Failure and Seepage Characteristics of Gas-Bearing Coal under Accelerated Loading and Unloading Conditions

Xiang Zhang 1,2, Kai Wang 1,2,3,*, Feng Du 1,2, Zhen Lou 1,2 and Gongda Wang 4

1 Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources, China University of Mining and Technology (Beijing), Beijing 100083, China; xzcumtb@126.com (X.Z.); fengducumtb@126.com (F.D.);
loganzl@163.com (Z.L.)
2 School of Emergency Management and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China
3 Hebei State Key Laboratory of Mine Disaster Prevention, North China Institute of Science and Technology, Beijing 101601, China
4 Mine Safety Technology Branch, China Coal Research Institute, Beijing 100013, China; wgdcumt@gmail.com
* Correspondence: kaiwang@cumtb.edu.cn; Tel.: +86-010-6233-9036

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Abstract: In actual mining situations, the advancing speed of the working face is usually accelerated, which may affect the failure and seepage characteristics of gas-bearing coal, and may even induce dynamic disasters. In order to discover the effects of such accelerated advancement of the working face, an experimental study on the failure and seepage characteristics of gas-bearing coal under accelerated loading and unloading conditions was carried out in this work. The results showed that the energy release was more violent and impactful under accelerated loading and unloading paths. The time required for the failure of the sample was significantly shortened. After being destroyed, the breakup of the sample was more severe, and the magnitude of the permeability was greater. Accordingly, the acceleration of the loading and unloading had significant control effects on the failure and permeability of coal and it showed a significant danger of inducing coal and gas dynamic disasters. Meanwhile, the degree of influence of the acceleration on the coal decreased with an increase in the gas pressure and increased significantly with an increase in the initial confining pressure. It was found that for a deep high-gas mine, the accelerated advancement of the working face under a high in situ stress condition would greatly increase the risk of coal and gas dynamic disasters. Then, the permeability evolution model of gas-bearing coal in consideration of changes in the loading and unloading rates was theoretically established in this work, and this permeability model was validated by experimental data. The permeability model was found to be relatively reasonable. In summary, the effects of accelerated loading and unloading on the failure and seepage characteristics of gas-bearing coal were obtained through a combination of experimental and theoretical studies, and the intrinsic relationship between the accelerated advancement of the working face and the occurrence of coal and gas dynamic disasters was discovered in this work.

Keywords: gas-bearing coal; accelerated loading and unloading; failure; permeability; coal and gas dynamic disasters

1. Introduction

Coal is an important basic energy source in China, which accounts for more than 50% of the primary energy consumption [1,2]. In recent years, with the gradual depletion of shallow green resources, coal mining has gradually extended to deeper areas, and the problems of high gas pressure,
high crustal stress, and low gas permeability have become increasingly prominent. Coal and gas
dynamic disasters occur frequently [3–6]. Under mining conditions, the stress field, fracture field,
and seepage field of the coal in front of the working face are subject to change [7–9]. Coal and gas
dynamic disasters are the result of the sudden failure of coal under the coupling effects of multiple
fields, and can be extremely destructive. The failure and permeability of coal under different mining
conditions can be studied using mechanical and seepage experiments under different loading and
unloading conditions.

The mechanical properties and permeability evolution of coal have been studied by numerous
researchers. The effects of the gas type, gas pressure, confining pressure, temperature, and other
factors on the strength and permeability of coal have been studied by some researchers [10–13].
Furthermore, some scholars have studied the mechanical and seepage characteristics of coal under
different stress paths. The change laws for the main mechanical parameters such as the friction angle,
Young’s modulus, and Poisson’s ratio, along with the confining pressure, have been obtained in
triaxial loading experiments [14]. These showed that the effective compressive strength increases
with the confining pressure, and the permeability of coal varies greatly under simulated in situ
stress conditions. The permeability change rules of gas-saturated coal under different conditions
have also been studied [15]. Experiments have shown that the permeability decreases with an
increase in the effective stress. Under complete stress–strain loading conditions and triaxial creep
stress conditions, the change rules for the permeability were found to be mainly dependent on the
failure mode of gas-saturated coal and the stage of creep deformation, respectively. The changes
in the peak deviatoric stress, lateral expansion ratio, and permeability under different paths were
obtained through experiments [16]. Meanwhile, some researchers in recent years have focused on
the mechanical and seepage characteristics of coal under cyclic loading [17–19]. The changes in
the damage, deformation, and permeability under different cyclic loading and unloading times and
stages were studied. At present, only a few scholars have studied the effects of different loading and
unloading rates on the mechanical behavior and permeability of coal and rock [20–22]. For example,
the mechanical response and failure mechanism of coal under different loading rates were studied
through experiments. The results showed that both the ultimate failure strength and absorbed energy
density before failure increase with the axial loading rate. The deviatoric stress is the cause of the
increases in the bearing strength and absorbed energy density, and it is the ultimate cause of failure [20].
Through experiments to determine the effects of the unloading rate on the mechanical behavior and
permeability evolution of coal, it was found that a higher unloading rate led to a decrease in the
bearing capacity and an increase in the unloading rate made the accumulated energy and dissipation
energy decrease. In addition, a higher unloading rate accelerated the rock failure and the increase in
the magnitude of the permeability was greater [21]. Based on a new experimental method, Jiang [22]
showed that with an increase in the initial hydrostatic stress, both the strength and corresponding
axial strain at failure increased. In contrast, the strength and strain decrease with an increase in the
loading–unloading rate. Moreover, the degree of the failure form was improved with an increase in the
loading–unloading rate.

Nevertheless, none of these studies considered the effects of accelerated loading and unloading
on the failure and seepage characteristics of gas-bearing coal. In on-site production, the advancing
rate of the working face is not fixed. The cycle progress and mining efficiency are often improved
by increasing the advancing rate, and the advancing rate of the working face shows the tendency
to increase. The acceleration of mining at the working face causes the accelerated loading of axial
stress, the accelerated unloading of radial stress on coal and rock, or both. The acceleration of the
loading and unloading will affect the failure and seepage characteristics of gas-bearing coal. However,
whether these effects are related to the occurrence of coal and gas dynamic disasters is still unknown.
In summary, the failure and seepage characteristics of gas-bearing coal under deep mining conditions
have not been fully studied. In addition, to the best of our knowledge, there have been few reports on
the effects of accelerated loading and unloading on the failure and seepage characteristics of gas-bearing
coal. Therefore, it is of great importance to systematically study the failure and seepage characteristics of gas-bearing coal under accelerated loading and unloading conditions, which will play a key role in the prevention and control of coal and gas dynamic disasters.

In this work, experimental and theoretical studies were combined. In the experimental study, the mechanical and seepage experiments of gas-bearing coal under two sets of comparative paths were carried out, and the influence law of the accelerated loading and unloading on the failure and seepage characteristics of gas-bearing coal was obtained. Based on the experimental study, a permeability evolution model of gas-bearing coal that considered changes in the loading and unloading rates was established and validated using experimental data. The results obtained in this work will be very valuable in the development and utilization of CBM (coalbed methane) and the prevention and control of coal and gas dynamic disasters.

2. Experimental Study

2.1. Sample Preparation and Experimental Program

The coal samples used in the experiments were collected from the Qin Shui Coalfield, located in Shanxi Province, China. The coal seam has an average thickness of 6 m and is relatively stable. The geological conditions are relatively simple. The gas content of the coal seam is 7.3 m$^3$/t at a minimum, 11.6 m$^3$/t at a maximum, and more than 8 m$^3$/t in most areas. In order to better represent the characteristics of the original coal and come closer to the actual conditions, raw coal samples were used in the experiments [23,24]. Samples conforming to the ISRM standard were made from chunks of the original coal. The specifications of the samples were φ50 × 100 mm, and the flatness of the end face was controlled to 0.05 mm.

The experiments were performed using an RLW-500G triaxial experimental system, which was mainly composed of a loading module, seepage module, temperature control module, and safety protection module. The triaxial experimental system has previously been described in detail [25] and will not be described in this work. Experiments were conducted under different loading and unloading paths, and the permeabilities of the coal samples were measured synchronously. The experimental system is shown in Figure 1.

![Triaxial experimental system](image)

**Figure 1.** Triaxial experimental system.

Based on the actual stress state of coal and rock during accelerated mining at the working face, two sets of comparative paths were put forward with some appropriate simplifications. The two sets of paths were conventional triaxial compression (CTC) and accelerated triaxial compression (ATC), along with the unloading confining pressure (UCP) and accelerated unloading confining pressure (AUCP). In the experiments, CO$_2$ was used instead of CH$_4$ because of the laboratory’s safety
regulations [26–29]. Five experimental groups were considered under each stress path. The initial conditions under each path were as follows: when the hydrostatic stress was 4 MPa, the gas pressure was 1 MPa, 1.5 MPa, or 2 MPa, and when the hydrostatic stress was 7 MPa or 10 MPa, the gas pressure was 2 MPa. The specific experimental schemes are described below.

Path ① (CTC):
I: First, the axial stress and radial stress were simultaneously loaded to predetermined values. After reaching the hydrostatic stress state, the gas was injected, and the gas pressure was fixed. When the adsorption reached equilibrium, the outlet valve was opened until the gas flow was stable. II: Second, the radial stress was kept constant, and the axial stress was loaded at the rate of 50 N/s in a force-controlled mode. Meanwhile, the seepage data were recorded and stored. III: Third, after the sample was damaged, the loading rate was controlled in a displacement-controlled mode until the residual strength of the sample was stable.

Path ② (UCP):
I: The first phase was the same as Path ①. II: Second, the radial stress was kept constant, and the axial stress was loaded to 40% of the axial peak strength of the sample under the same condition as the CTC path at a rate of 50 N/s. The seepage data were recorded and stored at the same time. Then, the loading rate was changed to 200 N/s until the sample was damaged. III: The last phase was the same as phase III under Path ①.

Path ③ (AUCP):
I: The first phase was the same as Path ①. II: The radial stress was kept constant, and the axial stress was loaded to 60% of the axial peak strength of the sample under the same condition as the CTC path at a rate of 50 N/s. At the same time, the seepage data were recorded and stored. III: Then, the axial stress was kept constant, and the radial stress was unloaded at a rate of 20 N/s in the force-controlled mode until the sample was damaged. IV: The last phase was the same as phase III under Path ①.

Path ④ (AUCP):
I, II: The first and second phases were the same as Path ③. III: The axial stress was kept unchanged, and the radial stress was unloaded to 90% of the initial radial stress at a rate of 20 N/s. IV: Then, the unloading rate was changed to 80 N/s until the sample was damaged. V: The last phase was the same as phase IV under Path ③.

Schematic diagrams of the two sets of comparative stress paths are shown in Figure 2.

**Figure 2.** Schematic diagrams of stress paths: (a) conventional triaxial compression (CTC); (b) accelerated triaxial compression (ATC); (c) unloading confining pressure (UCP); (d) accelerated unloading confining pressure (AUCP).

2.2. Experimental Results

Based on the above experimental conditions and schemes, experiments were carried out on the failure and seepage characteristics of gas-bearing coal under two sets of comparative paths.
2.2.1. Strength Characteristics

The stress–strain curves of gas-bearing coal under the two sets of paths are shown in Figures 3 and 4. During the process of reaching the hydrostatic stress state, the samples were compacted to some extent due to the loading of the axial stress and radial stress. As a result, the compaction phase of the stress–strain curve under each path was not obvious. The stress–strain curve mainly included the elastic deformation, plastic deformation, yield failure, and residual stress phase. Under different initial conditions and stress paths, the strength characteristics of the samples were significantly different.

The experimental results are listed in Tables 1 and 2. In Table 1, \( \sigma_3 \) is the initial radial stress, \( P \) is the gas pressure, \( V \) is the loading rate, \( \sigma_1' \) is the axial peak strength under triaxial compression, \( \sigma_r \) is the residual strength, \( \sigma \) is the difference between the peak strength and residual strength, \( n \) is the reduction ratio of the peak stress, and \( t \) is the time required for failure under the loading paths.

In Table 2, \( \sigma_1'' \) represents the axial stress at the start of unloading the radial stress, \( V' \) represents the unloading rate, \( \sigma_3' \) represents the radial stress at the time of sample failure, \( \sigma' \) represents the unloaded radial stress at failure, \( N \) represents the unloading ratio (the ratio of unloaded radial stress to initial radial stress), and \( t' \) represents the time required for failure under the unloading paths.

![Stress–strain curves under different loading paths](image)

**Figure 3.** Stress–strain curves under different loading paths: (a) CTC (\( \sigma_3 = 4 \) MPa); (b) CTC (\( P = 2 \) MPa); (c) ATC (\( \sigma_3 = 4 \) MPa); (d) ATC (\( P = 2 \) MPa).
Table 1. Experimental results under different loading paths.

| Paths | No. | σ3/MPa | P/MPa | V/N·s⁻¹ | σ1'/MPa | σr/MPa | n/% | t/s |
|-------|-----|--------|-------|---------|---------|--------|-----|-----|
| CTC   | 1-1 | 4      | 1     | 50      | 32.19   | 23.10  | 9.09| 28.24 | 1106 |
|       | 1-2 | 4      | 1.5   | 50      | 27.69   | 20.81  | 6.88| 24.85 | 930  |
|       | 1-3 | 4      | 2     | 50      | 23.70   | 17.76  | 5.94| 25.06 | 873  |
|       | 1-4 | 7      | 2     | 50      | 36.43   | 31.59  | 4.84| 19.32 | 1155 |
|       | 1-5 | 10     | 2     | 50      | 45.66   | 37.83  | 7.83| 13.29 | 1155 |
| ATC   | 2-1 | 4      | 1     | 200     | 35.57   | 23.41  | 12.16| 34.19 | 571  |
|       | 2-2 | 4      | 1.5   | 200     | 32.25   | 24.31  | 7.94| 24.62 | 486  |
|       | 2-3 | 4      | 2     | 200     | 28.20   | 20.35  | 7.85| 27.84 | 399  |
|       | 2-4 | 7      | 2     | 200     | 42.78   | 33.85  | 8.93| 20.87 | 574  |
|       | 2-5 | 10     | 2     | 200     | 57.98   | 38.03  | 19.95| 34.41 | 714  |

Figure 4. Stress–strain curves under different unloading paths: (a) UCP (σ3 = 4 MPa); (b) UCP (P = 2 MPa); (c) AUCP (σ3 = 4 MPa); (d) AUCP (P = 2 MPa).

Table 2. Experimental results under different unloading paths.

| Paths | No. | σ3/MPa | P/MPa | V'/N·s⁻¹ | σ3'/MPa | σr'/MPa | n/% | t'/s |
|-------|-----|--------|-------|---------|---------|--------|-----|-----|
| UCP   | 3-1 | 4      | 1     | 20.4    | 20      | 1.34   | 2.66 | 66.50 | 904  |
|       | 3-2 | 4      | 1.5   | 17.5    | 20      | 1.85   | 2.15 | 53.75 | 740  |
|       | 3-3 | 4      | 2     | 14.9    | 20      | 2.97   | 1.03 | 25.75 | 528  |
|       | 3-4 | 7      | 2     | 23.1    | 20      | 4.42   | 2.58 | 36.86 | 884  |
|       | 3-5 | 10     | 2     | 28.4    | 20      | 5.65   | 4.35 | 43.50 | 1148 |
|       | 4-1 | 4      | 1     | 20.4    | 20/80   | 1.51   | 2.49 | 62.25 | 734  |
|       | 4-2 | 4      | 1.5   | 17.5    | 20/80   | 1.91   | 2.09 | 52.25 | 610  |
| AUCP  | 4-3 | 4      | 2     | 14.9    | 20/80   | 3.02   | 0.98 | 24.50 | 481  |
|       | 4-4 | 7      | 2     | 23.1    | 20/80   | 4.63   | 2.37 | 33.86 | 741  |
|       | 4-5 | 10     | 2     | 28.4    | 20/80   | 5.99   | 4.01 | 40.10 | 893  |
It can be concluded from the results in Figure 3 and Table 1 that under the two loading paths, the strengths of the samples were significantly different under different initial conditions. Under the two loading paths, the peak strength of the sample decreased as the gas pressure increased, while increasing significantly as the confining pressure increased. Wang [30] and Li [31] also pointed out that under the same confining pressure, an increase in the gas pressure decreased the peak strength of coal, and the effect of the gas pressure on the peak strength was weakened as the confining pressure increased. When the confining pressure was the same, as the gas pressure increased, the gas pressure in the pore and crack structure of the coal increased, and the effective confining pressure of the coal decreased. In addition, an increase in the gas pressure led to greater gas adsorption and coal matrix swelling. Meanwhile, an increase in the gas pressure also had a certain compression effect on the coal matrix. Furthermore, as the gas pressure increased, the chemical action of the gas on the coal was enhanced. Under the combined physical and chemical effects, the strength of the coal was reduced.

After fitting the peak strengths of the samples under the two loading paths, it could be found that the peak strengths of the samples decreased linearly with an increase in the gas pressure and increased linearly with an increase in the confining pressure. The fitting curves are shown in Figure 5.

Comparing the strengths of the samples under different loading paths, it can be concluded that under the same initial conditions, the peak strengths of the samples under the ATC path increased by 11% to 27%, while the residual strengths did not show an obvious difference. Meanwhile, it can be found that the magnitude of the decrease in the peak stress and the reduction ratio of the peak stress were significantly improved. Under the ATC path, the elastic energy stored in the sample was higher than that under the CTC path, and the energy release was greater and more intense. During the loading process, part of the work done on the coal was applied to the development of cracks, and the others were stored in the coal in the form of elastic energy. Under the ATC path, the axial loading was accelerated, and the sample did not have sufficient time to respond. The cracks in the coal were not fully developed, and more work done on the coal was stored in the form of elastic energy. After reaching the bearing limit, the energy was suddenly released. The sample was destroyed by a more violent and impactful action. When the confining pressure and gas pressure were 10 MPa and 2 MPa, respectively, the residual strengths of samples under different loading paths were basically the same. The ratio of the peak stress reduction under the CTC path was 17.15%, while the ratio doubled to 34.41% under the ATC path.

The relationships between the reduction ratio of the peak stress and the gas pressure/confining pressure under different loading paths are shown in Figure 6. Although the relationships are not obvious, an analysis can clarify that under the same conditions, a larger reduction ratio for the peak stress will result in a more violent and impactful action at failure.
Despite the influence of the ATC path on samples, the influence degree of the ATC path on coal differed with the initial conditions. On one hand, as the gas pressure increased, the magnitude of the peak stress reduction ratio decreased from 21% to 11%, indicating that the influence degree of the ATC path on coal was weakening. On the other hand, when the gas pressure was 2 MPa, the magnitude of the peak stress reduction ratio rapidly increased from 11% to 100% with an increase in the initial confining pressure, indicating that the influence degree was significantly improved.

The times required for the failure of samples were also differed significantly according to the results listed in Table 1. Under the two loading paths, the time required for failure decreased as the gas pressure increased, and increased with an increase in the initial confining pressure. A comparison of the times under the different loading paths showed that under the same conditions, the time required under the ATC path was significantly shorter and was approximately half of that under the CTC path. Under the ATC path, the failure of the sample was more abrupt.

Based on the results of the two unloading paths in Figure 4 and Table 2, it can be found that, as the gas pressure increased, the radial stress at the time of sample failure increased, and the unloading ratio decreased. On the other hand, as the initial radial stress increased, the radial stress at the time of sample failure increased, and the unloading ratio increased.

After fitting the radial stress at the time of failure under the two unloading paths, it can be seen that the radial stress at the time of sample failure had linear function relationships with increases in the gas pressure and initial radial stress. The fitting curves are shown in Figure 7.

After the gas adsorption in the coal, the free gas expanded the volume of the coal and provided a force that opposed the radial stress. As a result, the effective confining pressure decreased. Furthermore, the gas molecules could also increase the distance between the coal particles, and the cohesive force
decreased. Meanwhile, some gas molecules existed in the form of chemical adsorption. The mechanical properties of the coal decreased under the combined effects [29,32–34]. As the gas pressure increased, the effective confining pressure of the sample decreased, and the radial deformation ability increased. Therefore, with less unloaded radial stress, the sample was more likely to yield and be destroyed. As the initial radial stress increased, the effective confining pressure increased, and the effect of the gas on the mechanical properties was weakened. Therefore, the high confining pressure limited the ability to deform radially, and a larger unloading ratio was needed for the failure of the sample.

After fitting the unloading ratio under different unloading paths, it could be seen that the unloading ratio was linearly related to increases in the gas pressure and initial radial stress, as shown in Figure 8.

![Figure 8. Fitting curves of unloading ratio under different initial conditions: (a) $\sigma_3 = 4$ MPa; (b) $P = 2$ MPa.](image)

Comparing the results listed in Table 2, it can be concluded that the influences of the unloading paths on the failure of the samples were obviously different. Under the same initial conditions, the radial stress at the failure of a sample increased and the unloading ratio decreased under the AUCP path. The sample was significantly more susceptible to failure under accelerated unloading conditions. The acceleration of the unloading radial stress caused the effective confining pressure to decrease more rapidly, and the mechanical and nonmechanical effects of the gas appeared sooner. The sample responded faster, and the stress state changed more quickly. The rapid decrease in the effective confining pressure led to a rapid release in the energy stored in the sample in the radial direction. Under the AUCP path, because of the acceleration of the unloading, the deviatoric stress increased more quickly, and the sample did not have sufficient time to fully develop cracks. Under the same conditions, the work done on the sample was the same. However, the unloaded radial stress at the time of failure under the AUCP path was smaller. Therefore, the release of energy under the AUCP path was more violent and impactful. After reaching the bearing limit, the energy was suddenly released, and the sample was destroyed.

Although the accelerated unloading path had significant effects on the failure of the samples, the influence degrees were different with different gas pressures and initial radial stresses. Under the AUCP path, when the radial stress was 4 MPa, the reduction magnitude of the unloading ratio decreased from 4.25% to 1.25% with an increase in the gas pressure. On the other hand, the reduction magnitude increased from 1.25% to 3.4% with an increase in the initial radial stress. This showed that the influence degree of the accelerated unloading path on the sample was weakened as the gas pressure increased, and a larger initial radial stress caused the accelerated unloading path to have a greater influence on the sample.

It can be obtained from Table 2 that the times required for failure under the two unloading paths decreased as the gas pressure increased, while they increased as the initial radial stress increased. Comparing the times required for failure under the different unloading paths, it can be found that,
under the same conditions, the time required for failure under the AUCP path was significantly shorter, at approximately 80% of that under the UCP path.

Based on the above analysis, it is obvious that the accelerated loading and unloading paths had profound influences on the failure of the coal, and the stress paths had significant control effects.

2.2.2. Permeability Characteristics

The stress–strain and permeability–strain curves of the two sets of comparative paths are shown in Figures 9 and 10, respectively. With an increase in the axial strain, the change in permeability mainly underwent four stages: a slow decrease, slow increase, rapid increase, and gradual stabilization.

Figure 9. Stress–strain curves and permeability–strain curves under different loading paths: (a) $\sigma_3 = 4$ MPa, $P = 1$ MPa; (b) $\sigma_3 = 4$ MPa, $P = 1.5$ MPa; (c) $\sigma_3 = 4$ MPa, $P = 2$ MPa; (d) $\sigma_3 = 7$ MPa, $P = 2$ MPa; (e) $\sigma_3 = 10$ MPa, $P = 2$ MPa.

The change in permeability was mainly due to the change in the pores and cracks of the sample during the loading and unloading processes. As can be seen from the two figures, when the axial
strain increases, the rapid increase in permeability lags behind the peak of the deviatoric stress as a whole. This showed that the rapid increase in permeability was induced by the failure of the sample and the formation of the through crack. After the failure of the sample, the gas flow increased, but it took time for the control acquisition system to register the increase in the gas flow. Therefore, a lagging phenomenon existed. Under the CTC path, when the initial radial stress and gas pressure were 10 MPa and 2 MPa respectively, the rapid increase in permeability was not obvious. This may be because no penetrating crack formed when the sample failed.

The change in permeability was mainly due to the change in the pores and cracks of the sample during the loading and unloading processes. As can be seen from the two figures, when the axial strain increases, the rapid increase in permeability lags behind the peak of the deviatoric stress as a whole. This showed that the rapid increase in permeability was induced by the failure of the sample and the formation of the through crack. After the failure of the sample, the gas flow increased, but it took time for the control acquisition system to register the increase in the gas flow. Therefore, a lagging phenomenon existed. Under the CTC path, when the initial radial stress and gas pressure were 10 MPa and 2 MPa respectively, the rapid increase in permeability was not obvious. This may be because no penetrating crack formed when the sample failed.

Figure 10. Stress–strain curves and permeability–strain curves under different unloading paths: (a) \( \sigma_3 = 4 \) MPa, \( P = 1 \) MPa; (b) \( \sigma_3 = 4 \) MPa, \( P = 1.5 \) MPa; (c) \( \sigma_3 = 4 \) MPa, \( P = 2 \) MPa; (d) \( \sigma_3 = 7 \) MPa, \( P = 2 \) MPa; (e) \( \sigma_3 = 10 \) MPa, \( P = 2 \) MPa.

Under the two loading paths, the original pores and cracks of the sample were first compacted, and the permeability decreased to the minimum. Then, damage occurred in the sample, and the permeability slowly increased. After the sample failed, the permeability rapidly increased and eventually almost stabilized. Figure 9 shows that under the ATC path, the corresponding axial strain was generally larger when the permeability of the sample started to rise rapidly. This showed that the
axial deformation of the sample was larger, and more energy had accumulated in the sample when the sample was close to failure. Therefore, when the sample failed, the energy release was more intense and impactful.

Under the two unloading paths, because of the loading of the axial stress, the volume of the original pores and cracks decreased, and the gas flow passage became smaller, leading to a decrease in the permeability. Then, the radial stress began to be unloaded. As a result, the deviatoric stress increased, and the average stress decreased, leading to a slow increase in the permeability. Damage occurred in the sample with the increase in the deviatoric stress, and the permeability continued to increase slowly. When the sample was destroyed, the formation of a penetrating crack caused the permeability to increase sharply and then eventually stabilize. It can be concluded from Figure 10 that, under the same conditions, the corresponding axial strain is generally smaller when the permeability begins to increase rapidly under the AUCP path. Before the unloading rate was changed, the axial deformations of the samples under the two unloading paths were the same. Then, the radial stress was continuously unloaded, and the axial strain continued to increase. However, the unloaded radial stress was smaller under the AUCP path. Therefore, the axial deformation was smaller when the sample failed. This also showed that the crack development under the AUCP path was insufficient, and the energy release was more violent and impactful.

It could also be found that the increase in the magnitude of the permeability under the accelerated loading and unloading path was larger than that under the conventional loading and unloading path. This indicated that under the accelerated loading and unloading path, the sample was more broken after failure, which confirmed the more impactful action found in the previous analysis.

2.2.3. Failure Characteristics

The failure modes of the gas-bearing coal under the two sets of comparative paths are shown in Figures 11 and 12.

![Figure 11](attachment:image_url)

**Figure 11.** Failure modes of samples under different loading paths: (a) $\sigma_3 = 4$ MPa, $P = 1$ MPa; (b) $\sigma_3 = 4$ MPa, $P = 1.5$ MPa; (c) $\sigma_3 = 4$ MPa, $P = 2$ MPa; (d) $\sigma_3 = 7$ MPa, $P = 2$ MPa; (e) $\sigma_3 = 10$ MPa, $P = 2$ MPa.
The fragmentation degree of the sample after failure was significantly improved, which was in accordance with the previous analysis. The failure characteristics of the gas-bearing coal under the different loading paths were basically the same, and the failure modes of the samples consisted of shear failure. Under the two loading paths, the samples were always in a triaxial stress state. The gas pressure and initial radial stress were kept unchanged, and the effective confining pressures of the samples were constant. With the loading of axial stress, the damage to the sample was mainly caused by interfacial slippage of coal particles, and the sample experienced shear failure under the effects of compression and shearing. From the figures, it is evident that the sample under the ATC path was more broken after failure. There was a higher stress concentration degree, along with more stored elastic energy and insufficient crack development under the ATC path. When the sample reached failure, the energy release was more intense and impactful, leading to the sample being more broken.

Under the different unloading paths, the failure characteristics of the gas-bearing coal were also basically the same, and the failure mode consisted of tensile and shear failures. Because of the unloading of the radial stress, the stress state of the sample gradually changed from a triaxial stress state to a uniaxial stress state. A decrease in the effective confining pressure caused the stored energy to be released radially. The compression and shearing action was gradually transformed into a tension and shearing action. Under the AUCP path, the accelerated unloading of radial stress resulted in a rapid decrease in the effective confining pressure, and the release of energy was more violent and impactful. The fragmentation degree of the sample after failure was significantly improved, which was in accordance with the previous analysis.

3. Theoretical Study

Based on the results of the previously described experimental study, it is obvious that the stress path, gas pressure, and initial confining stress have profound influences on the change in permeability during the loading and unloading processes. This section discusses the establishment of a permeability model for gas-bearing coal that considers changes in the loading and unloading rates. The rationality of this permeability model was verified using experimental data.

![Figure 12. Failure modes of samples under different unloading paths: (a) \( \sigma_3 = 4 \text{ MPa}, P = 1 \text{ MPa}; \) (b) \( \sigma_3 = 4 \text{ MPa}, P = 1.5 \text{ MPa}; \) (c) \( \sigma_3 = 4 \text{ MPa}, P = 2 \text{ MPa}; \) (d) \( \sigma_3 = 7 \text{ MPa}, P = 2 \text{ MPa}; \) (e) \( \sigma_3 = 10 \text{ MPa}, P = 2 \text{ MPa}. \) The failure characteristics of the gas-bearing coal under the different loading paths were basically the same, and the failure modes of the samples consisted of shear failure. Under the two loading paths, the samples were always in a triaxial stress state. The gas pressure and initial radial stress were kept unchanged, and the effective confining pressures of the samples were constant. With the loading of axial stress, the damage to the sample was mainly caused by interfacial slippage of coal particles, and the sample experienced shear failure under the effects of compression and shearing. From the figures, it is evident that the sample under the ATC path was more broken after failure. There was a higher stress concentration degree, along with more stored elastic energy and insufficient crack development under the ATC path. When the sample reached failure, the energy release was more intense and impactful, leading to the sample being more broken.
3.1. Permeability Model

The permeability evolution model of gas-bearing coal considering changes in the loading and unloading rates was established based on some ideal assumptions. The basic assumptions were as follows: (1) Coal is a homogeneous continuous medium. (2) Coal contains only a single-phase gas fluid. The gas in coal exists in an adsorbed and free state, and the gas flow conforms to Darcy’s law. (3) The process of gas adsorption and desorption in coal accords with the Langmuir adsorption equilibrium equation, and both of them are reversible. The free gas conforms to the Ideal Gas Law. (4) The coal particles and gas are incompressible. (5) The whole process is isothermal regardless of the influence of temperature change. (6) The deformation of coal is much smaller than the size of the coal. (7) The Klinkenberg effect is not considered.

According to the previous study, the permeability has a significant relationship with the porosity. The relationship between permeability and porosity can be expressed as follows [35,36]:

\[
k = \frac{d_e^2 \phi^3}{72(1 - \phi)^2}
\]

where \(k\) is the permeability of coal, \(\phi\) is the porosity and \(d_e\) is the effective diameter of coal particle.

From Equation (1), the relationship between permeability and initial permeability can be obtained as:

\[
\frac{k}{k_0} = \left( \frac{\phi}{\phi_0} \right)^3 \left( 1 - \frac{\phi_0}{1 - \phi_0} \right)^2
\]

where \(k_0\) and \(\phi_0\) present the initial permeability and initial porosity, respectively.

Since the porosity is much less than 1, the second item on the right side of Equation (2) can be omitted. Then, the relationship between permeability and porosity can be written as:

\[
\frac{k}{k_0} = \left( \frac{\phi}{\phi_0} \right)^3
\]

Based on the definition, the porosity can be expressed as:

\[
\phi = 1 - \frac{V_s}{V} = 1 - \frac{V_s(1 + \Delta V_s/V_{s0})}{V_0 + \Delta V} = 1 - \left( \frac{V_0 - V_{s0}}{V_0 + \Delta V} \right) \left( 1 + \frac{\Delta V_s/V_{s0}}{V_0 + \Delta V} \right) = 1 - \frac{1 - \phi_0}{1 + \varepsilon_v(1 + \varepsilon_s)}
\]

where \(V\) is the volume of coal, \(V_s\) is the volume of coal skeleton, \(V_0\) is the initial volume of coal, \(\Delta V\) is the volume change, \(V_{s0}\) is the initial volume of coal skeleton, \(\Delta V_s\) is the volume change of coal skeleton, \(\varepsilon_v\) is the volumetric strain of coal and \(\varepsilon_s\) is the volumetric strain of coal skeleton.

The initial volume and volume of coal are:

\[
V_0 = V_{p0} + V_{s0}
\]

\[
V = V_p + V_s
\]

where \(V_p\) and \(V_{p0}\) present the pore volume and the initial pore volume, respectively.

From Equation (5) and Equation (6), the volumetric strain can be expressed as:

\[
\varepsilon_v = \frac{V - V_0}{V_0} = \frac{V_p - V_{p0} + V_s - V_{s0}}{V_0} = \frac{V_p - V_{p0}}{V_{p0}} \frac{V_0}{V_0} + \frac{V_s - V_{s0}}{V_{s0}} \frac{V_{s0}}{V_0}
\]

where \(V_{p0}/V_0\) presents the initial porosity and \(V_{s0}/V_0\) can be represented by \((1 - \phi_0)\).

Rearranging Equation (7) leads to:

\[
\varepsilon_v = \varepsilon_p\phi_0 + \varepsilon_s(1 - \phi_0)
\]
where $\varepsilon_p$ is the pore compression strain and it can be written as:

$$\varepsilon_p = C_p (d\sigma - dp)$$  \hspace{1cm} (9)

where $\sigma$ and $p$ present the stress and gas pressure, respectively, $C_p$ is the pore volume compressibility [37].

According to the elastic theory of porous media, the stress–strain relationship can be expressed as [38]:

$$\varepsilon_{ij} = \frac{1}{2G} \sigma_{ij} - \left( \frac{1}{6G} - \frac{1}{9K} \right) \sigma_{kk} \delta_{ij} + \frac{\alpha}{3K} p \delta_{ij} + \frac{\alpha_s T}{3} \delta_{ij} + \varepsilon_{Lp}' \delta_{ij}$$  \hspace{1cm} (10)

where $G$ is shear modulus, $\sigma_{ij}$ is bulk stress tensor, $\sigma_{kk}$ is bulk stress, $\delta_{ij}$ is Kronecker symbol, $\alpha$ is Biot coefficient, $\varepsilon_{Lp}'$ is strain caused by adsorption, $K$ is bulk modulus, $\alpha_s$ is thermal expansion coefficient, and $T$ is the temperature change.

The shear modulus can be expressed as:

$$G = \frac{E}{2(1 + \nu)}$$  \hspace{1cm} (11)

where $E$ is elastic modulus, $\nu$ is Poisson’s ratio.

The bulk stress can be written as:

$$\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$$  \hspace{1cm} (12)

The Biot coefficient can be expressed as:

$$\alpha = 1 - \frac{K}{K_s}$$  \hspace{1cm} (13)

where $K_s$ is bulk modulus of coal skeleton.

The deformation caused by adsorption can be written as [39]:

$$\varepsilon_{Lp}' = \frac{\varepsilon_{Lp}}{P_L + p}$$  \hspace{1cm} (14)

where $\varepsilon_L$ is Langmuir volumetric strain, $P_L$ is Langmuir pressure.

Regardless of temperature change, the strain induced by temperature change can be neglected in Equation (10). Then, the volumetric strain of coal skeleton can be obtained with Equation (10), Equation (12) and Equation (14):

$$\varepsilon_s = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} = -\frac{1}{K} (\overline{\sigma} - \alpha p) + \frac{\varepsilon_{Lp}}{P_L + p}$$  \hspace{1cm} (15)

where $\overline{\sigma}$ is the average stress.

Then, the porosity evolution model can be obtained with Equation (4), Equation (8), Equation (9) and Equation (15):

$$\phi = 1 - \frac{\left(1 - \phi_0\right)\left[1 - \frac{1}{K} (\overline{\sigma} - \alpha p) + \frac{\varepsilon_{Lp}}{P_L + p}\right]}{1 - \phi_0 C_p (\overline{\sigma} - \alpha p) + \left(1 - \phi_0\right)\left[-\frac{1}{K} (\overline{\sigma} - \alpha p) + \frac{\varepsilon_{Lp}}{P_L + p}\right]}$$  \hspace{1cm} (16)

Substituting Equation (16) into Equation (3) leads to:

$$k = k_0 \left( \frac{1}{\phi_0} - \frac{\left(1 - \phi_0\right)\left[1 - \frac{1}{K} (\overline{\sigma} - \alpha p) + \frac{\varepsilon_{Lp}}{P_L + p}\right]}{1 - \phi_0 C_p (\overline{\sigma} - \alpha p) + \left(1 - \phi_0\right)\left[-\frac{1}{K} (\overline{\sigma} - \alpha p) + \frac{\varepsilon_{Lp}}{P_L + p}\right]} \right)^3$$  \hspace{1cm} (17)
Due to the change of loading and unloading rate, $\sigma$ can be expressed as:

$$
\sigma = \sigma_{10} + 2\sigma_{30} + \sum_{i = m}^{\nu_i t_i} + 2\sum_{j = n}^{\nu_j t_j} \frac{1}{3}
$$

where $\sigma_{10}$ and $\sigma_{30}$ are initial axial stress and initial radial stress, respectively, $\nu_i$ is the change rate of axial stress, $\nu_j$ is the change rate of radial stress, and $t_i$ and $t_j$ are the corresponding time, respectively.

The final form of the permeability evolution model considering changes in the loading and unloading rates can be obtained based on Equation (17) and Equation (18):

$$
k = k_0 \left\{ \frac{1}{\phi_0} - \frac{1 - \phi_0}{1 - \phi_0} \left( \frac{\sigma_{10} + 2\sigma_{30} + \sum_{i = m}^{\nu_i t_i} + 2\sum_{j = n}^{\nu_j t_j}}{3 - \alpha p} \right) \right. + \left. \frac{\epsilon L}{P_L} \right\}^3
$$

3.2. Model Verification

In order to verify the rationality of the permeability model, it was used to fit the experimental data. The rationality of the permeability model was ascertained through an analysis of the results. The basic parameters are listed in Table 3.

| Parameters                          | Symbol | Value |
|------------------------------------|--------|-------|
| Elastic modulus (MPa)              | $E$    | 2960  |
| Poisson’s ratio                    | $\nu$  | 0.4   |
| Bulk modulus (MPa)                 | $K$    | 4933.33 |
| Bulk modulus of coal skeleton (MPa)| $K_s$  | 14,800 |
| Initial porosity                   | $\phi_0$ | 0.04 |
| Initial permeability (mD)          | $k_0$  | 0.2   |
| Langmuir volumetric strain         | $\epsilon_L$ | 0.004 |
| Langmuir pressure (MPa)            | $P_L$  | 1     |

The permeability data fitting included two parts. In the first part, the permeability model was used to fit the permeability data of four stress paths under a hydrostatic stress state. This included the fitting of permeability data where the gas pressures were the same and the average stress was increasing, and the fitting of permeability data where the average stresses were the same and the gas pressure was increasing. There were four fitting groups in each situation. In the second part, an initial condition was selected, and the permeability changes under the four stress paths were fitted. Here, the initial conditions chosen were an initial radial stress and a gas pressure of 4 MPa and 2 MPa, respectively. According to the previous analysis, the slow increase and sharp increase in the permeability were mainly due to the plastic damage and destructive cracks, respectively. Therefore, the fitting interval was from the initial hydrostatic permeability (permeability in the hydrostatic stress state) to the minimum permeability. The fitting results for the first part are shown in Figures 13 and 14.

The fitting results showed that under the conditions where the gas pressures were the same and the average stress was increasing, the fitness values for the experimental data were 0.9725, 0.9612, 0.9545, and 0.9578. Under the conditions where the average stresses were the same and the gas pressure was increasing, the fitness values reached 0.9998, 0.9887, 0.9189, and 0.9963.

In the second part, the variation in coal permeability under the four stress paths were fitted under the conditions that the radial stress was 4 MPa and the gas pressure was 2 MPa. The fitting results were shown in Figure 15.
The permeability data fitting included two parts. In the first part, the permeability model was used to fit the permeability data of four stress paths under a hydrostatic stress state. This included the fitting of permeability data where the gas pressures were the same and the average stress was increasing, and the fitting of permeability data where the average stresses were the same and the gas pressure was increasing. There were four fitting groups in each situation. In the second part, an initial condition was selected, and the permeability changes under the four stress paths were fitted. Here, the initial conditions chosen were an initial radial stress and a gas pressure of 4 MPa and 2 MPa, respectively. According to the previous analysis, the slow increase and sharp increase in the permeability were mainly due to the plastic damage and destructive cracks, respectively. Therefore, the fitting interval was from the initial hydrostatic permeability (permeability in the hydrostatic stress state) to the minimum permeability. The fitting results for the first part are shown in Figure 13 and Figure 14.

**Figure 13.** Fitting results of permeability data under hydrostatic stress state: (a) CTC; (b) ATC; (c) UCP; (d) AUCP. (P = 2 MPa).

The fitting results showed that under the conditions where the gas pressures were the same and the average stress was increasing, the fitness values for the experimental data were 0.9725, 0.9612, 0.9545, and 0.9578. Under the conditions where the average stresses were the same and the gas pressure was increasing, the fitness values reached 0.9998, 0.9887, 0.9189, and 0.9963.

In the second part, the variation in coal permeability under the four stress paths were fitted under the conditions that the radial stress was 4 MPa and the gas pressure was 2 MPa. The fitting results were shown in Figure 15.

**Figure 14.** Fitting results of permeability data under hydrostatic stress state: (a) CTC; (b) ATC; (c) UCP; (d) AUCP. (σ_3 = 4 MPa).

From the fitting results in Figure 15, under the four stress paths, the fitness values for the experimental data reached 0.9873, 0.9695, 0.9395, and 0.9459.
Figure 14. Fitting results of permeability data under hydrostatic stress state: (a) CTC; (b) ATC; (c) UCP; (d) AUCP. ($\sigma_3 = 4$ MPa).

Figure 15. Fitting results under different paths: (a) CTC; (b) ATC; (c) UCP; (d) AUCP. ($\sigma_3 = 4$ MPa, $P = 2$ MPa).

From the fitting results in Figure 15, under the four stress paths, the fitness values for the experimental data reached 0.9873, 0.9695, 0.9395, and 0.9459.

The fitting results for the two parts showed that the theoretical calculations were in good agreement with the experimental data, and the overall fitting result was relatively good, which proved that the permeability model was reasonable.

4. Discussion

With the accelerated advancement of the working face, the stress state changes in the coal ahead of the working face are complicated. In some cases, the effects on the coal ahead mainly manifest themselves in accelerated loading in the axial direction, while some are mainly characterized by accelerated unloading in the radial direction. In addition, in some cases, the effects mainly manifest themselves in the combined actions of accelerated loading and accelerated unloading.

According to the results of the previously discussed study, under different gas pressures and initial confining pressures, the acceleration of the loading and unloading has a profound influence and significant control effect on the failure and permeability of coal. The influence degree of the accelerated loading and unloading paths on coal decreases with an increase in the gas pressure, and increases significantly with an increase in the initial confining pressure.

When the stress state of the coal in front of the working face is characterized by the combined actions of accelerated loading and accelerated unloading, the strength of the coal is enhanced. Meanwhile, the stress concentration increases, and the rapid decrease in the effective confining pressure causes the acceleration of the change in the stress state. The sharp damage to the coal is accelerated. At the moment of failure, the accumulated energy is released instantaneously, impacting and breaking the coal. The permeability increases sharply, and the adsorption gas is desorbed instantly, resulting in the acceleration of the diffusion and seepage. Based on the analyses, it can be concluded that the acceleration of the advancement of the working face has the significant danger of inducing coal and gas dynamic disasters. Moreover, for deep mines, the accelerated advancement of the working face
under a high-stress condition will further increase the degree of influence on the coal, and the risk of coal and gas dynamic disasters will be greatly enhanced.

From this work, it is easy to find that with the prominence of high gas pressure, high crustal stress, and low gas permeability problems, changes in the advancing rate of the working face, gas pressure, and in situ stress are the key factors affecting the failure and seepage characteristics of coal. In deep high-gas mines, in addition to the gas control measures, it is necessary to reduce the in situ stress by roof cutting and stress relief, water injection in the coal seam, the construction of prestress relief boreholes, and so on. More importantly, the advancing rate at the working face should be reasonably controlled to avoid the occurrence of coal and gas dynamic disasters.

5. Conclusions

In this work, the failure and seepage characteristics of gas-bearing coal under accelerated loading and unloading conditions were studied, and a permeability model that considered changes in the loading and unloading rates was established. In addition, the intrinsic relationship between the accelerated advancement of the working face and the occurrence of coal and gas dynamic disasters was found. The following conclusions can be drawn from the completed work:

(1) The strength of the coal increased and the reduction ratio of the peak stress was remarkably improved under an accelerated loading path. The strength of the sample decreased linearly as the gas pressure increased, whereas it increased linearly as the initial confining pressure increased. The damage to the coal was more violent and impactful and the time required for its failure was shortened by approximately half. The coal was more broken after failure and the failure form was shear failure. When the permeability increased rapidly, the corresponding axial strain was larger and the increasing magnitude of the permeability was greater.

(2) The unloading ratio decreased and the coal sample was more susceptible to failure under the accelerated unloading path. The damage to the coal was more violent and impactful, and the time required for failure was significantly shortened. The coal was more broken after failure, and the failure mode consisted of tensile and shear failures. The corresponding axial strain when the permeability increased sharply was smaller, and the increasing magnitude of the permeability was greater. The unloading ratio of the radial stress decreased linearly with an increase in the gas pressure, whereas it increased linearly with an increase in the initial confining pressure.

(3) The influence degrees of the accelerated loading and unloading paths on coal were both weakened with an increase in the gas pressure, whereas there were enhanced with an increase in the initial confining pressure. The time required for the failure of the coal under the accelerated loading and unloading paths gradually decreased with an increase in the gas pressure, whereas it increased with an increase in the initial confining pressure.

(4) A permeability model that considered changes in the loading and unloading rates was established and verified. The fitting results indicated that the permeability model was relatively reasonable.

(5) It is found that accelerating the advancement of the working face is likely to induce coal and gas dynamic disasters. For deep high-gas mines, it is extremely important to maintain a reasonable advancing rate at the working face.

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