Research Article

Mechanical Behaviors and Damage Evolution Characteristics of Predamaged Rock under Triaxial Compression Experiment

Jinshuai Guo, 1 Wenzheng Shang, 2 Jianbo Yuan, 2 and Zhigang Liu 2, 3, 4

1 School of Civil Engineering, Xuzhou University of Technology, Xuzhou, Jiangsu 221018, China
2 Institute of Mining Engineering, Shandong University of Science and Technology, Tai’an 271019, China
3 Shandong Energy Group, Jinan 250013, China
4 A Key Laboratory of Deep Coal Resource Mining, School of Mines, Ministry of Education of China, China University of Mining and Technology, Xuzhou 221116, China

Correspondence should be addressed to Zhigang Liu; 15865721818@163.com

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The underground rock was disturbed repeatedly during the excavation, resulting in its damage degree gradually accumulated. Therefore, the rock in practical engineering can be regarded as predamaged (PD) rock, and its mechanical behaviors are different from conventional intact rock. This paper proposed the calibrate method to evaluate the predamaged degree of rock based on acoustic emission (AE) ring counts, and the PD rock samples were prepared by uniaxial cyclic loading and unloading test. Then, the triaxial compression experiment of predamaged rock was carried out to study the influence of different predamaged degrees on mechanical behaviors and damage evolution characteristics. The results show that the peak stress and axial strain of PD rock decrease gradually with the increase of predamaged degree. The yield stage of PD rock was significantly shorter than that of intact rock, and it entered the dilation deformation earlier. Furthermore, the constitutive equation of the PD rock based on energy was constructed and the damage evolution characteristics of PD rock were analyzed. It was observed that the bigger the predamaged degree was, the earlier the rock entered the damage, and the failure mode was more complex and crushed. The research results can provide the theoretical basis for the stability control of engineering disturbed rock.

1. Introduction

The surrounding rock experienced multistress paths during the engineering disturbance, such as roadway excavation, blasting, and coal seam mining, resulting in the generation and accumulation of damage in the rock [1, 2]. Therefore, the rock in practical engineering can be regarded as predamaged (PD) rock, and its mechanical behaviors are different from conventional intact rock [3, 4]. The study of the mechanic’s behavior, damage, and failure characteristics of the PD rock are of great significance for the field of engineering.

However, the existing research on mechanical behaviors of rock mainly focused on intact rock, while the research studies on the PD rock were still in exploration [5–7]. Some scholars prefabricated regular cracks in rock samples to simulate the predamaged rock, and studied the influence of cracks number, length, and angle on mechanical behaviors and failure modes [8, 9]. The results indicated that the strength parameters (uniaxial compressive strength, residual strength, and elastic modulus) and deformation parameters (peak axial, radial, and volume strain) decrease with the increase in the number of preexisting cracks [9–13]. Wu et al. proposed that the yield platform was presented in the cracked rock sample with the length of preexisting cracks more than 23 mm [10]. Cao et al. analyzed the rock with different cracks angle and found that the rock sample takes a turn from wing crack propagation failure to crack coalescence failure with the increase of the angle [8]. Cheng proposed that the failure mode changed from shear failure to tensile failure as the length of preexisting crack increased [9]. Huang and Li proposed that the compaction stage of prefabricated crack rocks was obviously prolonged, and the brittleness of samples with cracks was more significant than that of intact samples [14]. With the increase of the crack angle, the peak strength of the sample first decreases and
then increases. The fracture dip angle of 45° was the dividing point of the variation of mechanical and deformation parameters [15, 16]. The variation of mechanical and deformation parameters of the sample with the crack length does not turn at the middle crack length, and the increase of the crack length will directly degrade the strength and mechanical and deformation behaviors of the rock [17].

Based on the comprehensive analysis of the above literature, the existing research mostly uses prefabricated regular cracks to study the influence law of predamaged rock mechanical behaviors. Although this method can study its basic influence characteristics and mechanism to a certain extent, the predamaged cracks in the existing research are mostly macrocracks with regular distribution, which is somewhat different from the random distribution and closure characteristics of microcracks in natural rocks.

Some scholars prepared rock samples with different predamaged degrees through a preloading test. Qiu et al. used the ratio of the stress level loaded on a rock to the peak strength under the corresponding conditions of rock to characterize the predamaged degree [18]. Hou et al. defined the predamaged degree based on the axial strain and elastic modulus and prepared samples with different initial damage degrees through a uniaxial preloading test [19]. Huang et al. defined the predamaged degree of coal samples based on strain energy and prepared coal samples with different initial damage degrees by cyclic loading and unloading test [20]. In conclusion, there is no uniform definition of PD rock, and the relevant research studies were still in exploration.

In view of the above problems, this paper used an AE ring count to calibrate the predamaged degree of rock and prepared rock samples with different predamaged degrees through grading cyclic loading and unloading test. Then, the triaxial mechanical experiment of PD rock was carried out to study the influence of different predamage degrees on rock mechanical behaviors, damage evolution, and failure characteristics.

### 2. Preparation of PD Rock Samples

The damage to rock is essentially the development and expansion process of internal cracks and which is accompanied by energy change. Therefore, the damage degree of rock can be calibrated by the accumulated energy [21]. The energy of rock is gradually accumulated during cyclic loading and unloading, and the damage degree is also changing. Then, rock samples with different predamage degrees were prepared by grading cyclic loading and unloading test.

#### 2.1. Definition of Predamage

AE technology has been used to study the material damage and fracture process for a long time. It is found that the release of strain energy during the generation, propagation, and penetration of internal microcracks will produce an AE ring count [22]. Therefore, the study on the change rule of AE ring count during the loading process of rock is helpful to reveal the damage evolution.

The microelement strength obeys a certain statistical distribution considered the statistical principle [23]. Therefore, the damaged area of the rock cross section can be described as follows [24]:

\[
S_d = S \int_0^\varepsilon \phi(x)dx,
\]

where \( S \) is the cross-sectional area of the material without damage; \( \phi(x) \) was the statistical distribution of microelement strength.

Then, the damage \( D \) can be obtained [22],

\[
D = \frac{S_d}{S} = \int_0^\varepsilon \phi(x)dx.
\]

Assuming that the number of AE ring counts per unit area of the damage element is \( n \), then the number of AE ring counts of damage area \( \Delta S \) to be generated can be expressed as follows:

\[
\Delta N = n \Delta S = N_d \frac{\Delta S}{S},
\]

where \( N_d \) is the accumulated AE ring counts when the damaged area is \( S_d \).

When the sample strain increment is \( \Delta \varepsilon \), the damaged area corresponding to the sample \( \Delta S \) can be calculated as follows:

\[
\Delta S = S_d \phi(x)\Delta \varepsilon.
\]

When the strain produced by the sample increased to \( \varepsilon \), the ratio of accumulated AE ring counts to which at complete damage can be obtained as follows:

\[
\frac{N_d}{N} = \int_0^\varepsilon \phi(x)dx.
\]

Combining the above (2) and (5), the relationship between damage and AE ring counts can be obtained as follows:

\[
D = \frac{N_d}{N}.
\]

The circular loading and unloading methods were adopted in this paper. Assuming that the rock was failure after \( n \) cycles of loading and unloading, then the predamage can be expressed as follows:

\[
D_0(k) = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^{\infty} N_i},
\]

where \( D_0(k) \) is the predamaged degree of \( k \) cycles of loading and unloading test; \( \sum_{i=1}^k N_i \) is the accumulated AE ring counts of \( k \) cycles of loading and unloading test; \( \sum_{i=1}^{\infty} N_i \) is the accumulated AE ring counts of \( n \) cycles of loading and unloading test.

#### 2.2. Test System

The MTS compression machine and PCI-2 AE monitoring system were adopted to prepare the PD rock, as shown in Figure 1. MTS machine circularly loads and unloads rock samples through the set stress path, and
collects stress-strain data in real-time. PCI-2 AE monitoring system collects the AE data during the compression test.

2.3. AE Characteristics of PD Rock Samples. Firstly, a rock sample (S-5) was selected to be cyclic loading and unloading until it was a failure. The accumulated AE ring counts during the whole loading and unloading process were monitored. The stress-strain and AE data are shown in Figure 2.

The S-5 rock sample was a failure after 19 cycles of loading and unloading. Comparing the accumulated AE ring counts and energy variation curve, it was observed that the loading peak of each cycle would correspond to the sudden rise of ring and energy. In the 7th cycle loading, the increase of the AE ring counts curve was significantly greater than in the previous cycles and the energy curve also showed a sharp rise. Therefore, the S-5 rock sample in the 7th cycle began to damage the rock. When the 17th cyclic loading was carried out, the AE ring counts and energy change degree were significantly larger than those of the previous cycles. Meanwhile, the microcracks in the rock began to connect. The S-5 rock sample formed a penetrating fracture and failure in the 19th cycle.

Based on the experimental results of the S-5 rock sample, four kinds of PD rock samples with different predamaged degrees were prepared by cyclic loading and unloading 7, 10, 13, and 16 times, respectively (S-1, S-2, S-3, and S-4). The stress-strain and AE data during the test are shown in Figure 3.

Comparing the stress and AE data in Figure 3, it can be seen that the accumulated AE ring counts and energy curve also show a sudden rise when the 4th, 6th, 7th, and 11th loading and unloading cycles were carried out, indicating that the rock sample begins to damage. Therefore, the cracks in the rock began to develop, and the damage continued to increase as the loading and unloading cycle increased.

According to the calculation method of the predamaged degree of rock in (7), the accumulated AE ring counts after loading and unloading cycles of S-1, S-2, S-3, and S-4 were counted, respectively. The predamaged degree of different rock samples can be obtained by comparing the accumulated AE ring counts of the S-5 rock sample, as shown in Table 1.

3. Triaxial Compression Experiment of PD Rock

3.1. Triaxial Experimental System. The experimental equipment adopts GDS triaxial system (Figure 4). The stress loading system is divided into an axial compression control system and confining pressure control system. The axial compression is applied by the axial hydraulic servo machine, and the confining pressure is applied by injecting hydraulic oil into the cell through the plunger pump.

3.2. Triaxial Experimental Scheme. First, the axial pressure and confining pressure were loaded to the original rock stress level, then the confining pressure was kept constant and the axial pressure was continuously loaded until the rock was a failure. OA section: equally loading axial pressure and confining pressure to 5.0 MPa ($\sigma_1 = \sigma_3$); section AB: keep confining pressure constant ($\sigma_3 = 5.0$ MPa) and continue to load axial pressure until the rock was a failure (Figure 5).

4. Mechanical Behaviors of PD Rock

4.1. Peak Stress. The axial strain, radial strain, and volumetric strain curves of S-0, S-1, S-2, S-3, and S-4 rock samples are shown in Figure 6.

The peak stress of each rock sample was fitted with the predamaged degree, as shown in Figure 7.

$$\sigma_f = 91.2D_0^3 - 111.7D_0^2 + 13.5D_0 + 42.2. \quad (8)$$

The peak stresses of S-1, S-2, S-3, and S-4 PD rock samples were 42.0 MPa, 40.0 MPa, 36.0 MPa, and 28.0 MPa, respectively, which were smaller than those of S-0 intact rock samples (42.2 MPa). Figure 7 indicates that peak stresses of PD rock gradually decrease with the increase of predamaged degree.

4.2. Deformation Characteristics. The stress-strain curves of S-1, S-2, S-3, and S-4 were similar to S-0, which can be divided into fracture compaction stage, elastic deformation
A macro-crack developed in cycle 17. The curve of accumulated AE counts and energy both show sudden rise.

Cracks begin to develop in cycle 7.

Figure 2: AE data of S-5 rock sample.

From the cycle 4, the curve of accumulated AE counts and energy gradually show sudden rise. It indicated that the damage gradually developed after cycle 4.

Figure 3: Continued.
The damage gradually developed in the rock after cycle 6.

The damage gradually developed in the rock after cycle 7.

The damage gradually developed in the rock after cycle 11.

Figure 3: AE data of PD rock sample. (a) S-1 rock sample. (b) S-2 rock sample. (c) S-3 rock sample. (d) S-4 rock sample.
stage, yield deformation stage, and postpeak stage, as shown in Figure 8.

The peak axial strain of PD rock samples (1.0%, 1.0%, 1.1%, and 1.2%) was significantly smaller than that of intact rock samples (1.3%), and the peak axial strain of rock samples decreases gradually with the increase of predamaged degree. Meanwhile, the ratio of YDS to the total strain of PD rock samples (51.3%, 52.9%, 58.1%, and 59.7%) was significantly bigger than that of intact rock samples (48.7%).

4.3. Dilation Characteristics. The volumetric strain curves of S-1, S-2, S-3, and S-4 PD rock samples and S-0 intact rock samples were compared and analyzed to study the influence of predamaged degree on rock deformation, as shown in Figure 9.

The dilatancy onset point (DOP) of S-1, S-2, S-3, and S-4 was 0.6%, 0.5%, 0.4%, and 0.4% of axial strain, respectively, which were less than 0.7% of intact rock. It indicated that the PD rock more easily entered the dilation deformation, and the volume deformation is smaller at the DOP.

5. Damage Evolution and Failure Characteristics of PD Rock

5.1. Damage Constitutive Equation. The damage variable was generally defined as the ratio of the number of failed units to the total number of units as $D = N_d/N$ [25]. The distribution of rock materials, in reality, was not homogeneous. The Weibull equation was usually used to simulate this non-uniform distribution in existing studies [26, 27].

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| Sample | Number of cycles | Accumulated AE ring counts | Predamaged degree/D0 |
|--------|------------------|-----------------------------|----------------------|
| S-0    | 0.0              | 0.0                         | 0.0                  |
| S-1    | 7.0              | 14.0                        | 0.1                  |
| S-2    | 10.0             | 19.8                        | 0.2                  |
| S-3    | 13.0             | 32.2                        | 0.4                  |
| S-4    | 16.0             | 61.1                        | 0.7                  |
| S-5    | 19.0             | 82.6                        | 1.0                  |

Figure 4: Triaxial experimental system of GDS.

Figure 5: Triaxial experimental stress path. (a) Designed stress path. (b) Experimental stress path.
distribution function and probability density function were expressed as follows:

\[
\begin{align*}
F(u) &= 1 - e^{-\left(\frac{u}{u_0}\right)^m}, \\
f(u) &= F'(u) = m \left(\frac{u}{u_0}\right)^{m-1} e^{-\left(\frac{u}{u_0}\right)^m},
\end{align*}
\]  

where \(u\) was the mechanical parameter (such as strength, strain, and elastic modulus) of the element, and the scaling parameter \(u_0\) was related to the average value of the element parameter. \(m\) was the scale parameter, the larger the value means the more uniform the material.

The internal damage of rock was accompanied by the dissipation process of energy. Therefore, when the energy \(U\) was selected as the mechanical parameter \(u\), (9) can be written as follows:

\[
\sigma_1 - \sigma_3 \text{ MPa} \\
\epsilon_3 \\
\epsilon_1
\]

Figure 6: Stress-strain curve of the PD rock. (a) S-0 rock sample. (b) S-1 rock sample. (c) S-2 rock sample. (d) S-3 rock sample. (e) S-4 rock sample.
\[ \sigma_f = (91.2D_0^3 - 111.7D_0^2 + 13.5D_0 + 42.2) \]

**Figure 7:** Fitting relationship of peak stress with a predamaged degree.

**Figure 8:** Stress-strain curve comparison of PD rock and intact rock. (a) S-1 rock sample. (b) S-2 rock sample. (c) S-3 rock sample. (d) S-4 rock sample.
\( f(\varepsilon) = \frac{m}{U_0} \left( \frac{U}{U_0} \right)^{m-1} e^{-\left(\frac{u}{u_0}\right)^m} \). \hspace{1cm} (10)

When the rock was in a stress state \( F \), there were as follows:

\[ N_d = \int_0^F N f(U) dF = N \left\{ 1 - e^{-\left(\frac{u}{u_0}\right)^m} \right\}. \hspace{1cm} (11) \]

Then, the damage variable \( D \) can be expressed as follows:

\[ D = \frac{N_d}{N} = 1 - e^{-\left(\frac{u}{u_0}\right)^m}. \hspace{1cm} (12) \]

According to relevant research studies, the energy absorbed by rock can be divided into two parts as follows: (1) the energy obtained by volume deformation; (2) the distortion specific energy leading to deformation. The energy of volumetric deformation will not cause damage, so the energy absorbed by rock damage \( U \) can be expressed as

\[ U = (1 - D) \frac{\sigma_1 - \sigma_3}{2G} = E(1 + \nu)(\epsilon_1) \frac{1}{2}. \]

According to the Lemaitre strain equivalence hypothesis, there were \( \sigma_1 = (1 - D) E \epsilon_1 \), which can be expressed as \( \sigma_1 = (1 - D) E \epsilon_1 + \nu(\sigma_2 + \sigma_3) \) in the triaxial state, in which \( E = (1 - D_0) \), \( E_0 \), \( E_0 \) was the elastic modulus of intact rock.

Then, the constitutive equation of the rock can be expressed as follows:

\[ \sigma_1 = e^{-\left(E(1+\nu)\epsilon_1/3U_0\right)^m} E \epsilon_1 + \nu(\sigma_2 + \sigma_3). \hspace{1cm} (13) \]

5.2. Damage Evolution of PD Rock. According to the experimental data, the parameters \( U_0 \) and \( m \) can be determined by fitting with (13), and then the damage variable changes of each rock sample can be obtained by substituting the (12), as shown in Figure 10.

Figure 10 shows that the damage degree of rock samples before the yield point was 0, because the initial cracks inside the rock have been completely closed, but no new cracks have been generated. The damage variable increases gradually after the yield point, which can be divided into initial development stage and accelerated development stage. In the initial stage of development, new cracks began to generate inside the rock, and the damage degree accelerates until the peak was completely failure.
Figure 10: Damage variable of PD rock. (a) S-0 rock sample. (b) S-1 rock sample. (c) S-2 rock sample. (d) S-3 rock sample. (e) S-4 rock sample.
The critical point of S-0, S-1, S-2, S-3, and S-4 PD rock samples which entered the initial development stage was 0.7%, 0.6%, 0.5%, 0.4%, and 0.4% of axial strain, respectively, and the critical point which entered the accelerated development stage was 1.0%, 0.9%, 0.8%, 0.7%, and 0.7% of axial strain, respectively. It indicated that the rock was more prone to damage as the increase of the predamaged degree.

5.3. Failure Characteristics. The crack distribution of S-0, S-1, S-2, S-3, and S-4 rock samples after failure is shown in Figure 11.

The crack propagation form was a present shear failure when the predamaged degree was small (S-0 and S-1 sample). But with the increase of predamaged degrees, the crack propagation form becomes more complicated. For instance, the cracks propagation form of the S-2, S-3, and S-4 rock samples were composed of tension and shear. Moreover, the failure form of rock was more crushed with the increase of predamaged degrees.

6. Conclusions

(1) For the cumulative damage characteristics of rock caused by multimining disturbances, a method for preparing rock samples with different predamaged degrees by cyclic loading and unloading test was proposed. The variation laws of AE data during the loading and unloading process were analyzed, and definition for calibrating the predamaged degree of rock based on AE ring counts was put forward.

(2) The triaxial compression experiment of PD rock samples was carried out. The experiment results show that the peak stress and axial strain of PD rock was less than that of intact rock, and which gradually decreased with the increase of predamaged degree. The ratio of yield stage to the total strain of PD rock was obviously larger than that of intact rock. The PD rock more easily entered the dilation deformation with the predamaged degree increased.

(3) The constitutive equation of PD rock based on energy was constructed, and the damage evolution characteristics were analyzed. The damage evolution process can be divided into the initial development stage and the accelerated development stage. The PD rock was more prone to damage as the increase of the predamaged degree. Moreover, the crack propagation and failure form of rock was more complex and crushed with the increase of predamaged degree.
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