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Dynamic Response and Energy Absorption Characteristics of Coal-Rock Material Systems under True Triaxial Impact Loading

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Abstract:

Deep coal mining exposes coal-rock systems to combined in-situ stress and dynamic disturbance, yet the role of material contrast and interfaces in impact failure remains unclear. True triaxial split Hopkinson pressure bar (TTSHPB) tests were conducted on coal, rock, and coal-rock composite specimens under identical multiaxial prestress conditions and impact velocities of 2.5m/s-8m/s. The stress-strain response, strain-rate behavior, failure characteristics, and energy evolution were compared. All specimens showed clear rate-dependent strengthening, with peak stress and energy absorption increasing with impact velocity. Rock exhibited the highest dynamic bearing capacity, followed by the coal-rock composite and coal, while coal exhibited the highest average strain rate. The composite showed a distinct post-peak response. At 6 m/s, its stress decreased from about 144 MPa to a residual-bearing level of 85-90 MPa before final instability. The composite also had the highest reflected-energy fraction (66%-67%) and the lowest transmitted-energy fraction (3%-4%), indicating strong stress-wave redistribution at the coal-rock interface. The results suggest that the composite evolves from pre-peak cooperative bearing to post-peak load redistribution, deformation incompatibility, and secondary instability. The coal-rock interface therefore plays a key role in stress-wave propagation, energy redistribution, and progressive failure under impact loading.

Keywords: Coal-rock composite; True triaxial impact; Dynamic response; Energy redistribution; Interface effect; Dynamic instability

1. Introduction

As shallow coal resources are gradually depleted, coal mining in China is continuously extending to greater depths. Deep coal and rock masses are generally subjected to the coupling of a “three-high and one-disturbance” environment, namely high in-situ stress, high geothermal temperature, high pore pressure, and strong mining-induced disturbance, under which their mechanical behavior and instability failure exhibit pronounced complexity, abruptness, and dynamic characteristics [1–3]. In this context, dynamic disasters such as rockburst, coal and gas outburst, and dynamic instability of roadway surrounding rock occur frequently and have become critical scientific and engineering issues restricting the safe and efficient exploitation of deep coal resources [4–6]. Extensive engineering practice has demonstrated that the occurrence of deep dynamic disasters is closely related not only to the physical and mechanical properties of coal and rock masses themselves, but also to multiple factors such as the in-situ stress state, structural combination form, and external disturbance intensity [7–8]. Therefore, a systematic investigation of the impact dynamic behavior of coal, rock, and their composite bodies under true triaxial conditions is of great significance for revealing the initiation and evolution mechanisms of deep coal-rock dynamic disasters.

Extensive studies have been conducted worldwide on the mechanical properties of coal and rock materials. Under static loading, previous research has mainly focused on the strength characteristics, deformation behavior, crack propagation, and failure modes of coal and rock masses under uniaxial and conventional triaxial conditions. Existing studies have shown that confining pressure can significantly enhance the peak strength and residual bearing capacity of

rocks, suppress tensile crack propagation, and promote the transition of failure mode from splitting failure to shear failure ^[9–11]. For coal, due to its well-developed pores and fissures, strong heterogeneity, and pronounced viscoelastic-plastic characteristics, the loading process usually exhibits a more complex evolution from compaction to elasticity, yielding, and instability, while its strength and deformation parameters are more sensitive to confining pressure and loading path ^[12–14]. In addition, some researchers have analyzed the progressive damage evolution and mesoscopic fracture mechanisms of coal and rock by means of acoustic emission, CT scanning, and digital image correlation, further revealing the multiscale nature of coal-rock instability ^[15–17].

In terms of dynamic behavior, scholars have systematically investigated the dynamic strength characteristics, strain-rate effect, energy dissipation law, and dynamic failure modes of coal and rock materials using test methods such as the split Hopkinson pressure bar (SHPB), drop hammer impact, and combined static-dynamic loading ^[18–20]. These studies indicate that coal and rock materials generally exhibit obvious strain-rate dependence, and their dynamic strength, peak stress, and fragmentation degree change significantly with increasing loading rate ^[21–22]. At the same time, the initial static stress has an important regulatory effect on the dynamic response of coal and rock masses. Appropriate prestress may enhance their dynamic bearing capacity, whereas excessively high static stress may induce cumulative damage and impact instability ^[23–25]. In terms of energy evolution, many studies have analyzed the energy conversion mechanism of coal-rock impact failure from the perspectives of incident energy, reflected energy, transmitted energy, and dissipated energy, and concluded that dynamic

instability is essentially the result of the combined action of energy accumulation, transmission, and transient release ^[26–28]. However, most existing dynamic studies have been carried out under uniaxial or conventional triaxial conditions, and relatively little attention has been paid to the true triaxial dynamic response, which is closer to the actual stress environment in deep underground engineering.

It is worth noting that the load-bearing medium in underground coal engineering is often not a single coal body or single rock body, but rather a heterogeneous system in the form of coal-rock composites, layered composite bodies, or media containing interfacial structures ^[29–30]. Owing to the significant differences between coal and roof-floor rocks in strength, stiffness, deformation modulus, wave impedance, and energy storage-release capacity, coal-rock composites often exhibit mechanical responses that differ from those of a single material under loading ^[31–32]. Existing studies have shown that the overall strength of a composite is usually controlled by its weakest part, and that the failure location, crack propagation path, and instability mode are closely related to the coal-rock arrangement, interface bonding properties, and loading direction ^[33–35]. Under static loading, coal-rock composites generally show obvious incompatible deformation and interfacial stress concentration, and local failure often initiates first in the coal or along the weak interface zone ^[36–37]. Under dynamic disturbance, due to wave reflection, transmission, and scattering at the interface, the propagation of stress waves, energy distribution, and crack evolution inside the composite are more complex than those in a single medium ^[38–39]. Although studies on coal-rock composites have increased in recent years, the research content is still mainly concentrated on uniaxial compression, conventional triaxial

compression, and simple impact conditions, and investigations into the impact dynamic behavior of composites under true triaxial stress environments remain insufficient ^[40–41]. Under a true triaxial stress state, the three principal stresses are generally unequal, and the intermediate principal stress effect as well as the principal stress difference have a non-negligible influence on the failure mechanism of coal and rock ^[42–43]. Compared with conventional triaxial tests, true triaxial tests can more realistically reflect the in-situ stress environment of coal and rock masses in deep underground engineering and reveal the regulatory role of the intermediate principal stress in strength enhancement, crack propagation direction, and failure mode transformation ^[44–46]. Existing studies have pointed out that under true triaxial conditions, rock fracture surfaces are more complex, crack propagation exhibits stronger directionality and spatial asymmetry, and the intermediate principal stress has a significant effect on volumetric deformation, local stress concentration, and brittle-ductile transition ^[47–48]. However, research on the impact dynamic characteristics of coal and coal-rock composites under true triaxial conditions is still at an early stage. Most related studies have focused on static strength and deformation analysis, and there is still a lack of systematic understanding of the dynamic response characteristics, failure mechanisms, and energy evolution laws of coal and coal-rock composites under impact loading within a true triaxial initial stress field. A review of the existing literature indicates that, on the one hand, considerable progress has been made in the study of coal-rock impact dynamics, but most work has focused on single materials and lacks in-depth discussion of the structural effects of coal-rock composites. On the other hand, although studies on the mechanical properties of

composites have gradually increased, they have mainly emphasized strength and failure analysis under static loading, with insufficient attention paid to interfacial transmission, synergistic instability, and energy dissipation mechanisms under impact disturbance. In addition, most existing studies adopt uniaxial or conventional triaxial stress paths, which cannot accurately reflect the actual stress state of deep coal and rock masses under complex true triaxial conditions. Therefore, it is imperative to investigate, from the perspective of a true triaxial stress environment combined with impact disturbance, the dynamic response law, damage evolution mechanism, and instability criterion of coal, rock, and their composite bodies under the coupling of multiple principal stresses.

Based on the above considerations, this study takes coal, rock, and their composite bodies as the research objects and investigates their dynamic behavior under coupled true triaxial static loading and impact disturbance. By analyzing the dynamic mechanical response, strength evolution, failure mode, and energy dissipation characteristics of specimens with different stress conditions and different composite forms, this study focuses on the controlling mechanism of true triaxial stress state on the impact instability behavior of coal, rock, and their composite bodies, and reveals the synergistic interaction among coal, rock, and the interface during dynamic failure. The results are expected to provide theoretical support for the mechanism analysis, risk identification, and prevention and control design of dynamic disasters such as rockburst in deep coal mines.

2. Experimental procedure

2.1 Specimen preparation

In this study, the coal-rock composite specimens were prepared by bonding bituminous coal and sandstone samples. The selected bituminous coal was collected from the Sijiazhuang mining area in Shanxi Province, China, whereas the sandstone was relatively homogeneous, with only a few minor fissures distributed along the bedding direction. The physical and mechanical properties of the coal, sandstone, and their composite specimens are listed in Table 1. Coal-rock composite specimens were prepared with a coal-to-rock height ratio of 1:1 by spot bonding with epoxy resin ^[49], resulting in cubic samples with dimensions of 50 mm*50 mm * 50 mm, as shown in Fig. 1. According to the methods recommended by the International Society for Rock Mechanics and Rock Engineering (ISRM) ^[50], the end-face non-parallelism of each specimen was controlled within 0.02 mm, and the maximum angular deviation between the two end faces did not exceed 0.25°. In addition, key factors such as joint characteristics, density, and wave velocity were fully considered during specimen selection in order to minimize the influence of specimen discreteness on the experimental results. The physical parameters of the specimens, including mass, density, and wave velocity, are summarized in Table 1. As can be seen from the table, the coal specimens used in the experiments exhibited relatively consistent values of mass, density, and wave velocity, which reduced experimental error and ensured the reliability and validity of the test results.



Fig. 1 The tested rock specimens with different lithologies

Table 1 Basic mechanical parameters of specimens of different lithologies

Specimen	Coal	Rock
Density ($\text{kg}\cdot\text{m}^{-3}$)	1129.80	2417.40
Uniaxial Compressive Strength (MPa)	11.75	67.30
Elastic Modulus (GPa)	0.74	15.31
Poisson's Ratio	0.24	0.11
Cohesion (MPa)	22.82	76.14
Internal Friction Angle ($^{\circ}$)	5.92	27.22

2.2 Experimental system

The impact dynamics tests were conducted using a true triaxial split Hopkinson pressure bar (TTSHPB) system. The experimental system mainly consisted of the following components: (1) an impact bar system, which was used to apply impact loading to the specimen and generate and transmit stress waves, thereby simulating the dynamic response and failure behavior of coal and rock under complex stress conditions; (2) a static preloading system, which was employed to apply multiaxial static prestress to the specimen; (3) a data acquisition system, which was used to monitor and record, in real time, key parameters during the test, including stress waves, stress, and deformation of the specimen; and (4) a velocity measurement system, which was used to accurately determine the impact velocity acting on the specimen during the loading process. A schematic diagram of the experimental system is shown in Fig. 2.

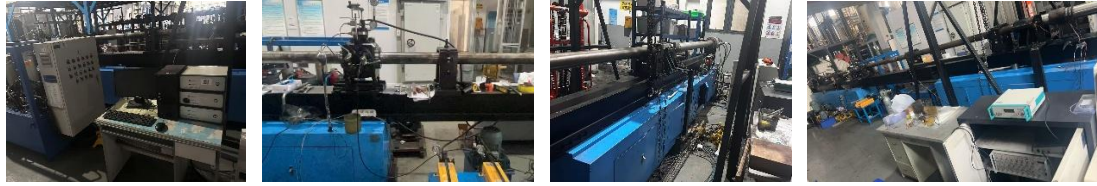
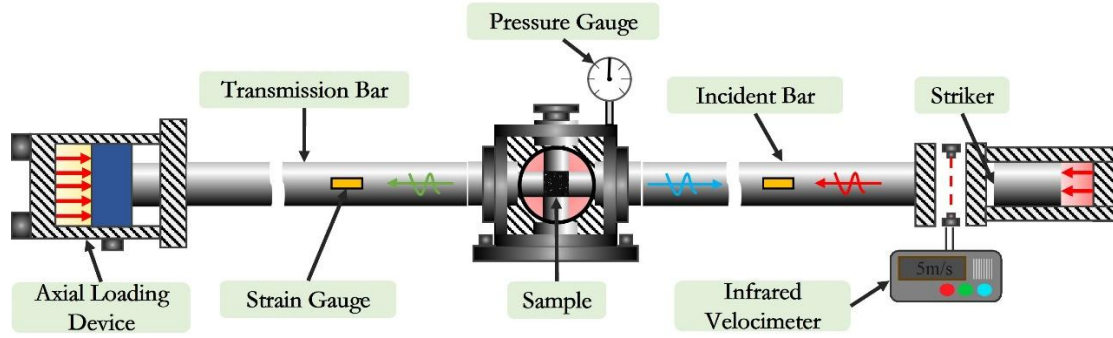


Fig. 2 Schematic diagram and photos of the system

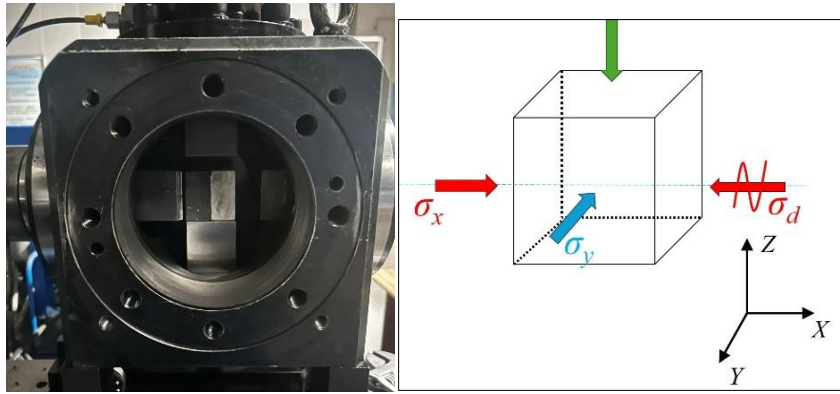


Fig. 3 Installation method of the coal-rock combination sample.

The data acquisition method of the SHPB system is based on the experimental principle of the Wheatstone bridge. The stress-wave signals generated during the impact test are amplified by an amplifier and then displayed on an oscilloscope. Based on the assumptions of uniform deformation and one-dimensional stress-wave propagation, the strain of the specimen can be calculated using Eq. (1).

$$\varepsilon_s = \frac{C_0}{l_s} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) d\tau \quad (1)$$

Where ε_s is the strain of the specimen; c_0 is the wave velocity in the bar, $\text{m}\cdot\text{s}^{-1}$; ε_i is the incident-wave strain signal; ε_r is the reflected-wave strain signal; ε_t is the transmitted-wave strain signal; and τ is the time interval for signal acquisition, in s .

According to the linear superposition principle of stress waves, the average strain rate of the specimen can be calculated using Eq. (2).

$$\dot{\varepsilon} = \left(\frac{c_0}{l_s} \varepsilon_i - \varepsilon_r - \varepsilon_t \right) \quad (2)$$

where $\dot{\varepsilon}$ is the average strain rate of the specimen, in s^{-1} .

According to Hooke's law, the stress of the specimen can be calculated using Eq. (3).

$$\sigma_s = \frac{AE_0}{2A_0} (\varepsilon_i + \varepsilon_r + \varepsilon_t) \quad (3)$$

where σ_s is the stress of the specimen, in MPa; E_0 is the elastic modulus of the pressure bar, in MPa; A is the cross-sectional area of the specimen, in mm^2 ; and A_0 is the cross-sectional area of the pressure bar, in mm^2 .

2.3 Method of experimentation

First, the coal-rock composite specimen was positioned between the incident bar and the transmitted bar, with the specimen axis carefully aligned with the axes of the pressure bars. As shown in Fig. 3, the rock end of the specimen was placed in contact with the incident bar, whereas the coal end was placed in contact with the transmitted bar, corresponding to the impact structure of the roof-coal seam system in the working face. After the static pre-stress was stabilized, the air compressor was activated to provide pneumatic power for the projectile. The infrared velocimeter and strain measurement system were then configured according to the experimental requirements. Subsequently, the projectile was launched to impact the incident bar at different velocities, generating stress waves that acted on the specimen. The detailed

experimental plan is shown in Table 2. During the impact procedure, the stress waves generated with each impact were recorded and analyzed. The progression of each stress wave profile was evaluated before initiating the subsequent impact. After the completion of the experiments, the coal samples were removed to examine the modes of failure.

Table 2 Experimental condition statistics

Specimen	Specimen ID	σ_x (MPa)	σ_y (MPa)	σ_z (MPa)	Launch Pressure (MPa)	Impact Velocity (m/s)
Coal	C ₁	2	6	6	0.015	2.5m/s
	C ₂				0.03	4m/s
	C ₃				0.034	4.5m/s
	C ₄				0.05	6m/s
	C ₅				0.07	8m/s
Rock	R ₁				0.015	2.5m/s
	R ₂				0.03	4m/s
	R ₃				0.034	4.5m/s
	R ₄				0.05	6m/s
	R ₅				0.07	8m/s
Coal-rock composite	RC ₁				0.015	2.5m/s
	RC ₂				0.03	4m/s
	RC ₃				0.034	4.5m/s
	RC ₄				0.05	6m/s
	RC ₅				0.07	8m/s

3 .Experimental results

3.1 Dynamic Stress-Strain Response Characteristics

3.1.1 Effect of Impact Velocity on the Dynamic Stress-Strain Response

Under the true triaxial initial stress conditions of $\sigma_1=2\text{MPa}$, $\sigma_2=6\text{ MPa}$, and $\sigma_3=6\text{ MPa}$, the dynamic stress-strain curves of coal, rock, and coal-rock composite specimens subjected to low- and high-impact velocities are shown in Fig 4. (a)-(c). Figure 4 presents the dynamic stress–strain curves of coal, rock, and coal-rock composite specimens under impact velocities of 2.5, 4, 4.5, 6, and 8 m/s. In general, all three specimen types exhibit a pronounced impact-velocity

effect. As the impact velocity increases, the curves extend toward higher stress and larger strain, accompanied by a continuous increase in peak stress and an overall extension of the post-peak deformation range.

For the coal specimens, the peak stresses at impact velocities of 2.5, 4, 4.5, 6, and 8 m/s are approximately 50, 64, 71, 91, and 117 MPa, respectively. The corresponding peak stresses of the coal-rock composite specimens are approximately 82, 103, 112, 144, and 171 MPa, while those of the rock specimens are approximately 112, 132, 153, 180, and 205 MPa. For each specimen type, the peak stress increases monotonically with impact velocity, indicating a distinct velocity dependence of the dynamic bearing capacity.

In addition to the increase in peak stress, impact velocity also affects the morphology of the post-peak branch. Under relatively low impact velocities, the specimens enter the instability stage shortly after reaching the peak, and the terminal strain remains limited. With increasing impact velocity, the post-peak branches extend over a broader strain range, indicating that the specimens undergo more extensive deformation before complete instability. At impact velocities of 6 and 8 m/s, the coal and coal-rock composite specimens exhibit prolonged post-peak softening, whereas the rock specimens maintain a substantial stress level during the post-peak stage. These observations demonstrate that increasing impact velocity enhances not only the peak bearing capacity but also the post-peak deformation and residual load-bearing characteristics.

The overall curve morphology also varies among the three lithologies. The coal specimens exhibit a gradual pre-peak ascending branch and reach the peak after a relatively extended

deformation process. The rock specimens show a rapid stress increase during the pre-peak stage, while the coal-rock composite specimens display a distinct transition between the initial loading stage and the post-peak response. These results indicate that, although impact velocity produces a strengthening effect in all three specimen types, their pre-peak stiffness, peak position, and post-peak evolution remain lithology dependent.

3.1.2 Stage-Dependent Response Characteristics of Different Lithologies

The right-hand panels of Fig. 4 further illustrate the representative stress–strain responses and stage divisions of the three specimen types at an impact velocity of 6 m/s. The curves can generally be divided into crack closure, rapid elastic loading, peak transition, post-peak softening, and final instability stages. However, the duration and stress evolution of each stage differ among the specimens.

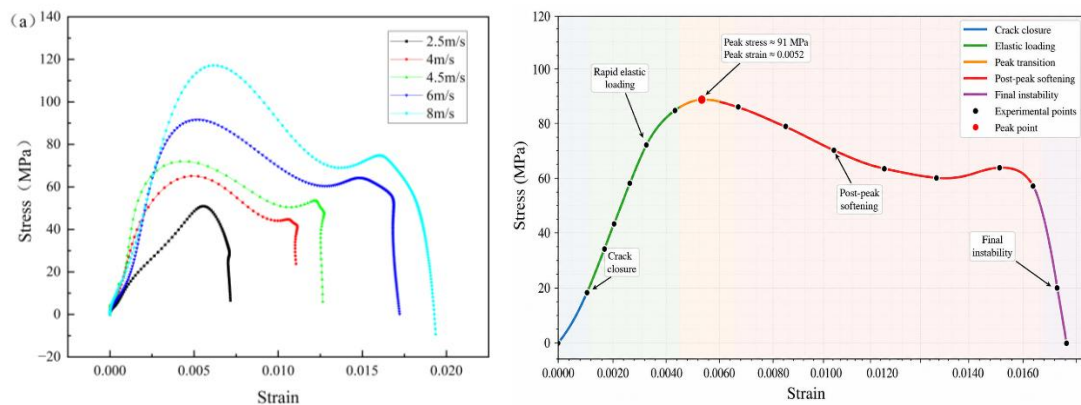
For the coal specimen, the peak stress is approximately 91 MPa, corresponding to a peak strain of about 0.0052. A distinct nonlinear compaction process occurs during the initial loading stage, after which the stress increases rapidly to the peak. Following the peak, the stress gradually decreases to approximately 60 MPa and exhibits a slight recovery near a strain of 0.015. The curve then undergoes an abrupt drop. The post-peak stage of the coal specimen extends over a relatively broad strain interval and is characterized by gradual softening followed by sudden instability.

For the coal-rock composite specimen, the peak stress is approximately 144 MPa, and the corresponding peak strain is about 0.0028. After the peak is reached, the stress decreases rapidly and subsequently forms a relatively stable residual-bearing stage within a stress range of

approximately 85–90 MPa. With further strain accumulation, the stress decreases again and the specimen enters the final instability stage. The curve therefore exhibits a distinct sequence of peak attainment, rapid stress reduction, residual bearing, and final failure.

For the rock specimen, the peak stress is approximately 180 MPa, corresponding to a peak strain of about 0.0028. The crack-closure stage is short, and the stress rises rapidly to the peak. The specimen then enters a continuous post-peak softening stage. Although the stress decreases progressively after the peak, a considerable load-bearing level is maintained over a relatively large strain range before final instability occurs. The response is characterized by rapid pre-peak loading and sustained post-peak stress reduction.

At an impact velocity of 6 m/s, the peak stresses of the coal, coal–rock composite, and rock specimens are approximately 91, 144, and 180 MPa, respectively. The corresponding peak strains are approximately 0.0052 for the coal specimen and 0.0028 for both the coal–rock composite and rock specimens. These results confirm that different lithologies exhibit distinct dynamic-strength characteristics, peak deformation behavior, and post-peak load-bearing responses.



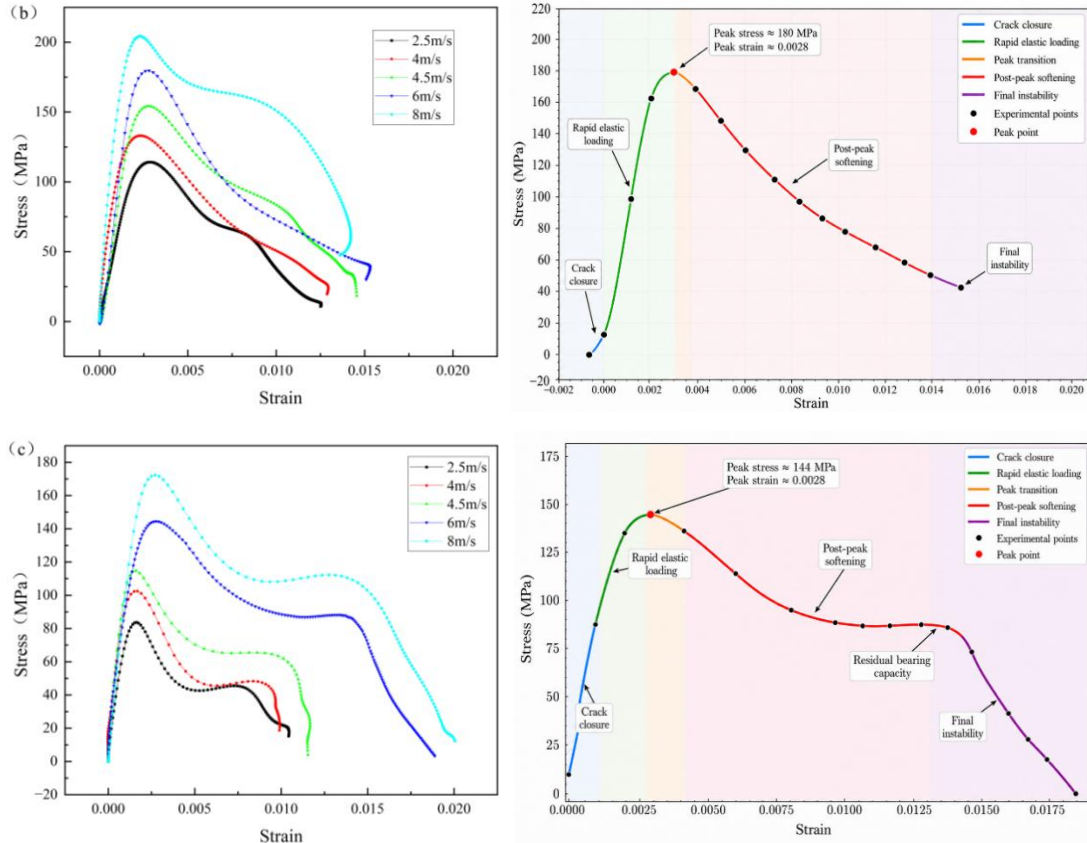
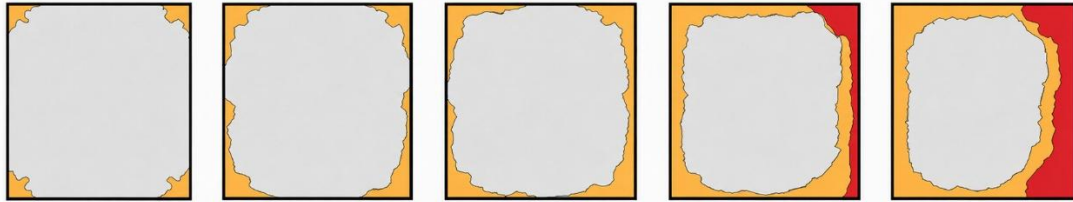
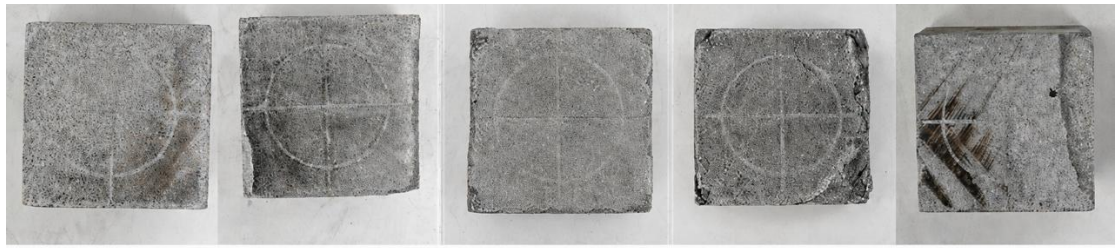


Fig. 4 Stress-strain curves of different lithology samples (a)coal (b)rock (c) Coal-rock composite

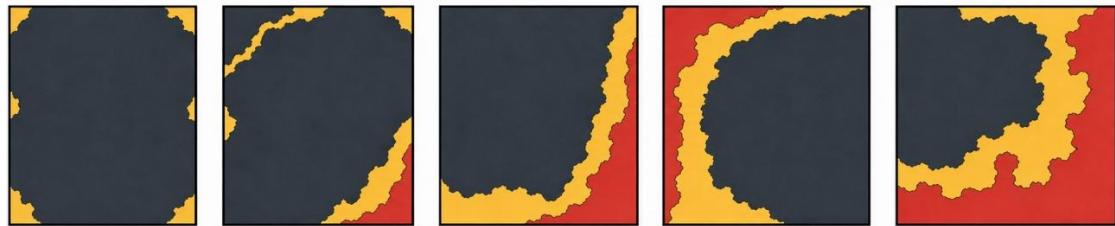
3.1.3 Failure Morphology and Damage Evolution under Different Impact Velocities

Figure 5 presents the post-impact failure morphologies and damage-zone distributions of the coal, rock, and coal-rock composite specimens, where the yellow and red regions denote damaged edge zones and severe spalling zones, respectively. With increasing impact velocity, all three specimen types exhibit a progressive expansion of damaged and spalled areas, indicating a transition from localized edge failure to extensive fragmentation. The rock specimens remain largely intact under low-velocity impact, with only minor corner chipping, whereas higher velocities promote boundary damage, crack propagation, and localized spalling. The coal specimens show a stronger response to increasing impact velocity, as damage rapidly extends from the edges toward the interior, accompanied by pronounced crushing and material detachment. At 8 m/s, severe fragmentation substantially reduces the intact load-bearing region.

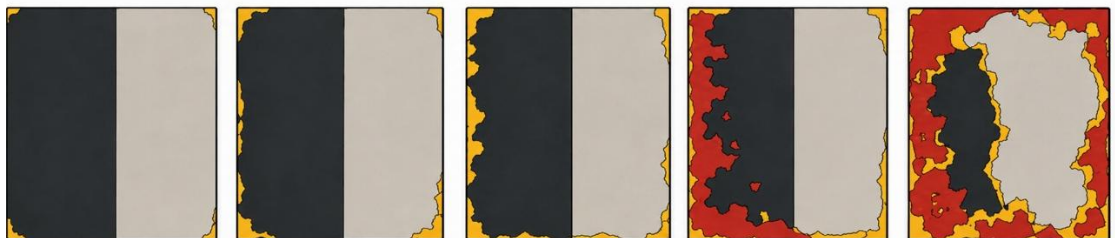
306 The coal-rock composite specimens exhibit distinctly heterogeneous and asymmetric failure.
307 At low impact velocities, damage is mainly confined to the outer boundaries, while increasing
308 impact velocity causes damage to develop preferentially within the coal component and near
309 the coal – rock interface. At 6 and 8 m/s, severe spalling, interface degradation, and large-scale
310 material detachment become increasingly evident. These failure characteristics are consistent
311 with the stress-strain responses shown in Fig. 4: the expansion of damaged and severely spalled
312 regions is accompanied by broader post-peak deformation ranges and larger terminal strains,
313 indicating that the increase in dynamic bearing capacity occurs together with more extensive
314 damage accumulation before final instability.



(a) 2.5 m/s (b) 4 m/s (c) 4.5 m/s (d) 6 m/s (e) 8 m/s



(a) 2.5 m/s (b) 4 m/s (c) 4.5 m/s (d) 6 m/s (e) 8 m/s



(a) 2.5 m/s (b) 4 m/s (c) 4.5 m/s (d) 6 m/s (e) 8 m/s

Fig. 5 Failure and damage evolution of different specimens under impact loading

3.2 Strain-rate dependence of dynamic mechanical parameters

3.2.1 Evolution of average strain rate with impact velocity

As shown in Fig. 6, the average strain rate of coal, rock and coal-rock composite specimens increases approximately linearly with increasing impact velocity. The fitting results indicate that the impact velocity has a significant controlling effect on the strain-rate level during dynamic loading. Under the same impact velocity, the average strain rate of coal is generally higher than that of the coal-rock composite and rock specimens, whereas the rock specimen exhibits the lowest strain-rate response.

This difference is closely related to the deformation capacity and internal structure of the specimens. Coal contains more primary pores and microcracks, and its relatively low stiffness allows greater deformation within a short loading duration, resulting in a higher average strain rate. In contrast, the rock specimen has a denser structure and higher stiffness, which restricts rapid deformation under impact loading. The coal-rock composite shows an intermediate response, indicating that its strain-rate behavior is jointly affected by the weak coal component, the high-stiffness rock component and the coal-rock interface.

Therefore, the increase in impact velocity not only enhances the loading intensity but also raises the strain-rate level of the specimens. This provides the basis for further analyzing the strain-rate dependence of dynamic strength, dynamic increase factor and energy absorption characteristics..

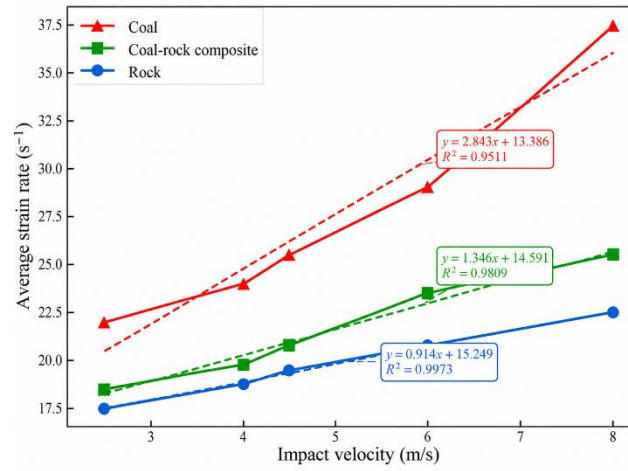


Fig. 6 Evolution of average strain rate with impact velocity for different lithology samples

3.2.2 Strain-rate dependence of dynamic strength and energy absorption

The relationships between average strain rate and dynamic mechanical parameters are shown in Fig. 7(a)–(c). It can be observed that the dynamic increase factor, peak stress and absorbed energy of the three types of specimens all increase with increasing average strain rate, indicating a clear strain-rate strengthening effect under impact loading.

As shown in Fig. 7(a), the DIF of coal, rock and coal-rock composite specimens increases approximately linearly with average strain rate. This suggests that the dynamic strength enhancement of the specimens becomes more pronounced as the loading rate increases. Compared with coal, the rock and coal-rock composite specimens show stronger strain-rate sensitivity in terms of DIF, which may be attributed to the more significant stress wave interaction and constraint effect during rapid loading. For coal, although the DIF also increases with strain rate, its growth is relatively gradual, reflecting the progressive closure and expansion of internal cracks.

Fig. 7(b) further shows that the peak stress increases with average strain rate for all specimens. The rock specimen exhibits the highest peak stress and the most obvious strength

enhancement, indicating its strong dynamic bearing capacity and high stiffness. The coal specimen shows a lower peak stress level because its internal pores and cracks promote damage accumulation during impact loading. The coal-rock composite displays an intermediate strength level, but its response is not a simple superposition of coal and rock. The difference in stiffness and wave impedance between coal and rock may induce stress concentration near the interface, thereby affecting the overall dynamic bearing capacity of the composite specimen.

As shown in Fig. 7(c), the absorbed energy also increases with average strain rate, indicating that specimens can absorb and dissipate more impact energy under higher loading rates. The absorbed energy of rock and coal-rock composite specimens increases more significantly than that of coal, suggesting that high-stiffness materials and composite structures have stronger energy storage and dissipation capacities under dynamic loading. For the coal-rock composite, the absorbed energy is closely associated with coal deformation, interface damage, crack propagation and frictional sliding between fractured blocks.

Overall, the results demonstrate that average strain rate is a key factor controlling the dynamic mechanical response of coal, rock and coal-rock composite specimens. With increasing strain rate, the dynamic strength and energy absorption capacity are enhanced, while the differences among the three types of specimens reflect the combined effects of material stiffness, internal defects and interface structure.

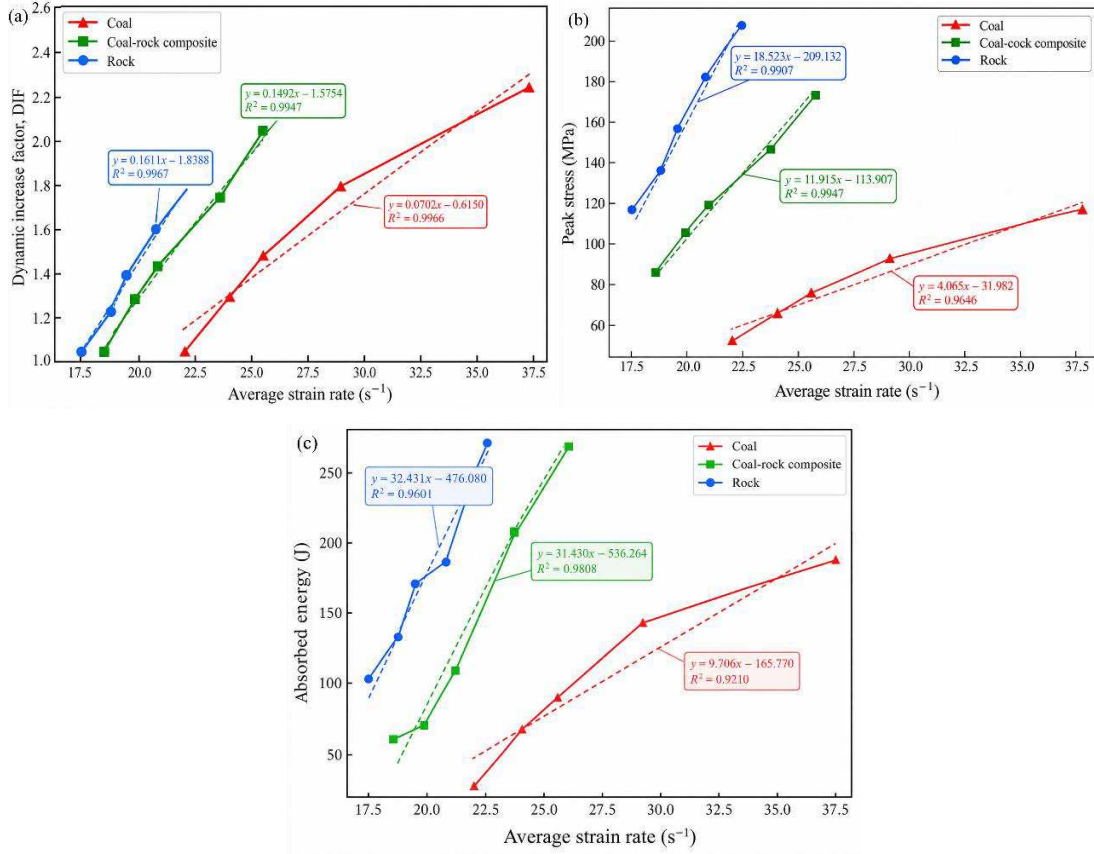


Fig. 7 Strain-rate dependence of dynamic mechanical parameters for different lithology samples
(a) DIF versus average strain rate (b) Peak stress versus average strain rate
(c) Absorbed energy versus average strain rate

3.3 Energy Evolution and Distribution Characteristics

The SHPB technique is based on the one-dimensional elastic stress-wave theory and the assumption of material homogeneity. The energy carried by the stress wave propagating in the pressure bar can be expressed as follows

$$W = \frac{Ac_0}{E_0} \int_0^t \sigma^2(t) dt \quad (4)$$

Where $\sigma(t)$ is the stress signal in the incident bar or transmission bar, in MPa. The stress-wave velocity c_0 can be calculated from the density ρ_0 and elastic modulus E_0 of the pressure bar, as follows:

$$c_0 = \sqrt{E_0/\rho_0} \quad (5)$$

Substituting Eq. (5) into Eq. (4) yields

$$W = \frac{A}{c_0 \rho_0} \int_0^t \sigma^2(t) dt \quad (6)$$

In addition, according to the principle of energy conservation, in the SHPB test, the total energy absorbed by the coal-rock composite specimen can be expressed as the difference among the incident energy, reflected energy, and transmitted energy ^[51], namely:

$$W_s = W_i - W_r - W_t \quad (7)$$

where W_s is the energy absorbed by the coal-rock composite specimen, in J; W_i is the incident energy, in J; W_r is the reflected energy, in J; and W_t is the transmitted energy, in J.

Figures (a)-(c) present the time-dependent evolution of incident, reflected, transmitted, and absorbed energies for the coal, rock, and coal-rock composite specimens under impact loading, while Figs. (a₁)-(c₁) further show the percentage variations of each energy component relative to the incident energy. Overall, the energy evolution processes of the three specimen types exhibit strong consistency, all undergoing an initial slow-growth stage, a rapid accumulation stage, and a final stable plateau stage. At the initial stage of impact, before the incident wave fully acts on the specimen, all energy components remain at relatively low levels. As the stress wave reaches the specimen and interacts with it, the incident energy increases rapidly, accompanied by synchronous growth in reflected, transmitted, and absorbed energies. After the impact process is completed, each energy component gradually approaches a stable value, and the sum of reflected, transmitted, and absorbed energies remains basically consistent with the incident energy, indicating that the experimental data generally satisfy the energy conservation relationship and can adequately reflect the energy partition characteristics during impact.

It should be noted that the absolute values of incident energy differ among the three specimen groups. Therefore, when comparing the impact responses of different specimens,

attention should be paid not only to the absolute energy values but also to the proportion of each energy component, so as to reveal the controlling role of material properties and structural configuration in impact energy distribution.

3.3.1 Energy Evolution under Impact Loading

Figure 8 shows the energy evolution of the coal, rock, and coal-rock composite specimens at an impact velocity of 6 m/s. For all three specimens, the incident, reflected, transmitted, and absorbed energies increase rapidly during the main loading stage and subsequently approach stable values. This indicates that energy input, redistribution, and dissipation occur primarily within a short impact-duration interval.

For the coal specimen, the incident energy stabilizes at approximately 305 J, while the reflected, absorbed, and transmitted energies reach about 180, 102, and 20 J, respectively. The corresponding stable values for the rock specimen are approximately 318, 100, 148, and 68 J. For the coal-rock composite specimen, the incident, reflected, absorbed, and transmitted energies stabilize at about 110, 74, 33, and 4 J, respectively. Although the temporal evolution of the energy components is generally similar, their final magnitudes and relative contributions differ considerably among the three lithologies.

3.3.2 Energy Partitioning Characteristics of Different Lithologies

The stable energy proportions reveal distinct lithology-dependent energy-partitioning patterns. For the coal specimen, reflected, absorbed, and transmitted energies account for approximately 59%-60%, 33%-35%, and 6%-7% of the incident energy, respectively. Thus, energy reflection dominates, whereas only a small fraction is transmitted through the specimen.

432 This distribution is associated with the developed pore-fracture structure and relatively low
433 wave impedance of coal, which enhance stress-wave reflection and attenuate energy
434 transmission.

435 For the rock specimen, the absorbed energy represents the largest proportion,
436 approximately 46%-47%, followed by reflected energy at 31%-32% and transmitted energy at
437 21%-22%. The relatively dense structure and higher wave impedance of rock facilitate stress-
438 wave propagation into and through the specimen, thereby reducing reflection and increasing
439 both transmission and internal energy dissipation. By contrast, the coal-rock composite exhibits
440 the highest reflected-energy proportion, approximately 66%-67%, while the transmitted and
441 absorbed energies account for only 3%-4% and 29%-30%, respectively. The pronounced
442 impedance discontinuity at the coal-rock interface intensifies stress-wave reflection and
443 restricts transmission. Therefore, the energy response of the composite is governed not by a
444 simple superposition of coal and rock behavior, but by heterogeneous structural effects and
445 interface-controlled energy redistribution.

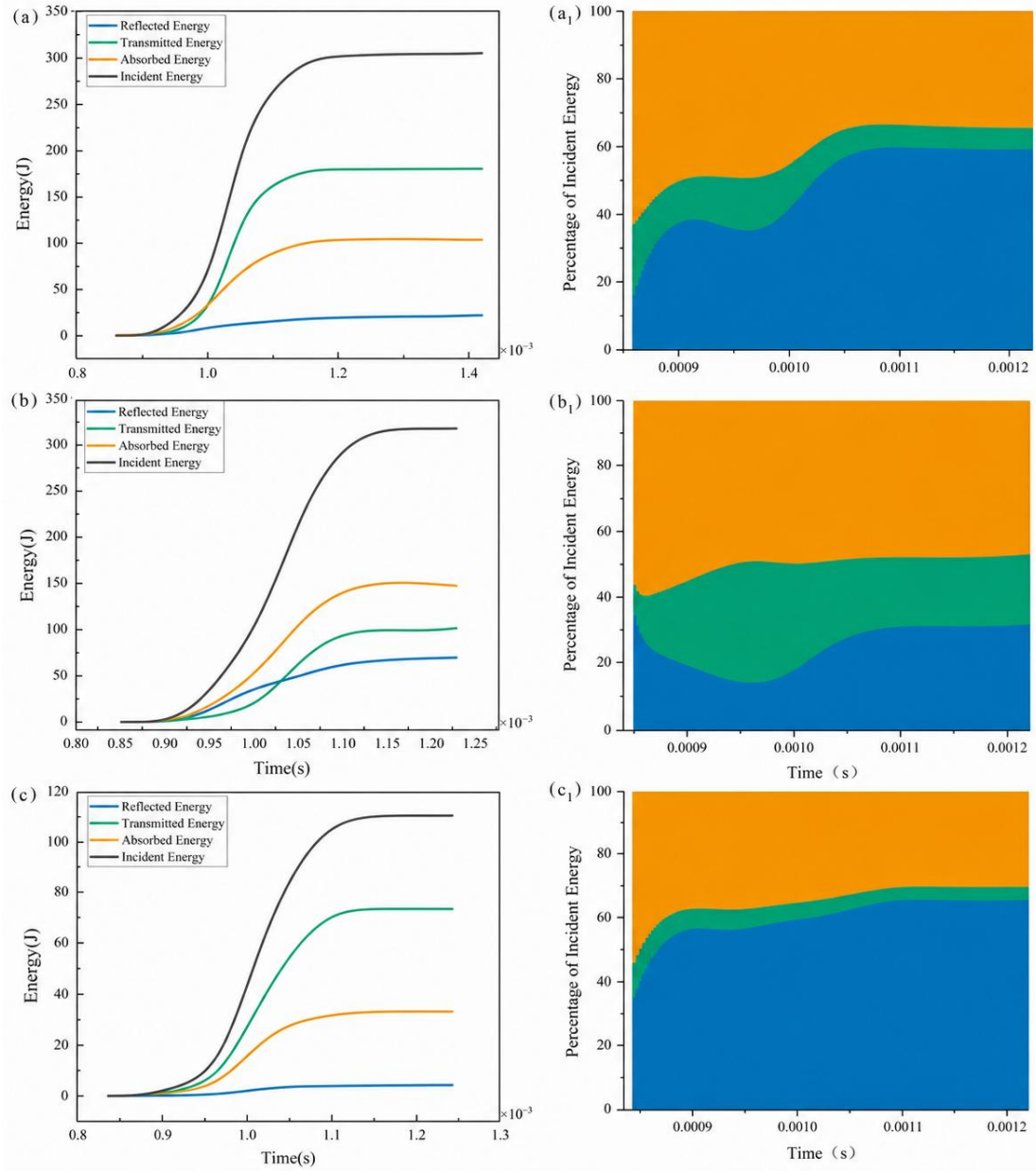


Fig. 8 Energy evolution and distribution characteristics of different lithology samples (a) coal (b) rock (c) Coal-rock combination

3.3.3 Normalized Energy Absorption Rate

To further reveal the temporal evolution characteristics of energy dissipation during impact loading, the normalized energy absorption rate was introduced, which can be expressed as

$$\frac{d(E_a/E_{a,max})}{d(t/t_p)} \quad (8)$$

where E_a is the absorbed energy, $E_{a,max}$ is the maximum absorbed energy, t is the loading time, and t_p is the characteristic impact duration. This parameter reflects the relative rate at which the specimen absorbs impact energy during the loading process. A larger value indicates that energy is absorbed and dissipated more rapidly within a short period, corresponding to a stronger dynamic response and more concentrated damage evolution. As shown in Fig.9, the curves of coal, rock and coal-rock composite specimens all present a typical single-peak pattern. At the initial loading stage, the energy absorption rate remains relatively low, which is mainly associated with the closure of primary pores and microcracks. With the continuous input of impact energy, the internal stress increases rapidly, accompanied by crack initiation and propagation, leading to a sharp rise in the energy absorption rate. After reaching the peak, the curves gradually decrease, indicating that the specimens enter the damage accumulation and instability stage, during which the ability to further absorb energy weakens. For the coal specimen, the peak energy absorption rate increases with increasing impact velocity, and the peak position shifts slightly toward an earlier normalized time. This indicates that higher impact velocity accelerates the energy absorption process and promotes more rapid damage evolution. Compared with high-velocity loading, the curves under lower impact velocities are broader and gentler, suggesting that coal undergoes a relatively gradual energy dissipation and failure process.

For the rock specimen, the normalized energy absorption rate is relatively high, especially under high impact velocity. The peak appears earlier and the curve rises more steeply, reflecting the strong instantaneous energy absorption capacity of rock. This behavior is closely related to

its higher stiffness and brittleness. Under impact loading, rock can rapidly accumulate elastic energy, and once the damage threshold is reached, crack propagation and energy dissipation occur more intensively.

For the coal-rock composite specimen, the curves are relatively gentle and the energy absorption process is more dispersed over time. This is mainly attributed to the mechanical mismatch between coal and rock and the interface effect. During impact loading, part of the incident energy is consumed by deformation coordination, interfacial damage, and stress-wave reflection and transmission at the coal-rock interface. As a result, the instantaneous concentration of energy absorption is weakened, and the failure process shows more obvious progressive and staged characteristics.

Overall, increasing impact velocity enhances the instantaneous energy absorption capacity of all specimens and advances the occurrence of the peak absorption rate. Rock mainly exhibits rapid energy accumulation and brittle dissipation, coal shows relatively progressive damage evolution, while the coal-rock composite presents a more complex and dispersed energy absorption process due to interface effects and deformation incompatibility. These results indicate that the dynamic failure of coal-rock composite under impact loading is controlled not only by the properties of coal and rock, but also by the structural effect of the interface.

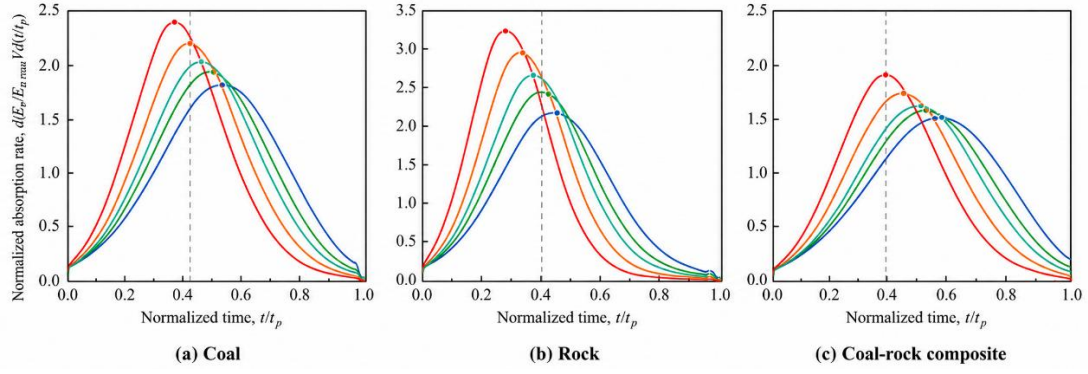


Fig. 9 Normalized energy absorption rates of different specimens under various impact velocities

3.3.4 Normalized Energy Absorption Rate

To further eliminate the influence of differences in the absolute incident energy under different impact velocities, the absorbed energy and loading time were normalized. The normalized absorbed energy curves are shown in the figure. The normalized absorbed energy can be expressed as:

$$\eta_a = \frac{E_a}{E_{a,max}} \quad (9)$$

Where E_a is the absorbed energy at any moment during impact loading, $E_{a,max}$ and is the maximum absorbed energy under the corresponding test condition. The horizontal coordinate t/t_p represents the normalized time. Through this treatment, the energy absorption rate and energy accumulation process of coal, rock, and coal-rock composite specimens under different impact velocities can be compared more intuitively.

As shown in the Fig. 10, the normalized absorbed energy curves of coal, rock, and coal-rock composite specimens all exhibit an obvious S-shaped increasing trend. The whole process can be divided into three stages: the initial slow energy absorption stage, the rapid energy absorption stage, and the later stable stage. At the initial loading stage, the normalized absorbed energy increases slowly, indicating that the specimen mainly undergoes closure of primary

cracks, local contact adjustment, and elastic energy storage, with relatively low energy dissipation. As the impact loading continues, the slope of the curve increases significantly, indicating that internal cracks begin to initiate, propagate, and coalesce rapidly, resulting in a sharp increase in absorbed energy. In the later loading stage, the curve gradually becomes stable and approaches 1, suggesting that the energy absorption capacity of the specimen reaches saturation and the failure process is basically completed.

From the perspective of impact velocity, as the impact velocity increases from 2.5 m/s to 8 m/s, the normalized absorbed energy curves of the three types of specimens shift leftward as a whole, and the normalized time required to reach $\eta_a=0.5$ gradually decreases. This indicates that the higher the impact velocity, the greater the proportion of energy absorbed by the specimen within a shorter time, and the more concentrated the energy input and dissipation process becomes. In other words, under high-velocity impact, the internal damage evolution of the coal-rock mass accelerates, crack propagation and coalescence occur earlier, and the specimen is more likely to enter the rapid damage and instability stage within a short time.

For the coal specimen, the normalized absorbed energy curve shifts forward noticeably with increasing impact velocity. Under low-velocity impact, the energy absorption process of coal is relatively delayed, indicating that the closure of pores and cracks and the progressive damage process last for a longer period. Under high-velocity impact, the curve rises rapidly, suggesting that crack compaction, initiation, and propagation in coal are significantly accelerated under stronger impact disturbance, and absorbed energy accumulates rapidly during

the early and middle stages. This behavior is closely related to the strong heterogeneity and well-developed fissures of coal.

The curves of the rock specimen rise relatively smoothly, and the slope in the rapid energy absorption stage is relatively large, indicating that rock has a stronger capacity for elastic energy storage and rapid energy dissipation under impact loading. Compared with coal, rock has a denser internal structure and fewer initial cracks. Therefore, its energy absorption process is mainly concentrated in the rapid crack propagation stage after elastic deformation. With increasing impact velocity, the time required for the rock specimen to reach the half-energy absorption state is advanced, indicating that higher impact velocity promotes rapid energy accumulation in rock and rapid dissipation during unstable crack propagation.

The normalized absorbed energy curves of the coal-rock composite also shift significantly forward with increasing impact velocity, and this forward shift is more pronounced under high-velocity impact. This indicates that the energy absorption process of the composite specimen becomes more concentrated under strong impact disturbance, and the damage development becomes more sudden. This is mainly because there are obvious differences in strength, stiffness, and wave impedance between coal and rock. When the impact wave propagates to the coal-rock interface, reflection, transmission, and local stress concentration occur, causing damage to initiate and propagate earlier near the interface and in the weak coal component. Therefore, the energy absorption process of the composite specimen is controlled not only by the weak mechanical properties of coal, but also by the interface effect and structural coordination deformation.

A comprehensive comparison of the three types of specimens shows that their normalized energy absorption characteristics have both similarities and differences. The similarity is that the energy absorption process of all specimens advances with increasing impact velocity, and the rapid energy absorption stage becomes shorter, indicating that coal, rock, and coal – rock composite specimens all exhibit significant impact velocity effects. The differences are as follows: the energy absorption process of coal is mainly controlled by the closure of primary fissures and progressive damage; the energy absorption process of rock is more concentrated in the rapid failure stage after elastic energy storage; and the coal-rock composite exhibits more obvious interface control and structural effects.

Therefore, the normalized absorbed energy curve can not only reflect the energy absorption rate of specimens under different impact velocities, but also reveal the timing characteristics of damage evolution and instability failure. Under high impact velocity, the specimen completes a large proportion of energy absorption within a shorter normalized time, indicating that the energy accumulation and dissipation processes are more intense and that dynamic failure is more sudden. For the coal-rock composite, the interface effect further intensifies local energy concentration and non-uniform damage development, which is an important reason for the complexity of its impact instability behavior.

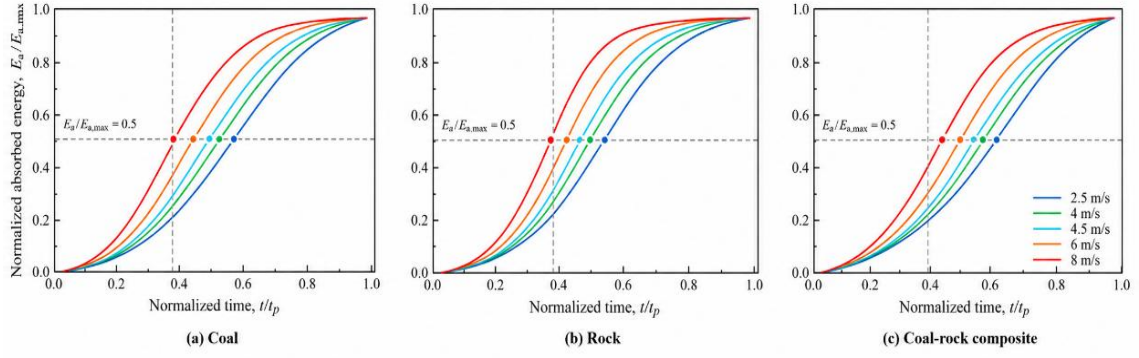


Fig. 10 Normalized energy absorption evolution under different impact velocities

3.3.5 Energy Absorption Density under Different Impact Velocities

To evaluate the energy dissipation capacity per unit volume of coal, rock, and coal-rock composite specimens under different impact velocities, the energy absorption density was introduced:

$$\omega_a = \frac{E_a}{V} \quad (10)$$

where ω_a is the energy absorption density, $\text{J} \cdot \text{m}^{-3}$; E_a is the absorbed energy, J; and V is the specimen volume, m^3 . Compared with absorbed energy, energy absorption density eliminates the influence of specimen size and better reflects the intrinsic energy dissipation capacity of the material. As shown in the Fig.11, the energy absorption density of all three types of specimens increases significantly with increasing impact velocity. When the impact velocity rises from 2.5 m/s to 8 m/s, the input impact energy increases, resulting in more intense crack initiation, propagation, coalescence, and fragmentation. Therefore, more energy is absorbed and dissipated per unit volume. This result is consistent with the normalized absorbed energy curves discussed above, indicating that higher impact velocities not only increase the total absorbed energy but also accelerate the energy accumulation and dissipation process.

For coal specimens, the energy absorption density is generally the lowest, increasing from approximately $0.12 \times 10^8 \text{ J} \cdot \text{m}^{-3}$ to $0.78 \times 10^8 \text{ J} \cdot \text{m}^{-3}$. This is mainly attributed to the well-developed pores and primary fissures in coal, which reduce its dynamic bearing capacity. Although part of the impact energy is consumed by crack closure and local compaction, the overall energy storage and dissipation capacity of coal remains relatively weak.

Rock specimens show the highest energy absorption density under most impact velocities, increasing from approximately $0.44 \times 10^8 \text{ J} \cdot \text{m}^{-3}$ to $1.14 \times 10^8 \text{ J} \cdot \text{m}^{-3}$. Due to their denser structure, higher strength, and greater stiffness, rock specimens can accumulate more elastic strain energy before failure. Under high-velocity impact, this stored energy is rapidly transformed into crack propagation energy, frictional dissipation, and fragmentation energy.

For the coal–rock composite specimens, the energy absorption density increases from approximately $0.27 \times 10^8 \text{ J} \cdot \text{m}^{-3}$ to $1.14 \times 10^8 \text{ J} \cdot \text{m}^{-3}$. At low impact velocities, the absorption density is lower than that of rock because the overall response is restricted by the weak coal component and the coal–rock interface. However, under high impact velocities, the absorption density increases sharply and becomes close to that of rock, indicating that coal crushing, rock cracking, interface sliding, and local stress concentration jointly contribute to energy dissipation.

Overall, under the same impact velocity, the energy absorption density is generally higher for rock and lower for coal, while that of the coal-rock composite lies between them and increases significantly under high-velocity impact. This indicates that material strength, internal structural integrity, and interface effects jointly control the energy absorption capacity. Coal

has a lower absorption density due to its developed pores and fissures; rock can accumulate and dissipate more energy because of its dense structure and high bearing capacity; and the coal-rock composite is controlled by both coal weakening and interface damage, showing limited absorption capacity at low velocity but enhanced dissipation under high-velocity impact.

In addition, the error bars in the figure are generally small, indicating good stability and repeatability of the energy absorption density results under different test conditions. With increasing impact velocity, the error range of some specimens becomes slightly larger, suggesting that high-velocity impact leads to more violent failure, greater uncertainty in crack propagation paths, interface damage, and fragmentation patterns.

Therefore, energy absorption density effectively characterizes the energy dissipation capacity per unit volume of coal, rock, and coal-rock composite specimens under impact loading. A higher impact velocity leads to greater energy absorption density and more intense energy accumulation and dissipation during failure. For the coal – rock composite, the interface effect and structural cooperative failure are significantly enhanced under high-velocity impact, which is an important reason for the rapid increase in energy absorption density and the complexity of its dynamic instability behavior.

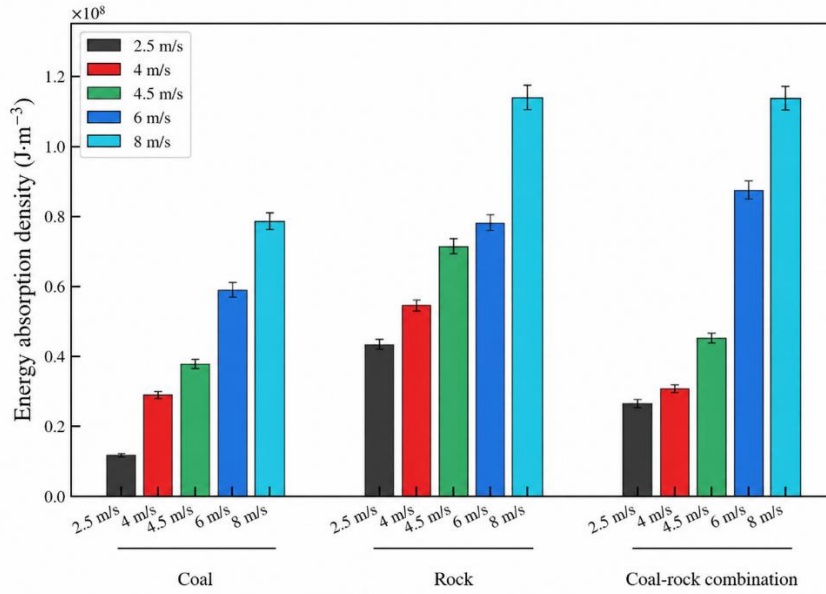


Fig.11 Energy absorption density of different specimens under different impact velocities

4. Discussion

4.1 Dynamic strengthening and lithology-dependent failure mechanisms

The experimental results demonstrate that coal, rock, and coal-rock composite specimens exhibit several common dynamic characteristics under the prescribed multiaxial prestress and impact loading conditions. Their stress-strain responses generally undergo crack closure, rapid loading, peak transition, post-peak softening, and final instability. Meanwhile, peak stress, average strain rate, absorbed energy, and energy absorption density increase with impact velocity, indicating a pronounced rate-dependent dynamic strengthening effect. Similar staged deformation and strain-rate-dependent behavior have also been reported for coal, rock, and coal-rock composites subjected to impact or coupled static-dynamic loading [13-18].

The increase in dynamic strength with impact velocity is related to the coupled effects of loading rate, crack-growth kinetics, and multiaxial constraint. At higher loading rates, the time available for stable crack initiation and propagation is shortened. Consequently, a larger number of microcracks must be activated within a shorter period before coalescing into a macroscopic

639 failure surface, allowing the specimen to temporarily sustain a higher stress level. Meanwhile,
640 the applied prestress restricts lateral deformation and alters crack propagation. Therefore, the
641 increase in peak stress is not solely caused by the increase in impact energy but reflects the
642 combined effects of strain-rate sensitivity, damage evolution, and multiaxial constraint.

643 Despite these common trends, the dominant failure mechanisms differ substantially among
644 the three specimen types. Coal contains abundant primary pores and fissures and has relatively
645 low stiffness. It therefore undergoes a more pronounced initial compaction process and
646 develops greater deformation within the short impact duration, resulting in the highest average
647 strain-rate response. Its damage process is characterized by progressive fissure closure, crack
648 initiation and coalescence, local crushing, and eventual instability. Thus, the dynamic failure
649 of coal is primarily governed by pre-existing defects and progressive damage accumulation.

650 In contrast, the rock specimen has a denser structure, higher stiffness, and significantly
651 greater dynamic bearing capacity. Its stress increases rapidly during the pre-peak stage, and a
652 considerable stress level is maintained after the peak. Rock also exhibits the highest energy
653 absorption density under most impact conditions. These characteristics indicate a failure
654 process dominated by high-stiffness load bearing and elastic energy accumulation, followed by
655 relatively concentrated crack propagation and fragmentation.

656 The coal-rock composite exhibits characteristics that cannot be fully explained by either
657 constituent material alone. Its response involves not only the mechanical contrast between coal
658 and rock but also stress-wave interaction and load redistribution across the interface. This
659 structural effect is further discussed in Section 4.3.

4.2 Energy redistribution and dissipation mechanisms

The energy results further reveal the lithology-dependent dynamic failure mechanisms. For coal, reflected energy accounts for approximately 59-60% of the incident energy, whereas transmitted energy represents only approximately 6-7%. The relatively high reflection and low transmission are associated with its low wave impedance and highly heterogeneous pore-fracture structure, which strongly attenuate stress-wave propagation.

For the rock specimen, the reflected-energy proportion decreases to approximately 31-32%, whereas the transmitted-energy proportion increases to approximately 21-22%. In addition, absorbed energy represents approximately 46-47% of the incident energy. The denser structure and higher wave impedance of rock therefore facilitate stress-wave propagation into and through the specimen, while its high stiffness and strength allow greater internal energy accumulation and subsequent dissipation through crack propagation and fragmentation.

The coal-rock composite exhibits a distinctly different energy-partitioning pattern. Its reflected-energy proportion reaches approximately 66-67%, the highest among the three specimen types, whereas the transmitted-energy proportion is only approximately 3-4%. This pronounced reflection cannot be interpreted solely from the properties of coal or rock. Instead, the mechanical and wave-impedance mismatch across the coal-rock interface causes substantial reflection and transmission when the stress wave propagates from the rock component toward the coal component. The resulting wave interaction also promotes dynamic stress redistribution and local stress concentration near the interface ^[14-16,22].

The normalized energy evolution provides further insight into the temporal characteristics of dynamic failure. For all three specimen types, increasing impact velocity shifts the normalized absorbed-energy curves toward earlier normalized times, indicating that a larger proportion of energy is absorbed and dissipated within a shorter period. Thus, increasing impact velocity not only increases the magnitude of energy input but also shortens the time scale of damage evolution, making dynamic failure increasingly rapid.

However, the dominant energy dissipation pathways differ among the specimens. In coal, energy is progressively consumed by fissure closure, crack propagation, crushing, and fragment rearrangement. In rock, a greater proportion of energy is stored elastically before being rapidly dissipated through brittle crack propagation and fragmentation. In the coal-rock composite, several mechanisms operate simultaneously, including coal deformation and crushing, stress-wave reflection and transmission, interface degradation and sliding, local stress redistribution, and eventual rock cracking.

The energy absorption density further supports this interpretation. At relatively low impact velocities, the energy absorption density of the composite lies between those of coal and rock, indicating that its energy dissipation is still strongly influenced by the weaker coal component. At higher impact velocities, however, the absorption density increases rapidly and approaches that of rock. This suggests that strong impact disturbance activates additional dissipation mechanisms throughout the composite, so that coal crushing, interface degradation, frictional sliding, rock cracking, and structural rearrangement jointly contribute to energy dissipation.

These results show that the composite should not simply be regarded as a material with properties intermediate between coal and rock. Instead, its energy response is governed by an evolving interface-mediated redistribution process, which provides an energetic basis for the staged failure behavior discussed below.

4.3 Non-additive structural response and coupled failure mechanism of the coal–rock composite

The key difference between the coal-rock composite and the single-material specimens is that its dynamic response cannot be described as a simple superposition of coal and rock behavior.

Across the investigated impact velocities of 2.5-8 m/s, the peak stress of the composite increases from approximately 82 to 171 MPa, consistently higher than that of coal (50-117 MPa) but lower than that of rock (112-205 MPa). This intermediate strength level reflects the competing and cooperative effects of the high-stiffness rock component and the mechanically weaker coal component.

More importantly, the composite exhibits a deformation and post-peak evolution pattern that is distinct from those of both constituent materials. At an impact velocity of 6 m/s, the peak stresses of coal, coal-rock composite, and rock are approximately 91, 144, and 180 MPa, respectively, whereas the corresponding peak strains are approximately 0.0052, 0.0028, and 0.0028. The substantially lower peak strain of the composite relative to coal indicates that the stiff rock component constrains the rapid deformation of the coal component during the pre-peak stage. Therefore, the coal and rock do not behave as mechanically independent blocks; instead, stress transfer through the interface enables a constrained cooperative bearing state.

721 This cooperative state becomes progressively unstable after the peak. Coal exhibits relatively
722 gradual post-peak softening, whereas rock undergoes a more continuous stress reduction while
723 retaining considerable bearing capacity. In contrast, the coal-rock composite displays a
724 characteristic sequence of peak attainment, rapid stress reduction, residual bearing, and
725 secondary instability. At 6 m/s, for example, the stress rapidly decreases from approximately
726 144 MPa after the peak and subsequently remains at approximately 85 – 90 MPa before
727 decreasing again toward final instability. This residual-bearing stage represents one of the
728 clearest mechanical characteristics distinguishing the composite from the single-material
729 specimens.

730 Based on these observations, the dynamic response of the coal-rock composite can be
731 interpreted as a two-stage structure-material interaction process. During the pre-peak stage, the
732 relatively stiff rock component constrains coal deformation, while interfacial stress transfer
733 allows the two components to participate jointly in load bearing. This constrained cooperative
734 interaction increases the dynamic bearing capacity of the composite relative to coal alone and
735 suppresses excessive pre-peak deformation.

736 After the peak stress is reached, damage preferentially develops within the weaker coal
737 component and near the coal-rock interface. The resulting degradation of deformation
738 compatibility causes dynamic load redistribution between coal and rock. As the damaged coal
739 region progressively loses bearing capacity, part of the load is transferred through the interface
740 to the less-damaged rock component, which provides a mechanical explanation for the observed
741 residual-bearing stage. With continued loading, coal crushing, interface degradation, local

sliding, and crack propagation progressively weaken the load-transfer path. Once these damage zones become interconnected, coordinated deformation between coal and rock can no longer be maintained, and the composite enters secondary instability.

The post-impact failure morphology further supports this interpretation. Damage in the composite is distinctly heterogeneous and asymmetric, with preferential failure occurring in the coal component and near the interface. As impact velocity increases, the damaged region evolves from localized boundary damage to extensive coal crushing, interface degradation, and material detachment. Therefore, the failure of the composite is neither controlled solely by the weak coal component nor governed by the high-strength rock component. The composite failure therefore reflects a transition from pre-peak cooperative bearing to post-peak interface-controlled load redistribution and structural instability. This structure-material coupled instability mechanism is schematically illustrated in Fig. 12.

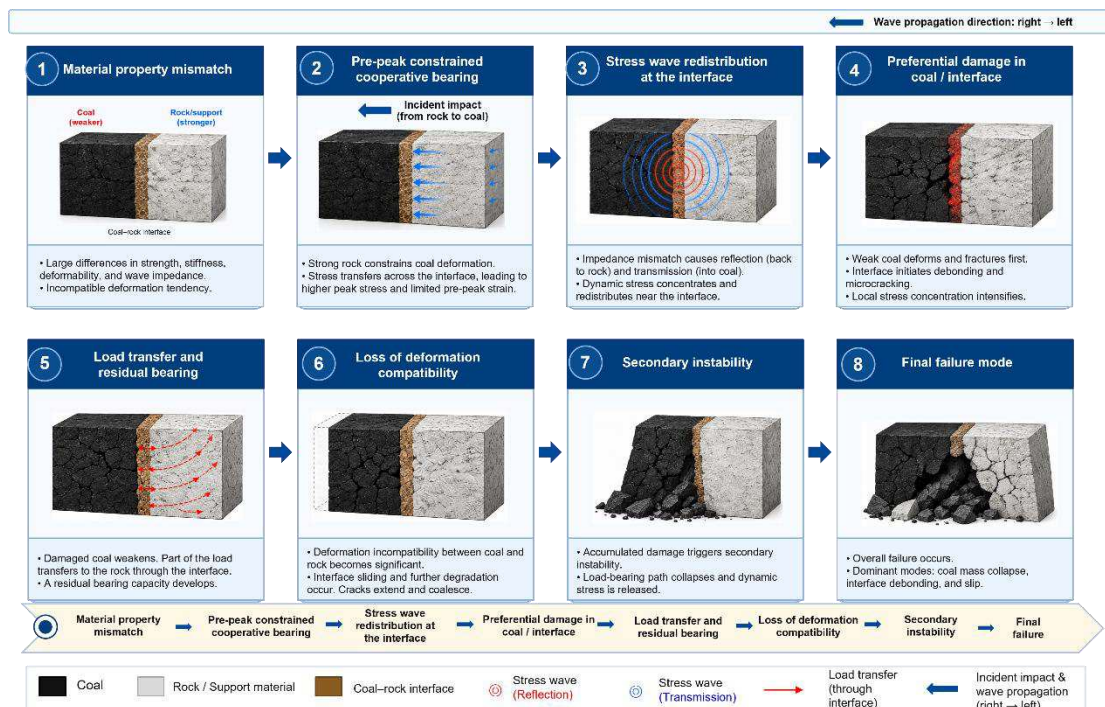


Fig.12 Structure-material coupled dynamic instability mechanism of the coal-rock composite under impact loading

4.4 Engineering implications for dynamic instability of deep coal–rock systems

The present results have important implications for the assessment of dynamic instability in deep coal mining. In particular, the stability of a coal-rock system cannot be evaluated solely from the strength or dynamic properties of coal. The coal-rock composite exhibits a substantially higher peak stress than coal alone, indicating that the constraint provided by competent roof or floor rock can enhance the apparent dynamic bearing capacity of the coal-rock system. However, this increase in peak bearing capacity should not necessarily be interpreted as an equivalent increase in structural stability.

The experiments show that the enhanced pre-peak bearing capacity of the composite is accompanied by strong interfacial wave reflection, heterogeneous damage development, and a distinct post-peak residual-bearing stage. A hard-rock-soft-coal system may therefore sustain a relatively high dynamic load before failure while progressive damage is already developing within the adjacent coal and interface region. Once deformation compatibility between coal and rock is lost, subsequent stress redistribution and damage coalescence may trigger delayed or secondary instability. Thus, the presence of residual bearing capacity after initial damage does not necessarily indicate a stable state.

This behavior is particularly relevant to hard-roof-coal-seam systems. Dynamic disturbances generated by roof fracture, fault slip, blasting, or other mining activities may propagate from competent rock toward the coal seam and undergo pronounced reflection, transmission, and redistribution at lithological interfaces. The coal-rock contact region and the adjacent weak coal

may therefore become preferential zones for dynamic stress concentration and damage initiation. Consequently, dynamic risk assessment should consider not only the mechanical properties of individual coal and rock units but also their stiffness and strength contrasts, interface condition, and dynamic load-transfer characteristics.

From the perspective of monitoring, particular attention should be paid to coal-roof and coal-floor transition zones, especially where stiff and strong strata are in direct contact with weak or highly fractured coal. Abnormal microseismic or acoustic-emission activity, rapid differential deformation, and localized energy release near these interfaces may provide useful indicators of the transition from cooperative bearing to interface-controlled instability.

The results also suggest that dynamic disaster mitigation should simultaneously target the disturbance source and structurally sensitive regions. For hard-roof-soft-coal conditions, weakening or preconditioning of competent roof strata can reduce the intensity of external dynamic loading, whereas destressing of the coal seam can lower the stored energy available for unstable failure. Meanwhile, maintaining support continuity and limiting excessive differential deformation near coal-rock boundaries may help reduce local stress redistribution and premature interface degradation. The roof, coal seam, and interface should therefore be treated as an integrated mechanical system rather than as independent structural components.

From this perspective, the engineering significance of the present study extends beyond the general observations that rock is stronger than coal and that increasing impact velocity enhances dynamic strength. More importantly, the results demonstrate that the transition from a single material to a coal-rock structural system fundamentally alters the pathways of load transfer,

stress-wave propagation, damage accumulation, energy redistribution, and post-peak instability.

The coal-rock interface therefore represents a critical structural link between external dynamic disturbance, localized damage evolution, and eventual system instability.

5. Conclusion

In this study, true triaxial impact tests were conducted on coal, rock, and coal-rock composite specimens to investigate their dynamic stress-strain response, strain-rate behavior, failure characteristics, and energy absorption mechanism. The results show that all specimens exhibit typical staged deformation characteristics under impact loading, including crack closure, rapid loading, peak transition, post-peak softening, and final instability. With increasing impact velocity, the peak stress, deformation capacity, absorbed energy, and energy absorption density increase significantly, indicating an obvious dynamic strengthening effect.

The dynamic responses of the three specimen types differ markedly due to their material properties and structural characteristics. Rock exhibits the highest dynamic bearing capacity and energy absorption capacity because of its dense structure and high stiffness, whereas coal shows a stronger strain-rate response owing to its low stiffness and developed internal defects. The coal-rock composite presents a more complex response controlled by both the weak coal component and the coal-rock interface, and its deformation and failure process cannot be regarded as a simple superposition of coal and rock behavior.

Energy analysis indicates that impact velocity plays a dominant role in enhancing energy input and dissipation. Rock mainly dissipates energy through internal cracking and fragmentation, while coal and coal-rock composites are more strongly affected by wave reflection, crushing, interface sliding, and local structural damage. In particular, the coal-rock

interface promotes stress-wave reflection and local stress concentration, leading to preferential damage in the coal part and near the interface.

Overall, the dynamic instability of coal-rock composites under true triaxial impact loading is governed by material heterogeneity, interfacial effects, and stress-wave redistribution. These findings provide experimental support for understanding the impact failure mechanism of deep coal-rock systems under complex in-situ stress and dynamic disturbance conditions.

Declaration of Competing Interest

All authors declare that there is no conflict of interest.

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