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Unloading impact failure mechanisms and kinetic energy analysis of coal-rock composites in deep roadways

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Abstract

Dynamic hazards induced by stress unloading during deep roadway excavation in coal-rock composite strata threaten the stability of underground engineering. To clarify the unloading impact failure mechanisms of coal-rock composites and quantify the failure intensity, loading and unloading experiments were conducted on specimens with five different coal-rock ratios (1:0, 2:1, 1:1, 1:2, 0:1) using a true-triaxial experimental system. The peak failure stress (σ_p) acoustic emission (AE) characteristics, failure patterns and kinetic energy were analyzed. The results show that the σ_p increased with increasing rock content. Composite specimens generally exhibited lower cumulative AE counts than single lithology specimens and exhibited progressive failure behaviour, including precursory small-scale grains ejection and multiple impacts. Since the total kinetic energy of ejected fragments may overestimate unloading impact failure intensity, a new parameter, the unit volume kinetic energy E_u, was proposed to address this limitation. The E_u values of composite specimens were higher than those of coal and sandstone specimens. These findings clarify the failure mechanisms and provide a crucial practical metric for assessing dynamic failure intensity in deep roadways.

Keywords

Coal-rock composite, Unloading impact failure, Failure pattern, Kinetic energy, Rockburst.

1 Introduction

With the rapid development of the economy, underground engineering projects continue to reach greater depths (Kang et al., 2023). Excavation of deep roadways in underground mines is prone to initiating dynamic hazards such as rockburst and coal-gas outburst (Du et al., 2024,). These hazards pose serious threats to worker safety and can cause significant property damage. Therefore, it is essential to focus on the unloading process associated with deep roadway excavation.

The coal-rock composites exhibit mechanical properties and failure characteristics distinct from those of single-lithology rock. Coal-rock composite strata have received increasing attention in research on the mechanisms of roadway dynamic disasters, particularly rockburst and coal-gas outburst (Bai et al., 2023). Zhang et al. (2025) studied the energy evolution characteristics of compound dynamic disasters based on triaxial experiments. However, the ejection of fragments during the unloading impact failure of coal-rock composites has not been thoroughly investigated.

The violent energy release during the instability of roadway surrounding rock can trigger high-velocity fragments ejection, contributing to dynamic hazards during roadway excavation (Gu and Ozbay 2015). The kinetic energy of fragments reflects the intensity of coal-rock composite unloading impact failure (Li et al., 2025). In previous unloading experiments, the total kinetic energy of fragments was often used as a key parameter to assess the kinetic energy of unloading impact failure (Hu et al., 2018). However, coal tends to be destroyed into fine fragments, leading to situations where the total kinetic energy of ejected fragments is high, but the failure intensity is low. Therefore, this paper proposes the unit volume kinetic energy (E_u). This parameter can more accurately characterize the unloading impact failure kinetic energy of coal-rock composites.

In this study, experiments were conducted on specimens with five different coal-rock ratios (1:0, 2:1, 1:1, 1:2, 0:1) using the true-triaxial system. The mechanical responses, failure patterns of specimens were analysed, with particular focus on calculating the E_u of unloading impact failure in coal-rock composites. The objective of this research is to investigate the unloading impact failure mechanisms and assess the failure intensity using $E_u$under triaxial stress conditions.

2 Experimental methods

2.1 Experimental specimen

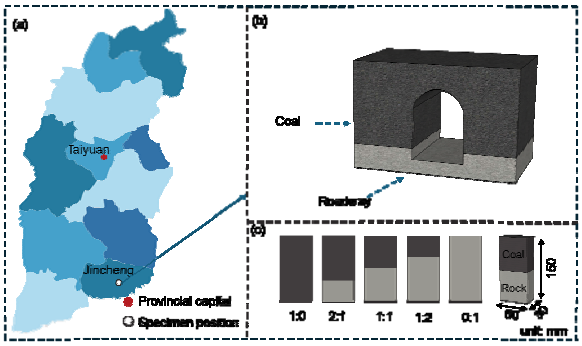


Fig.1 Coal-rock composite specimens: (a) Specimen position. (b) Diagram of roadway layout. (c) Diagram of specimen with five coal-rock ratios.

The interface between coal and sandstone was bonded using epoxy resin (Zhao et al., 2025). Coal and sandstone were obtained from the Jincheng, Shanxi Province, China. According to the recommended method of the ISRM (Ulusay et al., 2014), coal and sandstone were made into 50 × 100 mm cylindrical specimens and conducted uniaxial compression experiments to determine the uniaxial compressive strength (σ_c) and the elastic modulus (E). From these materials, specimens with dimensions of 150 mm × 60 mm × 30 mm were prepared. The five coal-rock ratios (1:0, 2:1, 1:1, 1:2, and 0:1) were selected to represent typical stratigraphic positions of deep roadways. For the convenience of subsequent description, specimens with coal-rock ratios of 2:1, 1:1, and 1:2 are referred to as "composite specimens". Fig.1 shows the prepared specimens.

2.2 Experimental equipment

The triaxial loading and unloading experiments were conducted by the true-triaxial experimental system (Fig. 2). The experimental system includes a true-triaxial experimental machine, a force acquisition instrument, an AE acquisition instrument and a four-camera high-speed photography system. It can perform sudden unloading in one direction, causing the force bar and loading indenter to drop rapidly to simulate the rapid unloading process caused by excavation in deep conditions.

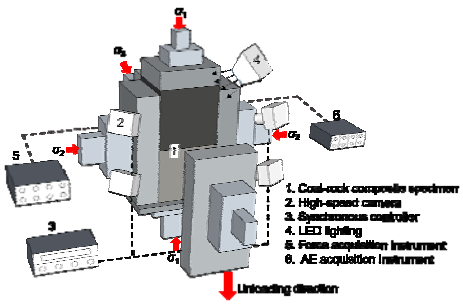


Fig. 2 True-triaxial experimental system.

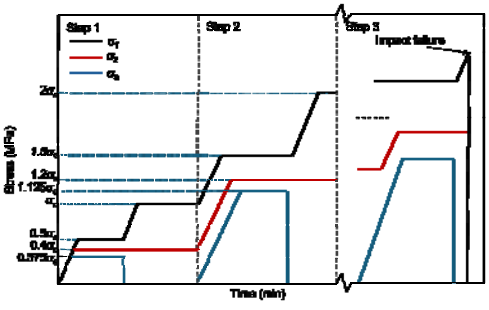


Fig. 3 Stress loading and unloading method.

2.3 Stress loading and unloading method

As shown Fig. 3, the specific steps of the experiment were as follows. (1) The triaxial stress σ_1, σ_2 and σ_3 were loaded to $0.5\sigma_c$, $0.4\sigma_c$ and $0.375\sigma_c$, respectively, at the loading rate of 0.1MPa/s. This state was maintained for 10 min. Then, the σ_3 was unloaded to 0 MPa at the unloading rate of 20 MPa/s, exposing the free face. The specimen was subsequently reloaded σ_1 at the loading rate of 0.1 MPa/s and increased by 0.5 σ_c. This state was maintained for 10min. (2) The triaxial stress was further loaded at the rate of 0.1MPa/s, with σ_1, σ_2 and σ_3 were increased by $0.5\sigma_c$, $0.4\sigma_c$ and $0.375\sigma_c$, respectively. After reaching these levels, the state was maintained for 10 min. The σ_3 was unloaded to 0 MPa at the unloading rate of 20 MPa/s, exposing the free face again. The σ_1 was once more loaded atthe loading rate of 0.1 MPa/s and increased by $0.5\sigma_c$. This state was maintained for 10 min while the free face was observed. (3) Step 2 was repeated until the specimen failed. The experiment stopped after the failure occurs.

3 Experimental Results

3.1 Mechanical response

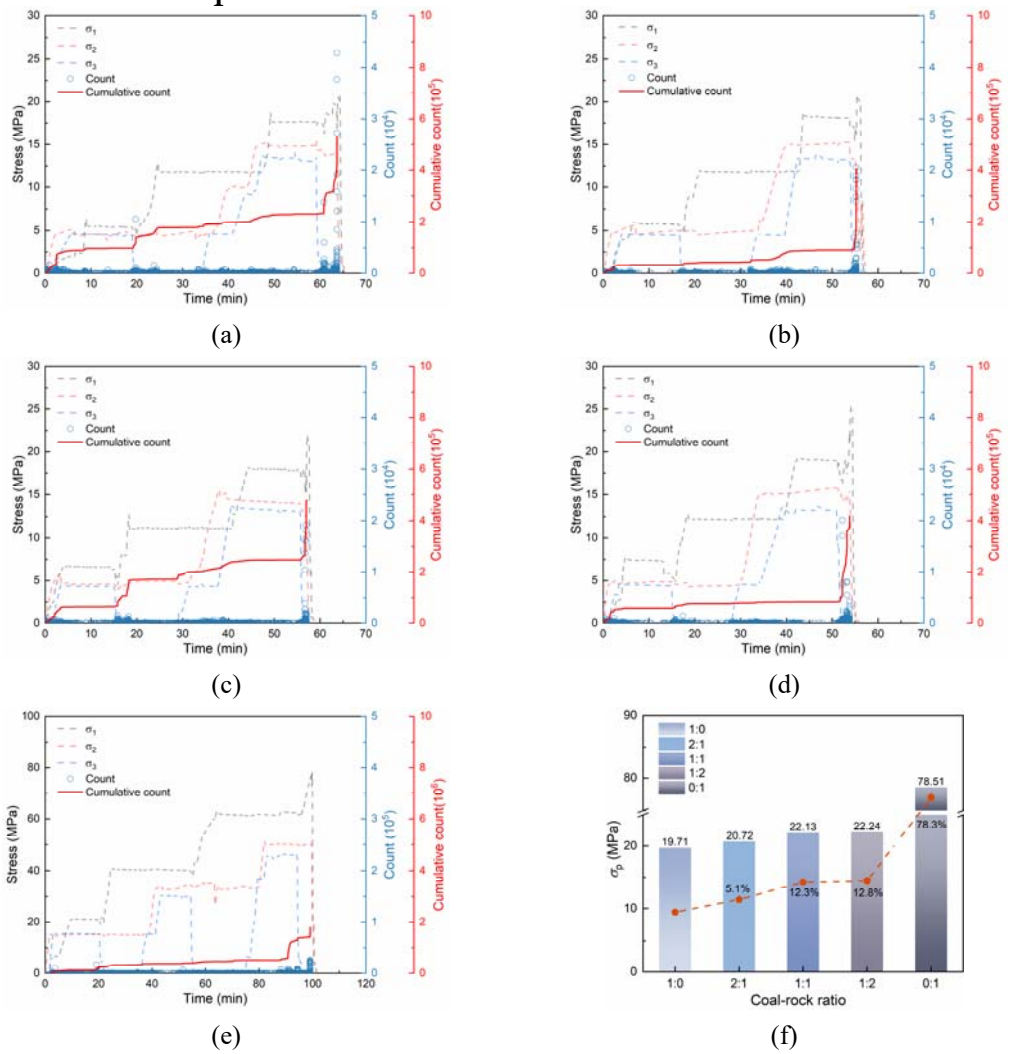


Fig. 4 Stress characteristics of specimens with different coal-rock ratios: (a)1:0. (b)2:1.(c)1:1.(d)1:2. (e) 0:1. (f) σ_p.

The stress-time curves, AE count and cumulative AE counts for specimens are shown in Fig. 4. A large increase in AE count occurs when the specimen's stress state is altered (such as during unloading or before failure), while at other times the AE count remains low. The cumulative AE counts reach the maximum value at the moment of unloading impact failure.

For specimens with coal-rock ratios of 1:0, 2:1, 1:1, 1:2 and 0:1, the σ_p were 19.71 MPa, 20.72MPa, 22.13 MPa, 22.24MPa and 78.51MPa, respectively. As coal-rock ratio changes from 1:0 to 0:1, the σ_p shows an overall increasing trend. When the ratio changed from 1:2 to 0:1, the σ_p increased abruptly from 22.13MPa to 78.51MPa. The results show that coal governs the peak stress in the unloading

impact failure of composite specimens. The cumulative AE counts values were: 5.28 $\times 10^5$, 4.03$\times 10^5$, 4.75$\times 10^5$, 4.24$\times 10^5$ and 1.79 $\times 10^6$, respectively. For cumulative AE counts, sandstone specimen had the highest value. The cumulative AE counts of the coal specimen were also higher than those of any composite specimen. These results show that AE activity during failure was more intense in single lithology specimens than in composite specimens.

3.2 Unloading impact failure pattern

3.2.1 Unloading impact failure process

Figs. 5 and 6 show the unloading impact failure processes captured by the four-camera high-speed photography system, with the moment when the loading indenter detachment (when σ_3 dropped to 0 MPa) defined as t=0 s. As shown in Fig. 5, the failure process of sandstone specimen can be divided into three stages in sequence: plate bending, plate splitting and fragments ejection. As shown in Fig. 6, the failure process of coal and composite specimens resembled that of sandstone specimen, involving the same stages of plate bending, plate splitting, and fragments ejection. However, small-scale grains ejection phenomenon was observed in the coal and composite specimens prior to significant plate bending or splitting. These results indicate that coal and composite specimens have a significant precursor phenomenon before unloading impact failure, in contrast to the sandstone specimen.

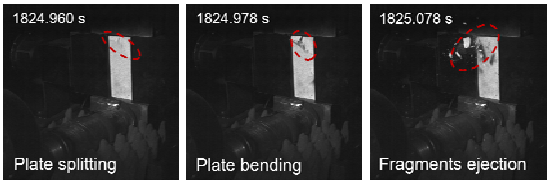


Fig. 5 Unloading impact failure process of sandstone specimen.

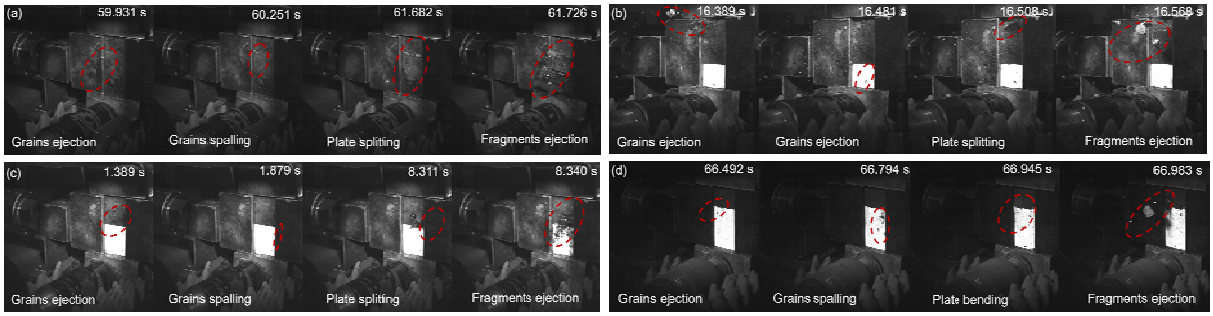


Fig. 6 Unloading impact failure process of specimens with different coal-rock ratios: (a) 1:0. (b) 2:1. (c) 1:1. (d) 1:2.

3.2.2 Multiple impact failure phenomenon of coal-rock composite

Typically, a single lithology specimen loses stability and collapses under unloading, and only one violent fragments ejection occurs during the failure process (Liu et al., 2025). In contrast, the composite specimens in our experiments exhibited multiple impact events during their progressive failure processes. Taking the specimen with coal-rock ratio of 2:1 as an example, multiple violent fragment ejections occurred during unloading. As shown in Fig. 7, the specimen experienced its first impact at 16.568 s, followed by a secondary impact 0.459 s later.

The results indicate that although the failure process of the composite is similar to that of coal specimen, the composite failure is gradual and staged due to the constraints of the embedded rocks in the composite. The unloading impact failure pattern of the composite specimens is influenced by both the material properties and their structural interaction. In essence, the failure mechanism of coal-rock composite under unloading impact is fundamentally different from that of a single lithologic specimen.

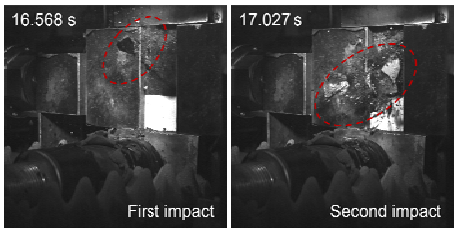


Fig. 7 Multiple impact phenomena of composite specimens.

3.3 Analysis of unloading impact failure kinetic energy

Previous researchers have used the total kinetic energyof ejected fragmentsas a metric to evaluate the unloading impact failure kinetic energy (Li et al., 2025). The total kinetic energy of unloading impact failure can be calculated by Eq.(1).

$$E_k = \sum_{i=1}^{n} \frac{1}{2} m_i v_i \tag{1}$$

WhereE_k is the total kinetic energy of theejected fragments, $m_i$is the mass of the fragment, v_i is the velocity of the fragment, i is the number of ejected fragments.

While this approach is applicable to single lithology specimens, it has limitations: the total kinetic energy is strongly influenced by the number of ejected fragments. The ejected fragments of composite specimens are mainly coal. Consequently, a higher E_k value can simply result from a larger quantity of low-energy coal fragments rather than a more violent failure event. This makes E_k a less reliable metric for comparing the unloading impact failure kinetic energy across coal-rock composites with different coal contents. To address this limitation, we propose a new parameter unit volume kinetic E_u. The E_u is given by Eq. (2)

$$E_u = \frac{E_k}{V} \tag{2}$$

Where V is the volume of coal in the specimen with coal-rock ratios of 1:0, 2:1, 1:1 and 1:2 or the volume of sandstone in the specimen with a coal-rock ratio of 0:1.

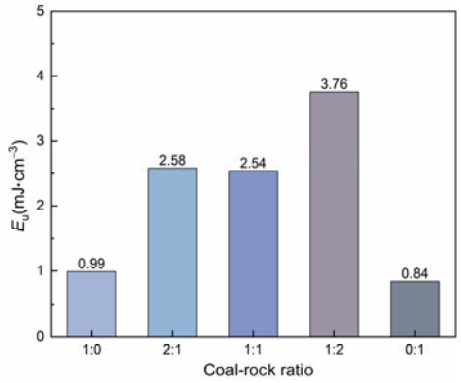


Fig. 8 Comparison of E_k and E_u for specimens with different coal-rock ratios.

From Eq. (2), the calculated E_u values were 0.99 mJ/cm³ (1:0), 2.58 mJ/cm³ (2:1), 2.54mJ/cm³ (1:1), 3.76 mJ/cm³ (1:2), and 0.84 mJ/cm³ (0:1). Fig. 8 shows the $E_u$values of specimens with different coal-rock ratios. Notably, the coal–rock combined specimens exhibited higher $E_u$values than the single-lithology specimens. This suggests that, during impact failure, part of the elastic strain energy stored in the sandstone component may be transferred to the coal component. The coal component, which has lower strength and stronger deformability, can then release this transferred energy more rapidly during failure. As a result, the kinetic energy of the composite specimen can exceed that of the sandstone and coal specimen, leading to a higher dynamic failure intensity.

4 Conclusion

This study investigated the unloading impact failure mechanisms and energy characteristics of coal-rock composite under triaxial loading and unloading conditions. The main findings are as follows:

(1) The failure patterns of coal-rock composites differed from that of single lithology specimens. In coal and composite specimens, precursor activity (in the form of small-scale grain ejections) was observed prior to the failure. The composites exhibited a progressive failure process with multiple impact events. The impact failure behaviour of composite specimens is influenced by both the material properties of the constituents and their composite structure.

(2)The σ_p increased with higher rock content. The increase in rock content enhances the composite's resistance to failure. The cumulative AE counts of composite specimens were generally lower than those for single lithology specimens.

(3) E_u provides a reliable basis for unloading impact failure assessment. Coal-rock ratio exhibited a nonlinear relationship with E_u: 0.99 mJ/cm³ (1:0), 2.58 mJ/cm³ (2:1), 2.54mJ/cm³ (1:1), 3.76 mJ/cm³ (1:2) and 0.84 J/cm³ (0:1). The higher E_u values of the composite specimens suggest that energy transfer from sandstone to coal may enhance the kinetic energy release during impact failure.

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