Research Article

Influence of Moisture Content on Creep Mechanical Characteristic and Mic-Fracture Behavior of Water-Bearing Coal Specimen

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Received 16 April 2022; Accepted 18 May 2022; Published 11 June 2022

Academic Editor: Yi Xue

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The most challenging aspect of constructing an underground reservoir is ensuring that the safety coal pillar has long-term stability. It is of great significance to study the creep mechanical behavior of coal pillars under water-rock interaction for the construction of underground reservoirs. Five kinds of coal specimens with different moisture contents (dry, 2.42%, 5.53%, 7.55%, and saturated) were prepared. The effect of moisture content on the creep mechanical behavior of coal specimens was studied by graded loading, and the acoustic emission signals during the creep loading of coal specimens were monitored. The results showed that with the increase in moisture content, the instantaneous strain and creep strain of coal specimens gradually increase, and the total time of the creep test, creep failure stress, and long-term strength generally decreases. The creep failure stress to peak strength and the ratio of long-term strength to peak strength were 73%~85% and 57%~65%, respectively, which are basically independent of water content. As the water content of the coal increased, the cumulative acoustic emission energy decreased, and the failure form of the coal specimen gradually shifted from tension failure ($\omega = 0\%$ and 2.42%), tension shear composite failure ($\omega = 5.53\%$) to shear failure ($\omega = 7.55\%$ and 10.08%). The research results can be used as a reference for the design and strength evaluation of coal pillars for underground reservoirs in coal mines.

1. Introduction

Coal mining in China shows a changing trend from the east to the west. China’s western region is rich in coal resources, but water resources are seriously scarce. The mining of underground coal resources will change the structure of the aquifer, and the water in the aquifer will enter the workplace through the water-conducting fracture zone, potentially resulting in flooding accidents at the working site. If mine water is discharged, water resources will be wasted and surface land salinization will be caused, seriously damaging the surface ecology [1, 2]. The idea of underground reservoir construction has become an important way to solve this problem [3]. However, it will also cause a series of new problems. For example, as the most important component of the underground reservoir, the safe coal pillar is seriously eroded by groundwater, as shown in Figure 1. Under the long-term action of overburden load, the coal pillar is prone to creep and instability, posing a major threat to the safe production of coal mines [4]. Therefore, the study of
the creep fracture behavior of water-bearing coal specimens can more accurately reveal the safety of the coal pillar fracture mechanism and provide a significant guarantee for the safe operation of underground coal reservoirs.

At present, researchers have carried out uniaxial compression tests, triaxial compression tests, and cyclic loading and unloading tests on materials such as sandstone [5–8], shale [9], and coal [10] under different water contents. Huang et al. [5] used uniaxial compression and triaxial compression tests to study the variation of peak strength of red sandstone with water content. Eeckhout and Peng [9] analyzed the influence of water content on the mechanical properties of shale. The findings revealed that the higher the water content is, the lower the elastic modulus and peak strength of shale are, and the larger the Poisson’s ratio is. Furthermore, Zhou et al. [8] studied static compression and dynamic tensile tests on dry and saturated sandstones. The internal water distribution of the tests was explored using nuclear magnetic resonance (NMR) technology. In addition, Tang et al. [10] discussed the fracture mechanism and infrared radiation characteristics of soft coal with different moisture contents. The results showed that soft coal’s compressive strength and elastic modulus with medium moisture content were the highest. However, the abovementioned research results did not involve the creep mechanical properties of water-bearing coal and rock mass. In summary, water is the main reason for reducing rock material strength [6]. The increase in water content changes the mechanical properties of rock materials, but the mechanical properties of rock materials with different lithologies are different, which mainly depends on the mineral composition of rock materials [11].

As a nondestructive monitoring method, acoustic emission monitoring technology can monitor acoustic emission signals in the loading process in real time. Through the analysis of the raw emission signals and waveforms, damage characteristics within coal and rock can be identified [12–14]. Water is an important factor that affects the acoustic emission characteristics of coal and rock in the loading process [15]. Even though researchers have conducted in-depth studies on the acoustic emission characteristics of rocks with different moisture content in the loading process [16–18], there are few reports on the acoustic emission characteristics of water-bearing coal specimens in the creep process. As a result, this research will supplement them.

This paper first introduces the preparation process of coal specimens with different moisture content and then carries out a creep test of coal specimens with different moisture content based on the results of the uniaxial compression test and monitors the acoustic emission signal in the process of creep fracture of water-bearing coal specimens. The axial deformation characteristics, failure stress characteristics, deformation rate characteristics, and long-term strength characteristics of water-bearing coal specimens were analyzed to explore the damage mechanism of micromechanical behavior of water-bearing coal specimens. The crack evolution law and cumulative acoustic emission parameter characteristics of water-bearing coal specimens were analyzed based on acoustic emission data. The research results can be used as a reference to evaluate the stability of underground reservoirs in coal mines.

2. Materials and Methods

2.1. Material Preparation. Figure 2(a) shows part of coal specimens and main test equipment. The coal specimens were taken from the Daliuta Coal Mine in Shenmu County, Shaanxi Province. According to the recommendations of the International Society for Rock Mechanics (ISRM), the coal specimens were processed into cylinders with a diameter of 50 mm and a height of 100 mm [19]. After removing the coal specimens with obvious surface cracks, the average p-wave velocity and density of the remaining coal specimens were measured. The average p-wave velocity and density of the coal specimens were 1836 m/s and 1750 kg/m$^3$. Since the p-wave velocity and density have a certain influence on the strength of coal and rock mass [20], the coal specimens with p-wave velocity and density close to the average were selected for subsequent tests. According to the XRD pattern analysis result (Figure 2(b)), the mineral composition of coal specimen and its proportion are as follows: quartz (0.4%), siderite (0.5%), calcite (2.7%), kaolinite (0.9%), and amorphous (95.6%). The average peak strength of coal specimens is 22.95 MPa, and the average elastic modulus is 1.92 GPa.

Figure 1: Structure diagram of the underground reservoir in the coal mine.
An electrohydraulic servo universal testing machine was used for loading equipment, and an acoustic emission monitoring system was used for monitoring equipment.

We strictly follow the following steps to prepare coal specimens with different moisture content:

1. Specimen selection: acoustic wave velocity was measured and weighed for the standard specimen preparation, and the coal specimen with density and wave velocity close to the average was selected.

2. Drying treatment: the screened specimens were put into the DHG9076 electric heating constant temperature drying oven. The drying temperature was 105°C, and the drying time was 24 h. After that, the specimen quality is weighed every 1 h until the two quality differences are less than 0.02 g; at that point, it is considered that the drying is completed. The specimens were cooled to room temperature in the drying box, and then, the wave velocity was measured again. The specimens with similar wave velocities were selected for subsequent tests.

3. Saturation treatment: selected 3 pieces of dry coal specimens were placed in a vacuum negative pressure suction device with added distilled water. Coal specimens were completely submerged in water, the extraction pressure was set to 100 kPa and the extraction time was set to 6 h. Coal specimens were weighed to determine their quality; the first and second differences were less than 0.02 g, indicating that the specimen had reached its saturated state.

4. Preparation of coal specimens with different moisture content: moisture content \( \omega \) is calculated according to formula (1). The variation rule of coal specimen moisture content \( \omega \) with time \( t \) obtained through the water immersion test is shown in Figure 3. It can be seen from the figure that the coal specimen moisture content \( \omega \) can be approximately divided into four stages with the increase of time: water content \( \omega \) rapid growth stage (I), stable growth stage (II), deceleration growth stage (III), and stable stage (IV). The saturated moisture content of a coal specimen \( \omega \) is about 10.02%. According to the
Table 1: Peak strengths of coal sample under different moisture contents.

<table>
<thead>
<tr>
<th>Test scenario</th>
<th>Test case</th>
<th>Strength (MPa)</th>
<th>Absolute deviation (MPa)</th>
<th>Relative deviation (%)</th>
<th>Mean value (MPa)</th>
<th>Standard deviation (MPa)</th>
<th>Coefficient of variation (%)</th>
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<td></td>
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<td></td>
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<td>NA</td>
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preparation scheme of coal specimen moisture content and the corresponding time nodes of different moisture content, the water-bearing coal specimens with a moisture content of 2.5%, 5%, 7.5%, and saturated are prepared successively. The corresponding soaking time \( t \) are 7.5 h, 19.0 h, 36.0 h, and 120 h, respectively. However, due to the difference in pore structure inside different coal specimens, the water content of coal specimens after soaking time is slightly different from the set value. The average water content of actual coal specimens is 2.42%, 5.53%, 7.55%, and 10.08%, respectively. The prepared coal specimens with different moisture content were wrapped with plastic film, sealed with a sealing bag, and put into the thermostat for use in the test.

\[
\omega = \left( \frac{m_s - m_d}{m_d} \right) \times 100\% , \tag{1}
\]

where \( \omega \) is the moisture content of the specimen, \( m_s \) is the mass of the specimen under different moisture content, and \( m_d \) is the mass of the coal specimen when it is completely dry.

### 2.2. Experimental Apparatus and Procedure

The universal testing machine and the acoustic emission acquisition system started and ended synchronously during the test. The water content of the coal specimens was 0%, 2.42%, 5.53%, 7.55%, and 10.08%, respectively, and there were 5 groups in total. Five uniaxial compression tests were carried out under each group of water content, respectively, to remove the group with the maximum peak strength and the group with the minimum peak strength, and the average value of the other three groups was taken. Table 1 shows the peak strength of coal samples under different moisture contents. The mean values of the peak strengths at each moisture content were 21.33 MPa \( (\omega = 0\%) \), 18.63 MPa \( (\omega = 2.42\%) \), 15.58 MPa \( (\omega = 5.53\%) \), 14.17 MPa \( (\omega = 7.55\%) \), and 13.50 MPa \( (\omega = 10.08\%) \), which is the basis for the subsequent creep test. The maximum coefficient of variation was 6.24\% \( (\omega = 5.53\%) \), indicating the repeatability of the test results.

Two RS-54A acoustic emission probes are symmetrically arranged 20 mm away from the end of the coal specimen and glued on the surface of the coal specimen by hot melt adhesive. The preamplifier was set to 40 dB, and the threshold value was 40 dB. The signal peak definition time, impact definition time, and impact locking time were 50 \( \mu \)s, 100 \( \mu \)s, and 500 \( \mu \)s, respectively.

According to the uniaxial compression test results, a total of 10 stress levels were set in the creep test, and the stress of the first level was 2 MPa, which was gradually increased by 2 MPa, as shown in Figure 4. The creep test was carried out by fractional loading; the creep data was processed by the Chen loading method [21], and the loading rate was 0.02 MPa/s. Due to the difference in the engineering environment, test loading equipment, and strength of coal and rock, the length of creep time of coal and rock varies from several decades to only 1 h. Therefore, the creep load retention time should be determined on a case-by-case basis. The water-bearing coal specimens studied in this paper had low strength and large porosity, which belong to the category of geological soft rock. Therefore, they also had creep characteristics in a relatively short time. In addition, the load applied by the testing machine is dynamically stable, and the long-term loading of the equipment consumes too much energy, which also means that the creep time should not be too long. In summary, the creep loading time is set at 4 h.

### 3. Results and Discussion

#### 3.1. Deformation Characteristics of Coal Specimens

The time-history curves of coal specimens creep with different moisture content are shown in Figure 5. It can be seen from Figure 5 that (1) when the stress level is low, coal specimen deformation only experiences decelerated creep and constant velocity creep; when the stress level is higher (the last stress level), the coal specimen will undergo three stages of decelerated creep, constant velocity creep, and accelerated creep. (2) The increase in water content accelerated the crack initiation and propagation process of the coal specimen, resulting in the gradual shortening of the total creep test time. For example, when the water content increases from 0% to 10.08%, the total duration of the creep test corresponding to each water content is 29.65 h, 25.12 h, 21.51 h, 20.95 h, and 16.62 h, respectively. Compared with a dry coal specimen, the total creep test times of 2.42%, 5.53%, 7.55%, and 10.08% decreased by 15.28%, 27.45%, 29.34%, and 43.95%, respectively. This is mainly because the influence of water on the creep failure of coal specimens has dual effects on time and space. In the initial loading stage, water is immersed inside the coal, resulting in a decrease in the degree of consolidation between mineral particles. With the constant improvement of the stress level, the coal specimens were gradually initiated, expanded, penetrated, and water immersed in the fractures caused secondary damage and further weakening of the coal specimens. The higher the water content, the more obvious this feature is. It can be concluded that during the long-term strength evaluation...
Figure 5: Time-history curves of creep and strain of coal specimens at different moisture contents: (a) $\omega = 0\%$, (b) $\omega = 2.42\%$, (c) $\omega = 5.53\%$, (d) $\omega = 7.55\%$, and (e) $\omega = 10.08\%$. (f) Summary of strain time-history curves under different water contents.
of the water-bearing coal pillar, the water-bearing state of the coal pillar cannot be ignored.

By further processing the creep test data, the relationship between instantaneous strain ($\varepsilon_{\text{in}}$) and creep strain ($\varepsilon_{\text{cp}}$) with water content and stress level is shown in Figure 6.

As shown in Figure 6, the instantaneous strain $\varepsilon_{\text{in}}$ increased linearly with increasing water content. For example, when the stress level was 8 MPa, the instantaneous strain corresponding to 2.42%, 5.53%, 7.55%, and 10.08% increased by 22.29%, 51.61%, 71.75%, and 106.19%, respectively, compared with dry coal specimens. The creep strain ($\varepsilon_{\text{cp}}$) increases nonlinearly with increasing water content. For example, when the stress level was 10 MPa, the moisture content $\omega$ increased from 0% to 2.42%, and the cumulative creep strain increment was only 0.0205%. The moisture content $\omega$ increased from 7.55% to 10.08%, and the cumulative creep strain increment was 0.2264%.

As shown in Figure 7, after sorting out the creep and instantaneous strains at the time of coal specimen failure, the variation characteristics of the instantaneous strains and creep at the time of creep failure were obtained with respect to water content. It can be seen from Figure 7 that the instantaneous strain and creep strain generated when the coal specimen was destroyed increased as the water content increased. The water content increased from 0% to 10.08%, while the instantaneous strain increased from 1.4875% to 2.1262%, with an increase of 42.94%. The creep strain increased to 160.37%, from 0.1605% to 0.4391%. This is mainly due to the increase in water content, which results in the softening and even dissolving of soluble mineral particles in the coal specimen, the decrease in cementation between particles, the weakening of the deformation resistance ability of the coal specimen, and the increase in deformation.

3.2 Characteristics of Failure Stress. Figure 8 shows the variation law of the creep failure stress of the coal specimens and its ratio to the peak strength with the water content. The water content significantly affects the stress level of creep failure of the coal specimens. The corresponding creep failure stress levels were 16 MPa, 14 MPa, 12 MPa, 12 MPa, and 10 MPa when the water content was 0%, 2.42%, 5.53%, 7.55%, and 10.08%, respectively. The creep failure stress showed an approximate linear decreasing trend with increased water content. In addition, the ratio of creep failure stress to peak strength is between 73% and 85%, which is basically independent of water content.
3.3. Deformation Rate Characteristics. The relationship curve between creep rate and time under different moisture content was obtained by calculating the slope of creep time history curves with different moisture content, as shown in Figure 9.

As can be seen from Figure 9, for any moisture content, the deformation rate of coal specimens at low stress levels mainly presents two stages of decrease and constant. At the last stress level, the deformation rate mainly presents three stages of decrease, constant, and increase, as follows:

1. When the stress level is low, the deformation rate of the coal specimen is relatively large at the initial stage of creep loading, and then, its deformation rate decreases rapidly and tends to be stable. For example, when the water content is 5.53% and the stress level is 2 MPa, the initial deformation rate is $2.3 \times 10^{-4} \text{mm/h}$, and after the creep time lasts for 4 h, the deformation rate decreases to $0.3 \times 10^{-4} \text{mm/h}$.

2. As the stress level increases, the deformation rate characteristics of coal specimens basically remain constant. However, the difference is that the initial and steady deformation rates of coal specimens increase significantly. For example, when the water content is 5.53% and the stress level is 10 MPa, the initial deformation rate is $61.3 \times 10^{-4} \text{mm/h}$, and the steady-state deformation rate is $0.9 \times 10^{-4} \text{mm/h}$, which are 26.65 times and 3 times of the first stress level, respectively.

3. It is revealed, by analyzing the relationship curve between the last stage deformation rate and time at each water content, that the deformation rate initially decreased rapidly, then tended to be stable, and ultimately rapidly increased. The steady-state stage was shorter than the deformation rate at each stress level before creep failure. For example, when the water content was 5.53% and the stress level reached 12 MPa, the initial deformation rate was $0.85 \times 10^{-2} \text{mm/h}$, and after only 1.46 h, the deformation rate rapidly increased to $4.22 \times 10^{-2} \text{mm/h}$.

3.4. Long-Term Strength Characteristics. The long-term strength of rock refers to the maximum stress that can remain stable under the action of the long-term stress field or deformation field [22]. In geotechnical engineering, the long-term strength of coal and rock mass is a key mechanical parameter for stability analysis and life prediction [23–26]. Currently, researchers mainly use indirect methods to determine the long-term strength of coal and rock mass, and the most commonly used methods include the isochronous stress-strain curve method and the steady-state creep rate methods. Most researchers define the inflection point of the isochronous stress-strain curve as the long-term strength of rock [24–26]. However, since the curve’s inflection point is not obvious, the range of long-term strength of coal and rock can only be provided generally. In addition, several researchers considered two straight-line intersection points as the long-term strength of rock for the steady-state creep rate-stress curves before and after the inflection point of linear fitting with data [27, 28]. In this paper, the first isochronous stress-strain curve method was used to determine the scope of the long-term strength of coal specimens, and then, the method of steady-state creep rate was used to determine the long-term strength of coal specimens under specific values.

Isochronous stress-strain curves of coal specimens with different moisture content were drawn using the method described by Tan [29]; the selected time nodes were 0.5 h, 1.0 h, 1.5 h, 2.0 h, 2.5 h, 3.0 h, and 3.5 h. As illustrated in Figure 10, stress increased nonlinearly as the strain increased, and the curve gradually deviated toward the strain axis. It should be noted that due to the short test time and limited test data, the inflection point of the isochronous stress-strain curve cannot be accurately obtained; however, the stress range of the inflection point can be obtained according to the characteristics of the curve. The water content was 0%, 2.42%, 5.53%, 7.55%, and 10.08%, and the stress range of the inflection point was 12 MPa~14 MPa, 10 MPa~12 MPa, 8 MPa~10 MPa, 8 MPa~10 MPa, and 6 MPa~8 MPa, respectively. In conclusion, when using the isochronous stress-strain curve method to obtain the long-term strength of coal specimens, the creep time should be increased as much as feasible and the range of stress loading grade should be reduced.

The long-term strength of coal specimens with different moisture contents as determined using the steady-state creep rate method is shown in Figure 11. The black dotted line in Figure 11 is the fitting line of all steady-state creep rate points; the two red dotted lines represent the fitting lines of the steady-state creep rate points before and after the inflection point. The long-term strength is the horizontal coordinate corresponding to the intersection of the two red
Figure 9: Deformation rate characteristics of coal specimens under different moisture contents: (a) $\omega = 0\%$, (b) $\omega = 2.42\%$, (c) $\omega = 5.53\%$, (d) $\omega = 7.55\%$, and (e) $\omega = 10.08\%$. 
Figure 10: Isochronous stress-strain curves of coal specimens under different water contents: (a) $\omega = 0\%$, (b) $\omega = 2.42\%$, (c) $\omega = 5.53\%$, (d) $\omega = 7.55\%$, and (e) $\omega = 10.08\%$. 
dotted lines. Figure 11 shows that the relationship curve between steady-state creep rate and stress increases exponentially, with $R^2 \geq 0.91$ in the fitting curve equation under each water content.

At the moisture contents of 0%, 2.42%, 5.53%, 7.55%, and 10.08%, the long-term strength values of coal specimens under different moisture contents were 13.46 MPa, 11.58 MPa, 9.11 MPa, 9.19 MPa, and 7.75 MPa, respectively. Under each moisture content, the long-term strength of the coal specimen decreases by 13.97%, 32.32%, 31.72%, and 42.42%, respectively.

It should be noted that the long-term strength of a coal specimen with 7.55% moisture content was slightly larger than that with 5.53% moisture content, but it did not affect the accuracy of the overall conclusion. The long-term strength under different moisture content accounted for

Figure 11: Relationship between steady creep rate and stress level of coal specimens under different moisture contents: (a) $\omega = 0\%$, (b) $\omega = 2.42\%$, (c) $\omega = 5.53\%$, (d) $\omega = 7.55\%$, and (e) $\omega = 10.08\%$.
about 63%, 62%, 58%, 65%, and 57% of the peak strength obtained by the uniaxial compression test. The results show that the ratio of long-term strength to peak strength was basically not affected by water content; therefore, the long-term strength can be predicted by the peak strength of coal specimens. Because the long-term strength determined by the steady-state creep rate method is within the range of the long-term strength determined by the isochronic stress-strain curve, the long-term strength determined by this method is reasonable and trustworthy.

4. Microscopic Mechanical Behavior of Water-Bearing Coal Specimens

Scholars have done a lot of research on the micromechanical behavior and damage characteristics of materials [30–34]. Based on the above test results, it can be observed that the failure stress and long-term strength of the coal specimens basically decrease as the water content increases (except for the 7.55% water content). However, the strains (instantaneous strain and creep strain) at the time of failure of the coal specimens increase as the water content increases. The reason for this result can be explained in Figure 12. Natural coal specimens are generally composed of three parts: (1) matrix, (2) defects such as pores and cracks, and (3) free water and bound water (Figure 12(a)). After the coal specimen is dried, there are only (1) and (2) (Figure 12(b)). After the coal specimen is soaked, the bound water attaches to the surface of soluble mineral particles, leading to the spalling or even dissolution of mineral particles, the increase of cracks and pore volume inside the coal specimen, and the initial damage of the coal specimen (Figure 12(c)). Coal specimen inner pore and fractures contain a large amount of free water, which is not affected by timely outer load discharge. The fractures and pore tips will produce a larger pore water pressure than the pore water pressure in the form of tensile stress distribution in fractures and pore tips. The greater the moisture content and the tensile stress, the greater the porosity and crack extended range, the greater the coal specimen, and the more damage occurred under low load (Figure 12(d)). In addition, the increase in water (free water and bound water) leads to increased pore and fissure volume in the coal specimen, which leads to an increase in deformation in the loading process of the coal specimen.

In conclusion, binding water leads to initial damage of coal specimens, while free water leads to superposition damage of coal specimens in the loading process. The combined action of the two is the main reason for the reduction in the strength and increased deformation of coal specimens. In fact, after the coal specimen is soaked, the bound water
and free water will dissolve and erode the mineral particles and the cementation between particles, leading to the spallation of mineral particles and the formation of larger water-conducting spaces, and the expansion of water-conducting spaces further promotes the development of pores and fractures. Therefore, the microscopic mechanism of water weakening coal specimens can be summarized as follows: the cementation between the water-weakened mineral particles, the continuous expansion of the water-conducting space, and strengthening the expansion range of microcracks.

Figure 13: Tensile shear crack evolution law and crack proportion of coal specimens under different moisture contents: (a) $\omega = 0\%$, (b) $\omega = 2.42\%$, (c) $\omega = 5.33\%$, (d) $\omega = 7.55\%$, and (e) $\omega = 10.08\%$. (f) Proportion of cracks.
5. Evolution Characteristics of Microcracks in Water-Bearing Coal Specimens

5.1. Evolution of Tensile and Shear Cracks in Coal Specimens under Different Water Contents. In the study by Shahidan et al. [35], the ratio of average frequency (AF) to rising angle (RA) was used to characterize the cracking mode. RA was obtained by rising time/amplitude and AF by ringing count/duration. This study also uses the method to analyze the cracking modes under creep failure of coal specimens under different moisture content. The obtained AF and RA values are normalized, and the diagonal line represents RA/AF = 1; when RA < AF, the tensile crack dominates the failure process, and when RA > AF, shear cracks dominate the failure process.

Figure 13 shows the AF-RA relationship curve and the macroscopic fracture diagram of coal specimen creep failure with water content change. As demonstrated in Figure 13, the total number of cracks gradually decreases with increased water content; however, the proportion of tensile and shear cracks shows a significant water content effect. For example, when the water content is ω = 0% and 2.42%, the proportion of tensile cracks is 72.5% and 62.4%, respectively, both of which are greater than 50%, and the failure of the coal specimen is mainly tensile. When the water content is ω = 5.53%, the proportions of tensile cracks and shear

Figure 14: Variation rule of AE energy and accumulated AE energy under different water contents: (a) ω = 0%, (b) ω = 2.42%, (c) ω = 5.53%, (d) ω = 7.55%, and (e) ω = 10.08%. (f) Cumulative acoustic emission curve with water content.
cracks are 51.2% and 48.8%, respectively, both located near 50%, and the coal specimens show a combination of tensile and shear failure. When water content \( \omega = 7.55\% \) and 10.08%, shear cracks account for 64.2% and 67.5%, respectively, both of which are more than 50%, and the coal specimens show shear failure. To sum up, the higher the moisture content of coal specimens, the more obvious the shear failure trend. The macroscopic fracture mode of coal specimens is primarily consistent with the evolution characteristics of tensile and shear cracks.

As the shear failure trend of coal specimens with higher water content becomes more apparent, the following explanation is given: the macroscopic fracture characteristics of coal specimens are closely related to the frictional resistance between mineral particles or microcracks [36, 37]. Under the action of an external load, the primary cracks in the coal specimen gradually close, but the existence of friction resistance will hinder the relative dislocation among particles. When the coal specimen contains water, the water plays the role of lubrication and reduces friction resistance. The higher the water content of the coal specimen, the lower the friction resistance, and the less the constraint of mineral particles or microcracks movement, which results in the tendency of coal specimen shear failure [38–40]. In addition, under the action of external load, the water in the pores and fissures will cause pore pressure, and the tensile stress concentration area will appear at the pores and fissures tips, which will lead to the tensile failure of coal specimens.

To sum up, the macroscopic fracture mode of coal specimens is closely related to the nature of coal specimens. In a water-bearing state, whether the coal specimen is mainly shear failure dominated by water lubrication or tensile failure dominated by pore pressure should be judged according to the actual failure form of the coal specimen. In this paper, coal specimens with low water content are mainly subjected to tensile failure; the effect of pore pressure is greater than that of water lubrication. Under high water content, shear failure is the main failure; water lubrication is greater than pore pressure.

5.2. AE Characteristics of Coal Specimens under Different Moisture Contents. Acoustic emission (AE) energy and cumulative acoustic emission energy reflect the energy released during the formation and expansion of cracks in coal specimens and the accumulation degree of internal damage [41]. Figures 14(a)–14(e) show the variation curves of strain, acoustic emission energy, and cumulative acoustic emission of coal specimens with varying water content over time. Figure 14(f) shows the variation curves of cumulative acoustic emission energy with water content.

The AE energy generally exhibits a gradual increase with increasing stress levels at any given water content. The water content \( \omega = 0\% \), as an example, the acoustic emission energy was low when the stress level increased from 2 MPa to 8 MPa. Coal specimens of load value did not reach the required stress level for crack initiation. The coal specimen does not have an obvious burst damage phenomenon, but since the coal specimen is a homogeneous material, a small number of AE events still appear. At this point, the cumulative AE energy curve slope is low, and this stage can be called the acoustic emission quiet period. When the stress level increases from 8 MPa to 12 MPa, the AE energy increases compared with the previous stage. However, the increase rate is small, and the new cracks gradually initiate and expand slowly, and the slope of the cumulative AE energy curve increases. This stage can be called the low-amplitude growth period of AE. When the stress level is greater than 12 MPa, the AE energy increases rapidly, the cumulative AE curve slope increases rapidly, and a large number of microcracks initiate, coalesce, and expand rapidly. This stage can be called the AE high-amplitude growth stage. In conclusion, the AE energy characteristics of coal specimens well reflect the damage evolution process of coal specimens. Therefore, it is of great significance to predict the creep deformation characteristics of coal specimens by using the AE signals during the loading process of coal specimens to ensure the safety and long-term stability of coal pillars in underground reservoirs.

In addition, during the loading process of each stress level, the AE energy increases, but in the loading stage, the AE energy gradually decreases and tends to be stable. The cumulative AE energy decreases nonlinearly with the increase of water content. This is mainly because the coal specimen is mainly a tensile splitting failure under the low water content. In the creep test, the crack needs a larger load to overcome the cohesion effect between mineral particles to achieve the purpose of crack initiation and expansion. Therefore, the creep failure requires higher energy. At high water content, the cohesion of the coal specimen decreases, and the crack initiation and propagation can be realized at a lower stress level, using less energy.

6. Conclusion

In order to study the long-term stability of coal pillars under water-rock interaction, taking the safety coal pillar of the underground reservoir as the research objective, the coal specimens with a water content of 0%, 2.42%, 5.53%, 7.55%, and 10.08% were prepared. The uniaxial compression graded creep test was carried out, and the acoustic emission signal during the loading process of the water-bearing coal specimen was monitored. The main conclusions are as follows:

1. Peak strength, creep failure stress, and long-term strength decrease with the increase of water content, but the ratio of creep failure stress and long-term strength to peak strength basically does not change with water content. The peak strength of the coal specimen can predict the creep failure stress and long-term strength

2. Under low stress levels, coal specimen deformation only experiences instantaneous deformation, deceleration, and constant velocity creep. The deformation of coal specimens goes through four stages: instantaneous deformation, decelerated creep, constant velocity creep, and accelerated creep. With
the increase of water content, the total length of the coal specimen creep test decreases gradually, and the instantaneous strain and creep strain produced when the coal specimen is destroyed increase gradually. With increased stress levels, coal specimens' initial and steady deformation rates increase significantly.

(3) Binding water leads to initial damage of the coal specimen, while free water leads to superposition damage of the coal specimen in the loading process. The major cause of the decrease in coal specimen strength and the increase in deformation is the combined effect of the two. The microscopic mechanism of the water-weakened coal specimens can be summarized as follows: water weakens the cementation between mineral particles, enlarges the water-conduction space, and intensifies the expansion range of microcracks.

(4) With the increase of water content, the failure mode of coal specimens showed a trend of transformation from tensile failure ($\omega \leq 2.42\%$), tension shear composite failure ($\omega = 5.53\%$) to shear failure ($\omega \geq 7.55\%$). The acoustic emission energy during the creep loading process of the water-bearing coal specimen has gone through three stages: the quiet period, the low-amplitude growth period, and the high-amplitude growth period. The cumulative acoustic emission energy decreases nonlinearly with the increase of water content.

**Data Availability**

Most of the data generated or analyzed during this study are included in this manuscript and all of the data are available from the corresponding author on reasonable request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This research was funded by the National Natural Science Foundation of China (52104100), China Postdoctoral Science Foundation (2021M703503), and open-ended fund of Hubei Key Laboratory for Efficient Utilization and Agglomeration of Metallurgic Mineral Resources (2020zy002).

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