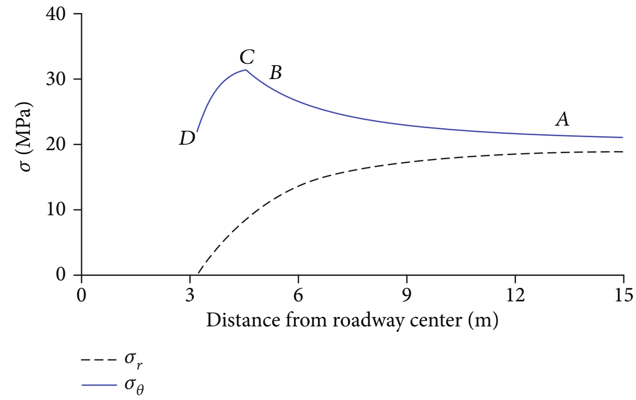
2.2. Experiment Scheme Design. According to the elastic mechanics, after the excavation of a circular roadway, the radial stress of surrounding rock often changes rapidly from the original rock stress p_0 to zero, while the shear stress increases from p_0 to $2p_0$. With the increase in the distance from the head-on, the roadway surrounding rock stress is constantly adjusted and gradually reaches equilibrium. The plastic zone (*BC* section) and failure zone (*CD* section) are formed from deep to shallow of the surrounding rock. The variances of the shear stress conform to the stress-strain curve of coal and rock, and the change of the radial stress is not obvious, as shown in Figure 3.

After the excavation of a roadway, the stress changes monitored on the surrounding rock from the depth to the surface stay consistent. The shear stress increases and the radial stress decreases, suggesting that the whole stress adjustment process is to increase shear stress and decrease radial stress. Therefore, the experimental stress path is expanded by unloading confining pressure and loading axial pressure [16] (see Table 1 for details).

At present, the common mining depth in China ranges from 400 to1000 m. In this experiment, a depth of 800 m was selected, resulting in the initial confining pressure at 20 MPa. When the coal sample was placed under a 20 MPa hydrostatic pressure, the sample begun to unload confining



(a) Before stress balance of surrounding rock



(b) After stress balance of surrounding rock

Figure 3: Stress distribution in the roadway surrounding rock.

Table 1: Summary of the experiment scheme.

Stress path		Engineering correspondence
Unloading confining pressure and loading axial pressure	Unloading rate effect Loading rate effect	Stress adjustment process of surrounding rock unloading in roadway excavation

pressure and increase axial pressure until the coal sample reached failure, as shown in Figure 4. The specific process includes the following. (1) Stress control mode. The confining pressure and axial pressure were loaded alternately at a rate of 5 MPa. Meanwhile, the confining pressure (axial pressure) $\sigma_2 = \sigma_3 = \sigma_1$ was loaded to the predetermined value of 20 MPa at the rate of 0.05 MPa/s. (2) Stress control mode. The confining pressure σ_3 was unloaded at the rate of v_3, with the axial pressure σ_1 loaded at the rate of v_1 until the coal sample reached failure. (3) Displacement control mode. After the coal sample started to fail, the axial pressure was loaded continually with the confining pressure unloading at the rate of 0.001 mm/s to obtain the full stress-strain curve.

2.3. Analysis on Mechanical Properties of Unloading Coal

2.3.1. Unloading Rate Effect. Combined with the unloading rate effect of the unloading confining pressure and loading axial pressure experiment, a stress-strain curve of coal under different unloading rates is shown in Figure 5.

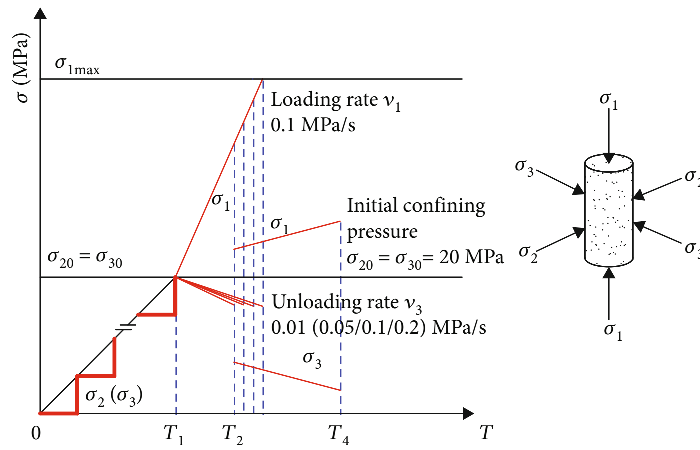
According to Figure 5, with the increase in unloading rate, the confining pressure decreases rapidly from 20 MPa, along with failure strength and axial strain of the coal body. The volume strain demonstrates an increasing trend, with obvious expansion phenomenon. In addition, the changes in the circumferential strain are limited. The relationship among coal strength, unloading rate, and confining pressure during the sample failure is shown in Figure 6.

As indicated in Figure 6, the failure strength of coal decreases with the increase in unloading rate, which indicates that the influence of unloading rate on the failure characteristics of coal is gradually weakening. The rapid unloading leads to dramatic decline of the confining pressure to zero quickly, creating conditions for lateral expansion and pressure relief. Meanwhile, considering that the uniaxial compressive strength is determined lower than the failure strength under high confining pressure, the triaxial loading and unloading experiment is rapidly transformed into a uniaxial loading experiment. Under the circumstance that the unloading rate exceeds a threshold value, the unloading rate actually reflects the uniaxial compression process of coal. Therefore, with the increase in unloading rate, the influence on the failure strength of coal gradually decreases and grows stable. The influence of the unloading rate is significant within the range of 0~0.1 MPa/s. When the coal body fails, the strength and confining pressure follow linear changes suggesting that a higher unloading rate leads to lower confining pressure and the failure strength.

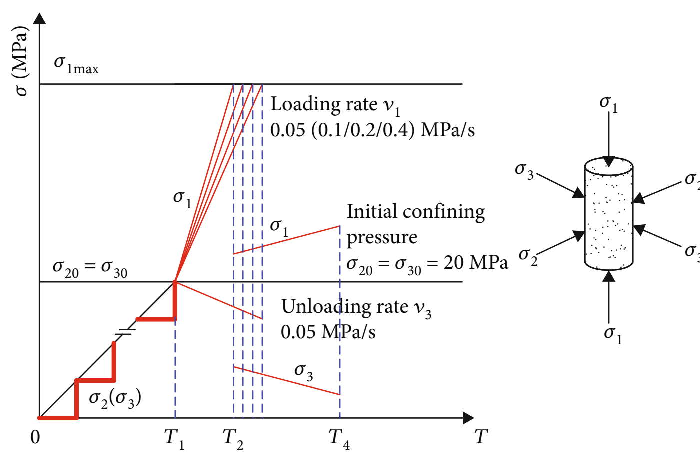
2.3.2. Loading Rate Effect. Based on the test results obtained from the experiment, the stress-strain curve of coal under different loading rates is shown in Figure 7.

According to Figure 7, the failure strength and axial strain of coal increased along with the increase in axial loading rate with limited changes in circumferential strain and volume strain. The relationship among coal strength, loading rate, and confining pressure at the moment of failure is shown in Figure 8.

As indicated in Figure 8, the influence of axial loading on the mechanical properties of coal is significant within the range of 0~0.2 MPa/s. In addition, a higher axial loading rate tends to increase the failure strength of coal suggesting that when the axial pressure was rapidly applied, the failure strength under a certain confining pressure can be reached within a short time. Due to the limited load action time on coal, the crack development inside the rock is limited with nonobvious damage accumulation. Under the circumstance that the bearing limit is exceeded, the main failure crack tends to develop instantly, resulting in failure. Therefore, to



(a) Unloading rate effect



(b) Loading rate effect

Figure 4: Schematic diagram of the stress path of unloading confining pressure and loading axial pressure.

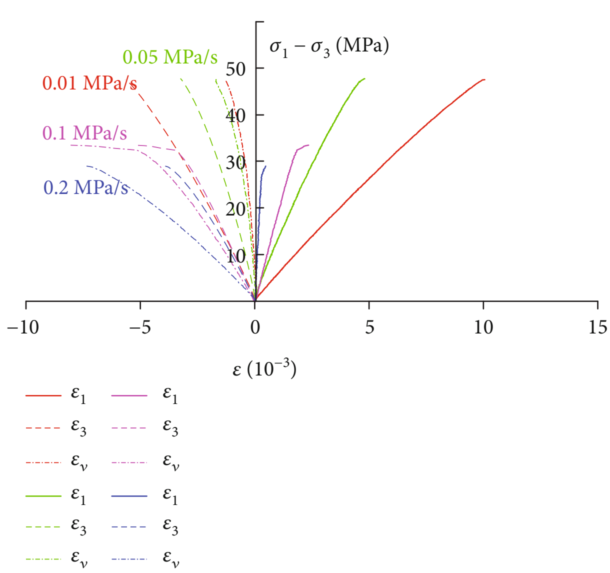


Figure 5: The stress-strain curves (unloading rate effect).

a certain extent, the failure strength of coal under corresponding confining pressure is improved by rapidly increasing axial pressure.

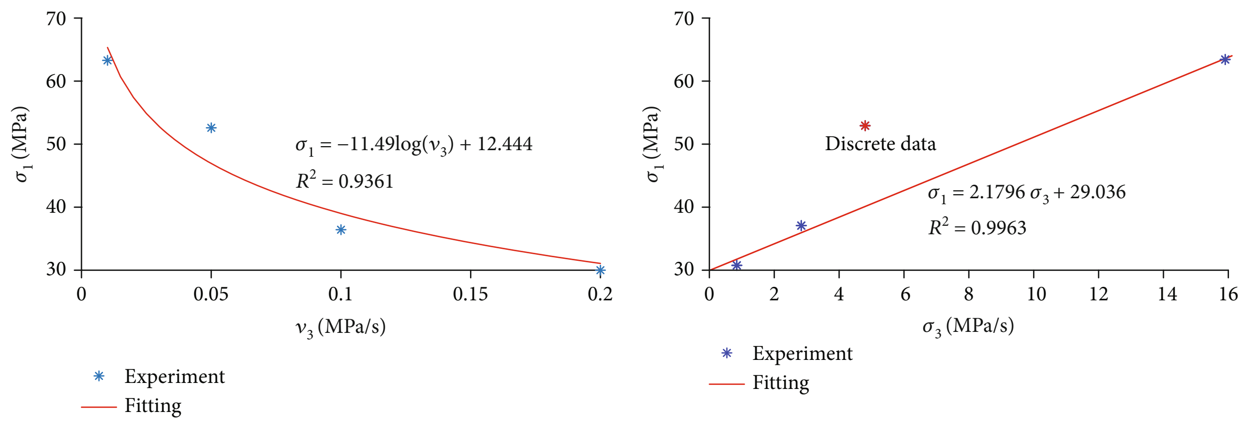
2.4. Analysis on Energy Characteristics of Unloading Coal

2.4.1. Unloading Rate Effect. In order to simplify the energy composition and calculation in the coal body during unloading, the following assumptions were made including the following: (1) part of the total work done by the experimental machine is converted into releasable deformation energy and stored in the coal body and (2) the rest of the work done by the experimental machine is converted into dissipative energy to generate cracks, degrade the coal body, or release in other forms [17–22]. The whole process of energy conversion can be expressed as

$$U = U_1 + U_3 = U_e + U_d, \tag{1}$$

where

$$U_1 = \int_0^{\varepsilon_{1(t)}} \sigma_1 d\varepsilon_1,$$
$$U_3 = 2\int_0^{\varepsilon_{3(t)}} \sigma_3 d\varepsilon_3, \tag{2}$$
$$U_e = \frac{1}{2}\sigma_1\varepsilon_1.$$



(a) Failure strength and unloading rate

(b) Failure strength and failure confining pressure

FIGURE 6: The relationship among unloading rate, axial pressure, and failure time.

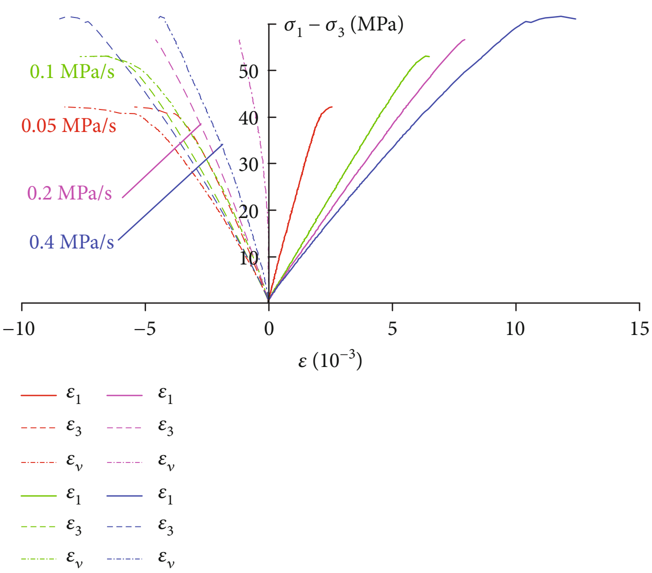
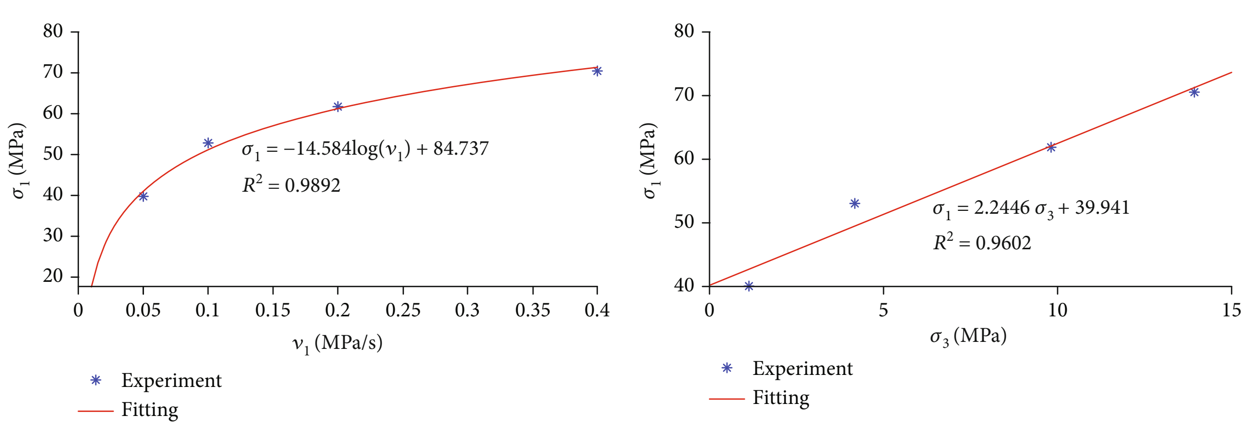


FIGURE 7: The stress-strain curves (loading rate effect).



(a) Failure strength and loading rate

(b) Failure strength and failure confining pressure

FIGURE 8: The relationship among loading rate, axial pressure, and failure time.

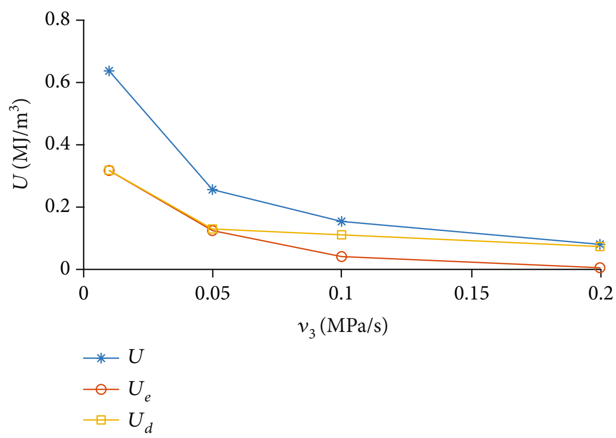


Figure 9: The energy-unloading rate curves.

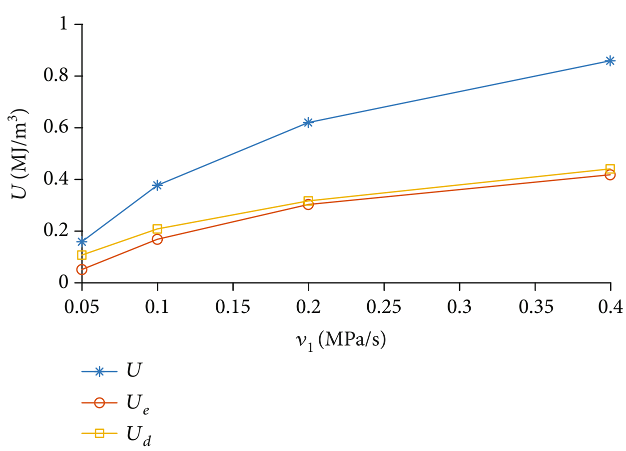


Figure 10: The energy-loading rate curves.

The energy of coal failure under different unloading rates is shown in Figure 9.

According to Figure 9, the energy required for coal failure is negatively correlated with the unloading rate, indicating that as the unloading rate increases, the energy required for coal failure tends to decrease in logarithmic form. Meanwhile, the conversion rate of deformation energy also decreases dramatically below 10% at an unloading rate of 0.2 MPa/s, indicating that a higher unloading rate leads to a lower conversion rate of deformation energy. Conversely, a higher conversion rate of dissipated energy can result in early occurrence of coal failure. When the unloading rate can exert a significant impact on the energy and mutual transformation, the unloading rate is below 0.1 MPa/s, with limited impact on the energy change.

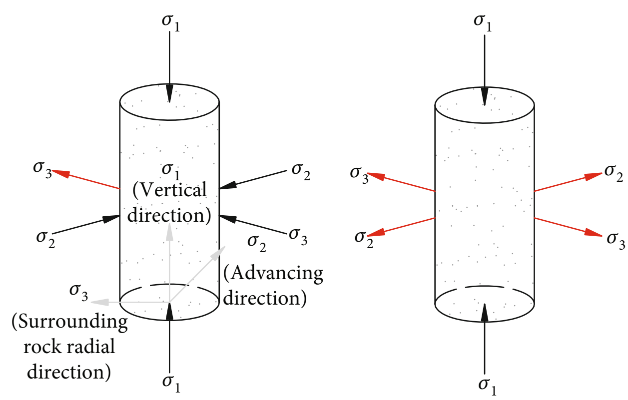
2.4.2. Loading Rate Effect. The relationship between the energy and the axial loading rate under the coal failure is shown in Figure 10.

As the axial loading rate increases, the energy required for coal failure increases in a logarithmic form. The increasing failure strength indicates that more energy is absorbed from rapid loading to failure. When the rate is greater than 0.2 MPa/s, the influence becomes more severe. No significant relationship between the transformation rate of deformation energy and the axial loading rate during unloading has been identified. In addition, the experiment suggests that transformation rate is about 20%~30% at the initial stage and 45%~50% at the near failure stage.

To sum up, the axial loading rate tends to shorten the effective accumulation time of microcracks, cause damage in the coal body, and improve the energy storage capacity of coal. Under the event that the axial loading rate varies in the range of 0~0.2 MPa/s, the axial loading rate has a greater influence on the strength and energy storage of coal, while the unloading rate produces the opposite effect. A higher unloading rate leads to a greater inhibition effect on the coal body's lateral deformation which contributes to the lateral expansion failure. The influence is prominent when the axial loading rate changes within the range of 0~0.1 MPa/s.

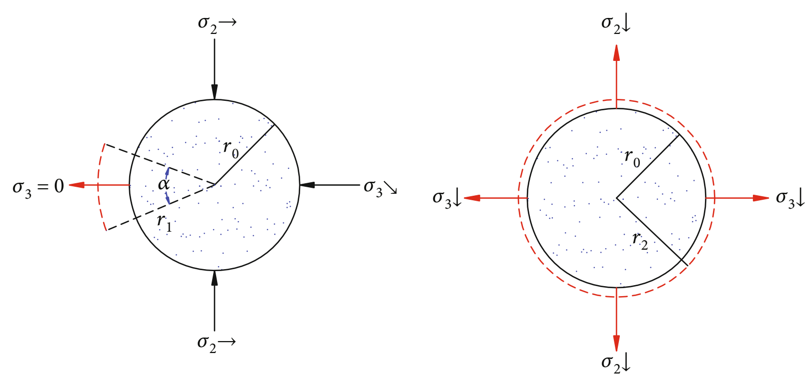
2.5. Discussion on the Differences between the Excavation Unloading and the Experimental Unloading. Different from the unloading experiment, in the original rock stress environment of three-dimensional compression, the coal body is in a state of pressurized energy storage. During the unloading process of excavation, mutual inhibition between surrounding rocks interacts with each other. The unloading rate will not evolve into a loading form of uniaxial compression, as shown in Figure 11. In actual engineering, the rapid excavation makes the mutual inhibition of surrounding rock weaken rapidly in a certain area, which immediately drops from a high confining pressure state to a low confining pressure stress environment (three-direction five-sided stress state), equivalent to completing the transformation from high initial confining pressure to low initial confining pressure in a short time, reducing the requirements of coal failure. Simultaneously, the shear stress increases synchronously, which intensifies the change of shear-radial stress difference, contributing the stress environment easier to reach the bearing limit of the coal body and creating conditions for the shallow surrounding rock to squeeze out into the free space of the roadway. Since the shallow surrounding rock still has a certain inhibitory effect on the deep surrounding rock, resulting in the coal body in a three-direction six-sided nonisostatic stress state, the crack development in the coal body decreases and gradually evolves into plastic deformation and elastic deformation.

Although the high-energy coal tends to be in a new equilibrium state through energy release in the form of deformation or even failure, various deformations and failures caused by energy release due to excavation unloading and experimental unloading are identified. As shown in Figure 12, r_0 refers to the nominal radius of microunit coal; V_0 and V indicate the volumes before and after energy release stabilizes, respectively, with ω_0 and ω being the internal energy density, respectively; r_1 (excavation unloading) and r_2 (experiment unloading) indicate the maximum nominal radius after deformation; and α refers to the excavation unloading energy release angle.



(a) Excavation unloading (b) Experiment unloading

Figure 11: Comparison of excavation unloading and experiment unloading.



(a) Excavation unloading (b) Experiment unloading

Figure 12: Comparison of excavation unloading and experiment unloading.

According to the law of conservation of energy, then

$$V_0\omega_0 = V\omega. \tag{3}$$

According to equation (3), the expansion volume of microunit coal is provided below:

$$\Delta V = \left(\frac{\omega_0}{\omega} - 1\right)V_0 = \frac{\alpha}{2\pi}\pi\left(r_1^2 - r_0^2\right) = \pi\left(r_2^2 - r_0^2\right). \tag{4}$$

The result of equation (4) is also as follows:

$$\frac{r_1^2 - r_0^2}{r_2^2 - r_0^2} = \frac{2\pi}{\alpha}. \tag{5}$$

From equation (5), the surrounding rock deformation caused by excavation unloading in the actual engineering is much more severe than in the experiment.

Generally speaking, the difference between the excavation unloading and the experiment unloading is similar to that of directional blasting and traditional blasting. Under the premise of given energy, the former one often leads to more obvious deformation in the coal, featured with more damage and a violent process. Therefore, a great deal of attention should be paid to the stress and energy adjustment process of surrounding rock disturbed by excavation in engineering practice for the purpose of minimizing and even avoiding the large deformation or rockburst accident of roadway excavation.

3. Conclusions

Combined with the stress distribution and variation characteristics of surrounding rock before and after roadway excavation, an experiment of unloading confining pressure and loading axial pressure of coal is designed. Based on the experiment, the coal body's failure mechanics and energy characteristics are identified and analyzed. Based on the experiment and data collected, the following conclusions are obtained:

(1) Increasing the axial loading rate can shorten the accumulation time of microcracks and damage and produces a strengthening effect on the coal body. When the axial loading rate ranges within 0~0.2 MPa/s, the axial loading rate tends to have greater influence on the coal body's strength, while the unloading rate provides conditions for lateral

deformation and dilatancy failure (intensifying coal body degradation). The influence of axial loading is prominent when within the range of 0~0.1 MPa/s

(2) Increasing the axial loading rate improves the energy storage capacity of coal, and each energy increases logarithmically while the unloading rate is opposite. When the coal body failed, the transformation rate of deformation energy and dissipated energy is obviously affected by the loading and unloading rate. With the increase in the axial loading rate, the transformation rate of deformation energy approaches 50%. As the unloading rate increases, the transformation rate of deformation energy decreases, resulting in high susceptibility of the coal body to damage

(3) Under the given energy conditions, compared with the experiment unloading, the coal deformation caused by excavation unloading is more obvious, featured with severer damage and a more violent process. According to the experiment and analysis, the stress and energy adjustment process of the surrounding rock disturbed by excavation should be valued by scholars in terms of improving the safety of roadway excavation

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that no conflict regarding the publication of this paper has been identified.

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