



ORIGINAL PAPER

TIME EFFECT OF DAMAGE AND DETERIORATION OF COAL-ROCK MECHANICAL PROPERTIES UNDER WATER-ROCK INTERACTION**Guangbo CHEN^{1, 2, 3, 4, 5)}*, Wei TANG¹⁾, Tan LI¹⁾*, Eryu WANG¹⁾,
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Received 22 July 2025

Accepted 25 November 2025

Available online 11 December 2025

Keywords:

Water-rock interaction

Mechanical properties

Deterioration effect

Damage model

Deterioration mechanism

Multi-scale

ABSTRACT

In geotechnical engineering and underground mining engineering, coal and rock are often in the water-immersed environment, and the mechanical properties of coal and rock under the water-rock interaction show different degrees of deterioration. For this reason, coal and sandstone samples were prepared under six water immersion times of 10 d, 20 d, 30 d, 40 d, 50 d and 60 d, and uniaxial compression tests were carried out, and the results showed that: 1) With the increase of immersion time, the water content of coal and sandstone samples showed different degrees of increase, and finally gradually stabilized. The increase in water content of coal samples is more obvious than that of sandstone samples. 2) The compressive strength of coal and sandstone under water-rock interaction has obvious deterioration effect, and the deterioration effect of coal samples is more obvious than that of sandstone samples. The compressive strength of coal sample decreased by 50.55%, and the compressive strength of sandstone samples decreased by 10.92 % after being immersed in water for 60 d. 3) With the increase of water immersion time, the bursting energy index of coal and sandstone samples decreased to varying degrees, and the bursting liability was gradually weakened. 4) The water immersion time and coal rock material have a great influence on the failure characteristics of the sample, mainly in five aspects of crack length, crack initiation position, the angle between the crack and the axial direction of the sample, the number of cracks, and the failure type. 5) The damage model based on immersion time was constructed by using the damage theory. With the increase of immersion time, the damage degree of the sample increased gradually. 6) The calculation formula of void ratio is derived. The larger the pseudo void ratio is, the smaller the compressive strength will be. 7) The deterioration effect of the mechanical properties of coal rock under the water-rock interaction is the result of the gradual accumulation of the internal damage of coal and rock. Under the water-rock interaction, the physical and chemical effects inside the coal rock sample cause microscopic damage. 8) The multi-scale system of coal-rock structure under the water-rock interaction is constructed, and the water-rock interaction is analyzed from micro-scale, meso-scale and macro-scale. The research results can provide reference for the predicting the mechanical properties and studying the stability of rock mass in water-rich environments.

1. INTRODUCTION

The mechanical properties of coal and rock have always been a focus of academic and engineering research. The mechanical properties of coal and rock are influenced by the environment (Lai et al., 2024; Liu, 2009; Huang et al., 2020; Yao et al., 2021; Si et al., 2024). In recent years, with the progress and development of society, a large number of water conservancy and hydropower projects represented by the Three Gorges have been completed and put into use (Deng et al., 2017; Chen et al., 2022; Chen et al., 2024; Chen et al., 2025). The reservoir bank slopes of the Three Gorges and other reservoirs are in the water-immersed environment for a long time, which leads to the weakening of the mechanical properties of the slope rock mass and seriously affects the stability of the reservoir bank slopes. In addition, with the deepening of mining depth and the increase of mining

intensity, large water mines and water-rich mining are extremely common. In this case, coal and rock are in the water-immersed environment, and mechanical properties are gradually deteriorated, which may easily lead to geological disasters such as roadway collapse and rock burst, which will affect the production safety of coal mine and the life safety of operators (Yang et al., 2010; Song et al., 2023). Additionally, in order to alleviate the shortage of water resources in the central and western regions, many underground reservoirs have been established and put into operation by using goaf of coal mines. The coal and rock dams of the reservoirs have been in the water environment for a long time, and the reservoir dam mass have been gradually destroyed, which has seriously affected the stability of the reservoir dams (Gu, 2015). Many geotechnical and underground mining engineering studies have shown that the

mechanical properties of coal and rock deteriorate to varying degrees under the action of immersion. Therefore, the mechanical properties of coal and rock under water-rock interactions have become the focus of many experts and scholars.

Many experts have conducted extensive research on water-rock interactions, mainly focusing on rock and coal. Deng et al. (2021) and Chai et al. (2023) studied the wave velocity, static and dynamic compressive strength and energy dissipation characteristics of jointed rock samples under the action of dry-wet cycle and continuous immersion. David et al. (2024), Rappich et al. (2024) and Razi et al. (2024) studied the water rock interaction of rocks in different natural environments and summarized the storage patterns of trace elements in rocks after water rock interaction. Shao et al. (2021) studied the influence of different water-bearing states on rock creep behavior, and analyzed the change and relationship between the main creep parameters and acoustic emission events in the creep process. Li et al. (2022) constructed mudstone catastrophe prevention and control technology system based on multi-scale analysis. Jin et al. (2017) analyzed the stress-strain relationship of rock triaxial compression under the different soaking time, and studied the variation law of mechanical parameters of shale. Newman et al. (2023) elucidated the mechanism of water rock interaction and its significance for the restoration of flooded mines. Huang et al. (2020) studied the evolution law of mechanical parameters and microscopic parameters of argillaceous slate and established the softening model of argillaceous slate under the water-rock interaction. Xiao et al. (2020) studied the creep characteristics of red mudstone under different water pressures. Wang et al. (2020) studied the weakening characteristics and weakening mechanism of the main mechanical parameters of metamorphic sandstone under the action of circulating water and rock. Wang et al. (2018) studied the effect and mechanism of water content on the splitting tensile strength of sandstone. Liu et al. (2022) studied the evolution process of microstructure of soft rock with different immersion time, and established the evolution model of water-rock interface in the softening process of soft rock. Dou et al. (2021) studied the mechanical behavior of granite cracks under different immersion time. Zhang et al. (2022) studied the deterioration characteristics of sandstone in the Qingyang North Grottoes and the migration law of surface mineral composition and elements. Guo et al. (2021) studied the strength attenuation mechanism of glauberite salt rock under different water-rock interaction time. Wu et al. (2020) studied the strength damage and acoustic emission characteristics of fractured sandstone under the influence of repeated immersion. Igor et al. (2024) studied the water storage capacity of rocks after water rock interaction. Many experts have conducted extensive research on coal (rock). Zhang et al. (2018) explored the influence of three factors of immersion time, gradation and axial compression displacement

on the fractal characteristics of particle size distribution and compaction characteristics of bearing broken coal samples. Jiang et al. (2022) studied the comprehensive influences of bedding and water immersion on the mechanical properties of coal. Lu et al. (2018; 2019) analyzed the composition of coal and studied the meso-structure evolution characteristics of coal under different immersion time. Song et al. (2020) studied the gas adsorption and desorption characteristics and pore structure distribution characteristics of air-dried coal under different immersion time. Yang et al. (2019) investigated the effects of different wetting drying cycles on the mechanical properties and microstructure of rock mechanics. Qiao et al. (2019) simulated the impact of the dry wet cycle process in the reservoir area on the long-term stability of the reservoir bank slope. In addition, Chen et al. (Chen et al., 2021; Chen et al., 2023a; Chen et al., 2023b) also carried out uniaxial compression tests on three types of coal-rock combined bodies under different immersion times, studied the evolution law of mechanical properties and acoustic emission damage characteristics of coal-rock combined bodies under water-rock interaction, and analyzed the deterioration mechanism of coal-rock combined bodies under the water-rock interaction.

It is well known that the mechanical properties of coal and rock mass have certain deterioration effect under the water-rock interactions. However, the deterioration effects of the coal and rock mass are different under the same water-rock interaction conditions. At present, there are few studies on the difference in mechanical property deterioration between coal and rock under the water-rock interactions.

Accordingly, water-rock interaction tests were conducted on coal and sandstone specimens under six different water immersion durations to investigate the deterioration effects of water content, compressive strength, and impact characteristics. Additionally, the crack evolution features of coal and sandstone were compared and analyzed; a damage model was established based on acoustic emission to examine the damage characteristics of the specimens; the damage of specimens under water-rock interaction was analyzed from the micro-scale; and a multi-scale deterioration system for coal-rock structures under water-rock interaction was constructed to analyze the water-rock interaction from the micro-scale, meso-scale, and macro-scale. The research results provide references for predicting the mechanical properties and studying the stability of engineering rock masses in water-rich environments.

2. TEST SCHEME

Samples were collected from a coal mine in the Shandong Energy Group. Complete and uniform large rock blocks were selected for the field. The selected rock samples were sealed with plastic wrap and stored in wooden boxes. The foam is placed at the bottom and around to reduce the damage to the rock during



Fig. 1 Sample processing equipment. (a) coring machine, (b) cutting machine, (c) grinding machine.

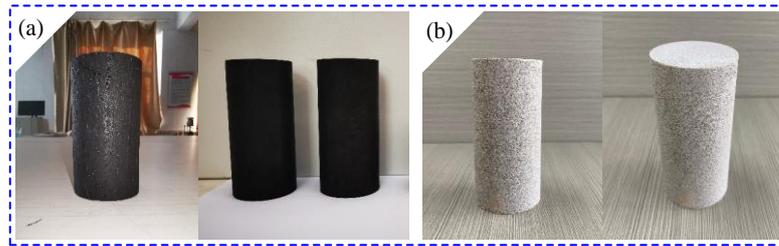


Fig. 2 Coal and sandstone samples. (a) coal, (b) sandstone.

transportation, and then transported to the laboratory for processing. According to the *Code for rock tests in water and hydropower projects (SL264-2001)*, the sample sizes are selected as $\phi 50 \times 100$ mm cylindrical standard specimen. Sample processing was carried out according to national standard *Methods for determining the physical and mechanical properties of coal and rock*. The sample preparation process minimizes disturbance to the samples as much as possible, and the coring speed should not be too fast. It is then processed into a standard sample through cutting, grinding and other processes. The coring, cutting and grinding machines used for specimen processing are shown in Figure 1. After the processing of the sample is completed, remove the samples with obvious cracks on the surface, as well as those with unsatisfactory size and flatness. Qualified typical samples were prepared, as shown in Figure 2. For the purpose of guaranteeing the experiment's scientific validity and reliability, three identical specimens were fabricated per test condition, with three parallel tests performed accordingly. The final experimental data were determined by calculating the average of the results obtained from these parallel tests.

The test processes were as follows:

1. First of all, all coal and rock samples were dried, the samples were placed in a $105\text{ }^{\circ}\text{C}$ oven to dry for 24 h, all moisture was removed from the samples, and the water content of the samples was considered 0. A uniaxial compression test was performed on the dried samples to obtain mechanical parameters, such as the compressive strength.
2. The dried coal and rock samples were immersed for 10, 20, 30, 40, 50, and 60 days for a total of

six groups. After the immersion was completed, the excess water on the surface of the sample was wiped off with a wet wipe, and the test was immediately performed. The samples are numbered according to the following rules: M represents coal and Y represents sandstone, for example, M-30-2 represents the second coal sample immersed in water for 30 days.

3. The TAW-2000kN rock testing machine (Fig. 3) was used to carry out uniaxial compression tests on coal and rock samples. Displacement loading was selected as the loading method, and the displacement loading rate was 0.002 mm/s . Static loading has a minimal effect on the mechanical properties of the specimens. In static loading, the strain rate of the specimen ranges from $10^{-5}/\text{s}$ to $10^{-3}/\text{s}$, and with the specimen height being 100 mm, the loading rate ranges from 0.001 mm/s to 0.1 mm/s . 0.002 mm/s belongs to the static loading category, and the influence of this loading rate on the mechanical properties is negligible.
4. Concurrently, acoustic emission (AE) tests were conducted. The SAEU2S multi-channel acoustic emission monitoring system was employed to monitor AE activities during the specimen failure process, with the following test parameters: a data acquisition frequency of 1000 kHz, a sampling length of 2048 points, a time interval of $2000\text{ }\mu\text{s}$, a waveform threshold of 40 dB, and a preamplifier gain of 40 dB. Eight sensor probes were uniformly arranged on the surface of each specimen, and petroleum jelly was applied between the probes and the specimen to ensure tight contact between the probes and the coal-rock material. Prior to the formal test, a signature pen

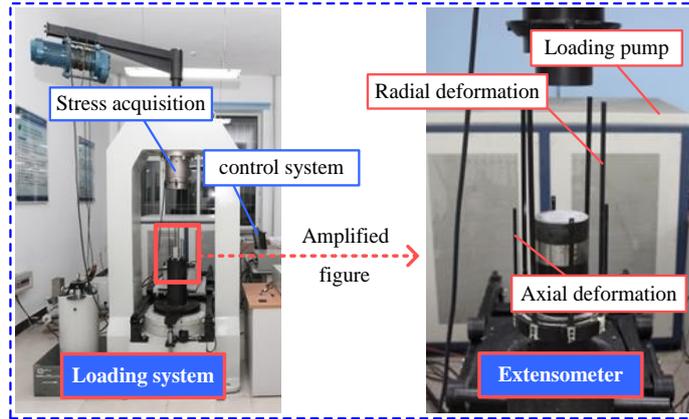


Fig. 3 The TAW-2000 kN rock testing machine.

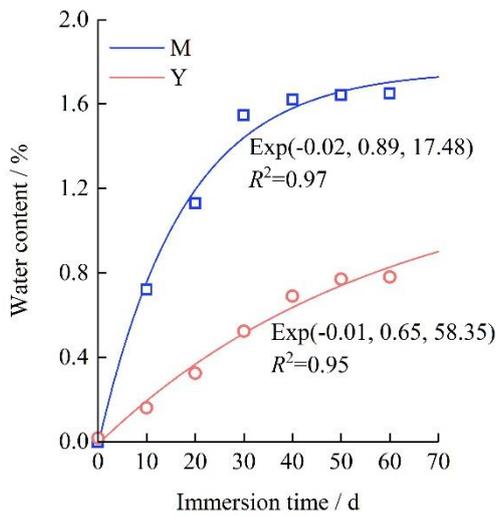


Fig. 4 Relationship between water content and immersion time of coal and rock samples.

was used to tap the specimen to simulate an AE signal source; the output data of each probe was inspected to confirm their normal operation before initiating the test.

3. ANALYSIS OF DIFFERENCES IN DETERIORATION OF COAL AND ROCK MECHANICAL PROPERTIES

3.1. ANALYSIS OF DIFFERENCES IN COAL AND ROCK MOISTURE CONTENT

After drying, samples were weighed and recorded as m_0 . After the samples were immersed in water, excess water on the surface of the samples was wiped off with a wet wipe, and the samples were weighed and recorded as m_i . The moisture contents ω_M (moisture content of coal samples) and ω_Y (moisture content of rock samples) of the samples were calculated according to the Equation (1), and Figure 4 was drawn according to the data.

$$\omega = \frac{m_i - m_0}{m_0} \times 100\% \quad (1)$$

It can be seen from Figure 4 that with the increase of immersion time, the moisture content of coal and rock samples increases to varying degrees. The moisture content of coal samples increases obviously. At the beginning of immersing, the moisture content of coal samples increases greatly, and the slope of the fitting curve is large. With the increase of immersion time, the slope of the curve gradually decreases, and the moisture content increases slowly. After immersing for 40 days, the moisture content of the coal samples is basically not increasing, and it is stable at about 1.65%. For sandstone samples, the moisture content increases slowly in a nearly straight line during the immersion period. After 50 days of immersion, the growth of moisture content starts to slow down, and the slope of the curve gradually became smaller. After immersing for 60 days, the moisture content of sandstone samples is 0.78%. On the whole, the moisture content of coal samples and sandstone samples increases with the increase of immersion time, and finally gradually stabilizes at a certain value.

3.2. ANALYSIS OF DIFFERENCES IN COMPRESSIVE STRENGTH OF COAL AND ROCK UNDER WATER-ROCK INTERACTION

Figure 5 shows the average compressive strength deterioration curve of coal and rock under different immersion times. It can be seen from Figure 5 that the compressive strength of the coal and rock shows an obvious deterioration effect under the action of water-rock. With an increase in the immersion time, the compressive strength decreases gradually. The compressive strength of coal samples respectively immersed in water for 0~60 days was 22.55 MPa, 16.95 MPa, 12.69 MPa, 11.93 MPa, 11.40 MPa, 11.21 MPa and 11.15 MPa. The compressive strength of the coal samples gradually decreased under the

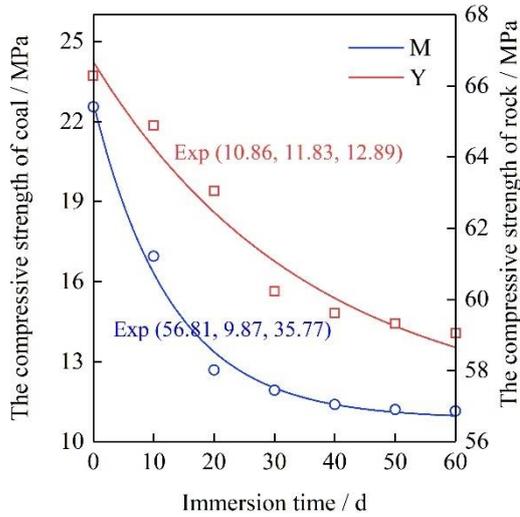


Fig. 5 Relationship between compressive strength and immersion time of coal and rock samples.

water-rock interaction. After 60 days of immersing, the compressive strength of coal samples decreases from 22.55 MPa to 11.15 MPa, which decreases by 11.40 MPa, which is 50.53 % of the initial compressive strength. The compressive strength of sandstone samples respectively immersed for 0~60 days was 66.29 MPa, 64.89 MPa, 63.04 MPa, 60.23 MPa, 59.61 MPa, 59.31 MPa and 59.05 MPa. After 60 days of immersing, the compressive strength of sandstone samples decreased from 66.29 MPa to 59.05 MPa, which decreased by 7.24 MPa, which was 10.93 % of the initial compressive strength. From this point of view, under the water-rock interaction, the compressive strength of the coal samples decreased more than that of the rock samples, and the deterioration effect was more obvious than that of the sandstone samples. In addition, it was found that the deterioration effect of the compressive strength of coal and rock is non-uniform, and the deterioration effect is different for different immersion periods.

The total decreasing range D' is defined as the decrease in compressive strength of the samples under water-rock interaction compared with that before immersion, and the total deterioration degree d' is defined as the decrease in compressive strength of the sample under water-rock interaction compared with that before immersion, which are expressed by the following Equations:

$$D' = \sigma_0 - \sigma_n \quad (2)$$

$$d' = \frac{(\sigma_0 - \sigma_n)}{\sigma_0} \times 100 \% \quad (3)$$

where,

σ_0 - Compressive strength of the samples before immersion in water, MPa;

σ_n - Compressive strength of the samples after immersion in water, MPa.

Stage reduction D is defined as the reduction in the compressive strength of the samples at a certain stage of immersion under the water-rock interaction, and stage deterioration d is defined as the reduction in the compressive strength of the samples under the water-rock interaction at a certain stage of immersion, which are expressed by the following Equations:

$$D = \sigma_n - \sigma_{n+1} \quad (4)$$

$$d = \frac{(\sigma_n - \sigma_{n+1})}{\sigma_n} \times 100 \% \quad (5)$$

where,

σ_n - Compressive strength of the samples before a certain immersion stage, MPa;

σ_{n+1} - Compressive strength of the samples after a certain immersion stage, MPa.

To study the non-uniformity of the deterioration effect of compressive strength of coal and rock, the deterioration of compressive strength of coal and rock in different immersion periods is drawn according to the data, as shown in Figures 6 and 7. The compressive strength of coal samples decreased by 5.60 MPa, and the stage deterioration degree was 24.83 %, and the compressive strength of sandstone samples decreased by 1.40 MPa, and the stage deterioration degree was 2.11 % after immersing for 0~10 days. The compressive strength of coal samples decreases by 4.26 MPa, and the stage deterioration degree is 25.16%, and the compressive strength of sandstone samples decreased by 1.85 MPa, and the stage deterioration degree was 2.85 % after immersing for 10~20 days. From this point of view, the deterioration effect of the compressive strength of coal samples is more obvious than that of sandstone samples during 0~20 days immersion in water. During this period, the compressive strength of coal samples decreased by 43.74 %, whereas that of the sandstone samples decreased by 4.90%. After immersion for 20~30 days, the compressive strength stage declines curve and the stage deterioration curve of coal samples show a steep decline trend, while the compressive strength stage declines curve and the stage deterioration curve of sandstone samples show an upward trend. In this stage, the compressive strength of coal samples decreased by 0.76 MPa, and the stage deterioration degree is 5.98 %. The compressive strength of sandstone samples decreased by 2.81 MPa, and the stage deterioration degree is 4.46 %. It can be seen that the deterioration effects of coal and rock samples at various stages are different, which also reflects that the deterioration rate of coal and rock compressive strength are different. The degradation rates of the coal samples were higher than those of the sandstone samples. In the immersion stage of 20~30 days, the deterioration effect of sandstone samples reaches the maximum, while the deterioration effect of coal samples has been weakened. Subsequently, with the increase in immersion time, the deterioration effect of the coal and rock samples gradually weakened. The

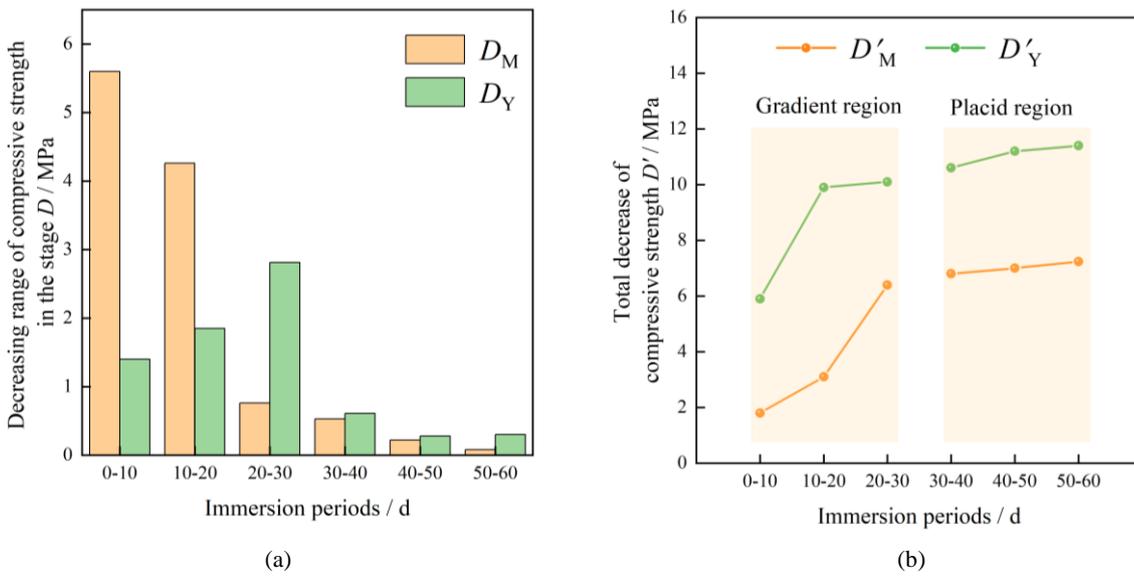


Fig. 6 Decrease of compressive strength of coal and rock samples in different immersion periods.
 (a) Decreasing range of compressive strength in the stage in different immersion periods
 (b) Total decrease of compressive strength in different immersion periods

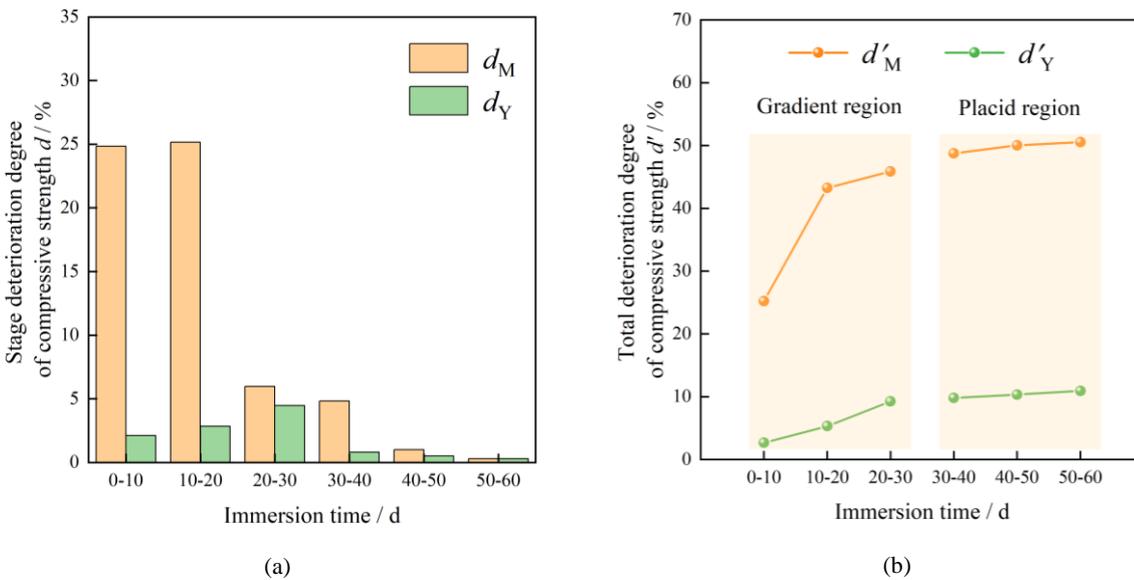


Fig. 7 Deterioration degree of compressive strength of coal and rock samples in different immersion periods.
 (a) Stage deterioration degree of compressive strength in different immersion periods
 (b) Total deterioration degree of compressive strength in different immersion periods

total decrease of compressive strength and the total deterioration curve of coal samples also reflect this rule. Both curves are convex, which indicates that with the prolongation of immersion time, the deterioration effect gradually weakens. From the curve, we can infer that the deterioration effect is very weak when the immersion time reaches a certain value and the mechanical properties of the samples do not change. From the total decrease in compressive strength and total degradation curve of coal rock samples, it can be seen that after 60 days of immersion, the compressive

strength of coal samples decreased by 11.40 MPa, and the total degradation degree was 50.53 %; The compressive strength of sandstone samples decreased by 7.24 MPa, with a total degradation rate of 10.93 %. Both the total decrease in compressive strength and the total deterioration degree of coal samples are higher than those of sandstone samples, which indicates that the deterioration effect of mechanical damage of coal samples is more significant than that of sandstone samples.

Table 1 Impact energy index and impact tendency of coal and sandstone under different immersion time.

Immersion time /d	Impact Performance					
	Coal	Impact tendency	Evaluation Criterion	Sandstone	Impact tendency	Evaluation Criterion
10	4.38	Weak	No: $K_E < 1.5$ Weak: $1.5 \leq K_E < 5$ Strong: $K_E \geq 5$	7.41	Strong	No: $K_E < 2$ Weak: $2 \leq K_E < 3$ Midume: $3 \leq K_E < 5$ Strong: $K_E \geq 5$
20	4.16	Weak		4.56	Midume	
30	3.55	Weak		2.36	Weak	
40	3.00	Weak		1.83	No	
50	2.80	Weak		1.26	No	
60	2.65	Weak		1.18	No	

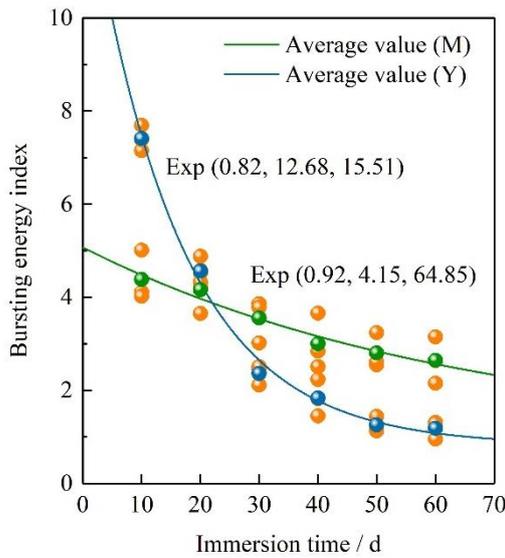


Fig. 8 Relationship between bursting energy index and immersion time of coal and rock samples.

3.3. ANALYSIS ON THE DIFFERENCE OF IMPACT EFFECT OF COAL AND ROCK UNDER THE WATER-ROCK INTERACTION

The failures of coal and rock are divided into stable and unstable failures. Stable failure and unstable failure are two crucial concepts in rock mechanics, each with distinct implications and manifestations in rock engineering. Stable failure typically refers to the gradual, phased, and slow failure of coal or rock that occurs after the material reaches its maximum bearing capacity. This failure process has a relatively long duration, is non-violent, and usually takes place in weak rock masses- a scenario commonly encountered in coal mine roadways or shallow rock engineering where weak rock formations dominate. In contrast, unstable failure emphasizes the transition process of coal or rock from a stable state to an unstable state; it is a dynamic process characterized by a short duration, intense destruction, and sometimes accompanied by loud noises. This type of failure is often observed in hard rock masses, such as in deep mining engineering or hard rock tunnel excavations, where sudden energy release during failure may pose significant risks to engineering safety. In engineering practice, the

unstable failure of coal-rock under certain disturbance conditions can easily lead to geological disasters, and is also a part of the study of the mechanical properties of coal and rock. The impact propensity of coal and rock is an important mechanical property of coal and rock, which can indicate the difficulty of instability and failure of coal and rock samples. It is of great significance to explore the difference in the impact tendency of coal and rock under the action of water rock in order to understanding the instability and failure of coal and rock under water-rich conditions and immersing environments.

In this study, the impact energy index K_E is considered an important parameter for determining the impact tendency of coal and rock. The impact energy index K_E is the ratio of the elastic energy accumulated before the peak to the deformation energy consumed after the peak under uniaxial compression. Because of the differences of the coal and rock materials, the judging standards of the impact tendency of coal and rock samples are different. For coal samples, the impact tendency was divided into no impact tendency, weak impact tendency and strong impact tendency. When $K_E < 1.5$, it is considered that there is no impact tendency; when $1.5 \leq K_E < 5$, it is considered as weak impact tendency; when $K_E \geq 5$, the strong impact tendency is considered. For rock samples, the impact tendency is divided into no impact, weak impact, medium impact and strong impact. When $K_E < 2$, it is considered that there is no impact tendency; when $2 \leq K_E < 3$, the weak impact tendency is considered; when $3 \leq K_E < 5$, it is considered that the medium impact tendency; when $K_E \geq 5$, the strong impact tendency is considered. According to this standard, the impact tendency of coal and rock samples was determined. The coal and rock impact energy index and their determination results are shown in Table 1 and Figure 8.

It can be seen from Figure 8, with the increase of immersion time, the impact energy index of coal and sandstone samples decreased in varying degrees, and the impact tendency tends to weaken. In the initial stage of immersion, the impact energy index decreased rapidly, and then with the increase of immersion time, the impact energy index decreased slowly, and is basically stabilized at a certain value. The coal samples are more obvious than the sandstone samples in this rule. After 60 days of immersion in water, the

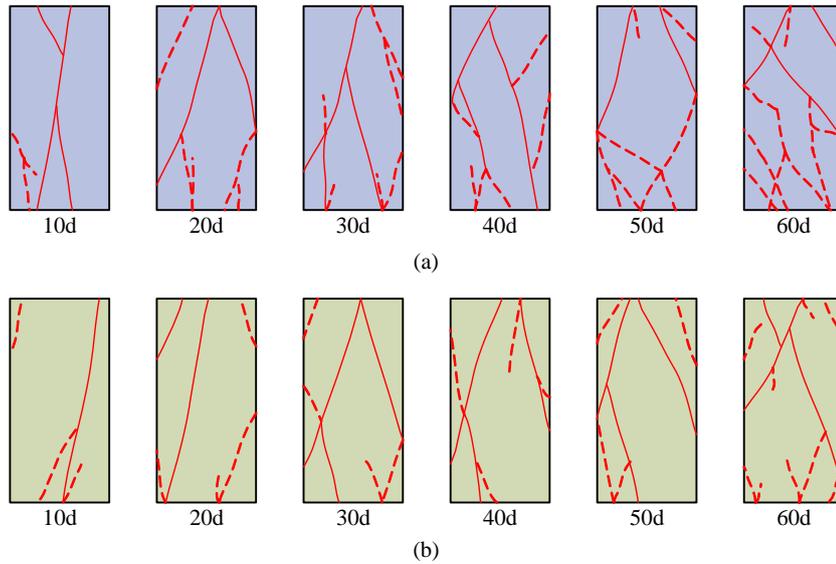


Fig. 9 Failure characteristics of coal and rock samples under different immersion time. (a) coal, (b) sandstone.

impact energy index of sandstone samples decreased from 4.38 (medium impact) to 2.65 (weak impact), decreased by 39.50 %. The impact energy index of coal samples decreased from 7.41 (strong impact) to 1.18 (no impact), decreased by 84.08 %. It can be seen that the impact energy index of coal samples is more significantly affected by water-rock interaction.

In addition, the impact tendency of the coal samples has a strong impact (7.41) after 10 days of immersion, and the impact tendency has a weak impact (4.56) after 20 days of immersion, but these data are close to a strong impact. The impact pressure has a weak impact after 30 days of immersion, and the impact energy index was 2.36. On an engineering scale, coal seam water injection is often used to prevent rock bursts. The test rules provide a good reference for coal seam water injection in engineering, particularly in terms of water injection time. According to the test data, it was necessary to inject water into the coal seam for 30 days in advance. As long as prevention is strengthened, safe mining can be fully guaranteed. However, the sandstone sample immersed for 10 d had a medium impact, and it still had a weak impact until it was immersed for 60 d. The impact of immersion on the impact tendency of the sandstone samples was not significant. In addition, it is difficult to construct a rock immersion model. Therefore, when coal and rock coexist, the coal is injected with water. However, water injection into a rock mass is also common during the construction of underground tunnels.

4. ANALYSIS OF COAL AND ROCK FAILURE CHARACTERISTICS UNDER THE WATER-ROCK INTERACTION

When the coal and rock samples were loaded, a layer of approximately transparent sulfuric acid paper was wrapped around them and clamped with

rubber bands. After the samples were destroyed, the cracks were traced on sulfuric acid paper, and Figure 9 was drawn according to the cracks condition of the sample. Figure 9 reflects the failure characteristics of the coal and rock samples under different immersion time. The red solid line in the figure is the main crack, the red dotted line is the secondary crack, and there are some small cracks have little effect on the damage to the sample, which are not shown in the figure.

At the initial stage of immersion, the upper and lower end faces of the samples are penetrated by a whole crack, which is the main crack of samples failure, and leads to the failure of the samples directly; The crack length is long, and the crack initiation position is mainly near the upper and lower end faces of the samples, or propagates along the main crack; The crack angle (the angle between the crack and the axial direction of the samples) is 0~15°. From the crack distribution, the failure form of samples belongs to brittle failure. With the increase of immersion time gradually, the main control cracks of the sample failure change from 1 to 2 or even more, and the main control cracks do not penetrate the upper and lower end faces of the samples, but two or more cracks jointly penetrate the upper and lower end faces of the samples; the crack length gradually becomes shorter, and the crack initiation position is not only limited to the vicinity of the upper and lower end faces, but also irregular. This irregularity is mainly due to the irregularity of internal damage caused by water-rock interaction of the samples; The crack angle increases gradually, ranging from 15° to 45°; The total number of cracks has evolved from the initial 4~5 to 15~20. Judging from the crack morphology and distribution, the failure form of samples belongs to plastic failure.

The failure modes of coal and rock samples under the same immersion time are different, and the evolution laws under the water-rock interaction are

Table 2 Effects of immersion time and coal and rock materials on failure characteristics of samples.

Influence factor	Coal sample	Sandstone sample	Short-term immersion	Long-term immersion
Length of crack	Short	Long	Long	Short
Position of crack initiation	Irregularity	Sample boundary	Upper and lower end faces	Irregularity
Angle of crack	Large	Small	0~15°	15~45°
Number of master cracks	More	Less	Less	More
Number of cracks	More	Less	Less	More
Type of failure	Inclined to plastic failure	Inclined to brittle failure	Brittle failure	Plastic failure
Rate of water-rock interaction	Fast	Slow	Fast	Slow

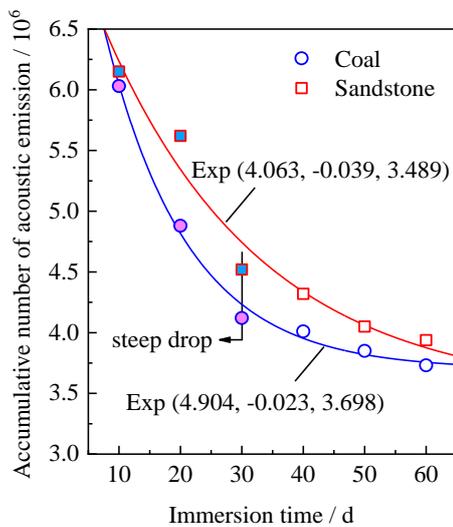


Fig. 10 Cumulative acoustic emission counts of specimens under different water immersion durations.

also different. After immersing for 10 days, the failure characteristics of coal and rock samples are roughly the same. There is a whole crack running through the upper and lower ends of the sample, and the crack length is longer. The crack initiation position is also mainly near the upper and lower end faces of the samples, or along the main crack. The crack angle is between 0° and 15°. From the perspective of crack morphology and distribution, failure mode of coal and rock samples belong to brittle failure. By observing the number of cracks in coal and rock, it is found that the number of cracks in coal samples are more than that in sandstone samples, which are related to the original structure of coal and rock. After 20 days of immersion in water, the failure characteristics of coal samples changed obviously, and the main cracks became two, which did not penetrate the upper and lower end faces of the samples. The number of cracks increased, the length of cracks shortened, and the cracks angle increased, showing weak plastic failure characteristics; However, the failure characteristics of sandstone samples after immersion for 20 days are basically the same as those after immersion for

10 days, both of which are obviously brittle failures. It is worth noting that with the prolongation of immersion time, the failure characteristics of sandstone samples also change, which is consistent with the evolution of coal samples. Therefore, the influence of water-rock interaction on the failure characteristics of sandstone samples is smaller than that of coal samples, and it lags behind coal samples obviously. This is because the structure of coal samples is relatively loose, while the structure of sandstone samples is relatively compact. They have different water absorption and different water-rock interaction rates. The water-rock interaction rate of coal samples is faster, and the water-rock interaction rate of sandstone samples is slower. In general, the cracks of coal samples are longer than that of rock samples, and the crack initiation position of coal samples have obvious irregularity. The sandstone samples are mainly concentrated at the boundary of the samples. Compared with rock samples, coal samples have larger crack angle, more cracks, and more obvious plastic failure characteristics than that of rock samples.

The immersion time have a great influence on the failure characteristics of the samples, it is mainly manifested in five aspects: crack length, crack initiation location, angle between crack and axial direction of samples, number of cracks, and failure type, the specific effects are shown in Table 2.

5. DAMAGE MODEL CONSIDERING IMMERSION TIME

5.1. ANALYSIS OF ACOUSTIC EMISSION DAMAGE CHARACTERISTICS IN COAL ROCK UNDER DIFFERENT WATER IMMERSION DURATIONS

The macroscopic failure of coal rock is essentially the result of cumulative damage within the specimen under load, and this damage accumulation can be reflected by the cumulative acoustic emission counts during loading. Based on the acoustic emission data obtained from the experiments, the relationship between water immersion time and cumulative acoustic emission counts was plotted and fitted, as shown in Figure 10. The following quantitative relationship between cumulative acoustic emission counts and water immersion time:

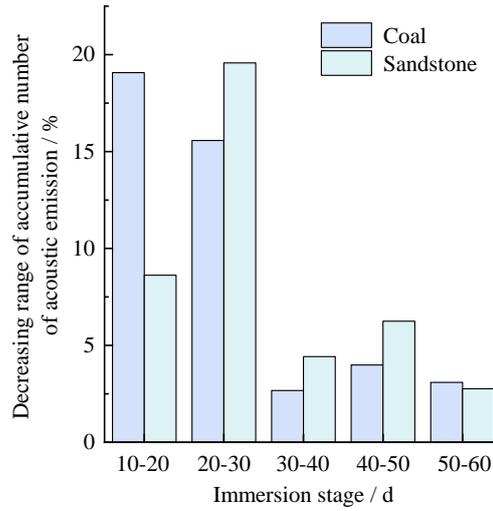


Fig. 11 The decrease of acoustic emission cumulative number of samples in different immersion stages.

$$N(t) = A \exp(-Bt) + C \quad (6)$$

where,

$N(t)$ —cumulative acoustic emission counts;

t —water immersion time.

Cumulative acoustic emission characteristics of coal specimens under varying immersion durations:

$$N(t) = 4.904 \exp(-0.023t) + 3.698 \quad (7)$$

Cumulative acoustic emission characteristics of Sandstone specimens under varying immersion durations:

$$N(t) = 4.063 \exp(-0.039t) + 3.489 \quad (8)$$

As showed in Figure 10, the water immersion time exerted a pronounced influence on the cumulative acoustic emission activity in both coal and sandstone samples. The coal specimen after 10-60 days water immersion exhibited cumulative acoustic emission counts of 6.03×10^6 , 4.88×10^6 , 4.12×10^6 , 4.01×10^6 , 3.85×10^6 , 3.73×10^6 times, the cumulative acoustic emission counts of coal samples decreased by 19.07 %, 15.57 %, 2.67 %, 3.99 %, and 3.09 %, respectively; The sandstone specimen after 10-60 days water immersion exhibited cumulative acoustic emission counts of 6.15×10^6 , 5.62×10^6 , 4.52×10^6 , 4.32×10^6 , 4.05×10^6 , 3.94×10^6 times, the cumulative acoustic emission counts of coal samples decreased by 8.62 %, 19.57 %, 4.42 %, 6.25 %, and 2.76 %, respectively, as shown in Figure 11. The above analysis indicates that the cumulative acoustic emission counts decreased significantly during the 0-30 days of immersion, while the decline slowed down during the 40-60 days of immersion. In the initial stage (0-30 days), both coal and sandstone exhibited a notable reduction in cumulative acoustic emission counts, indicating substantial water-rock interaction-induced damage to the samples. As the immersion

time increased, the cumulative counts continued to decrease; however, the rate of decline gradually diminished. This suggests that the deterioration effect progressively weakened with prolonged water-rock interaction.

It is noteworthy that the initial damage characteristics of coal and sandstone specimens, such as pre-existing fractures and structural composition, exert a certain influence on their cumulative acoustic emission counts. However, under identical conditions, the impact of the immersion duration on the cumulative counts follows a consistent pattern.

5.2. DEVELOPMENT OF A TIME-DEPENDENT DAMAGE MODEL ACCOUNTING FOR WATER IMMERSION EFFECTS

Under the water-rock interaction, the strength of both coal and sandstone decreases, and this interaction serves as a critical factor in rock damage and deterioration. Acoustic emission can quantitatively characterize the internal structural damage and degradation of specimens, exhibiting an inherent correlation with damage variables and constitutive relationships. Therefore, the damage theory can be applied to establish an AE-based damage model that incorporates the immersion time. Based on continuum damage mechanics theory, Tang and Xu (1990) demonstrated that the cumulative count of AE events exhibits strong consistency with the damage variable.

The damage variable D_s characterizes the damage degradation state of the specimen, and is expressed as:

$$D_s = \frac{A_d}{A} \quad (9)$$

where,

A_d —the total area of microdefects on the bearing cross-section;

A —the cross-sectional area in the initial state.

Under uniaxial compression conditions, the influence of water immersion on specimen geometry is negligible. Thus, the specimen can be assumed to be initially undamaged prior to immersion, that is, $D_s=0$. When cross-section A reaches complete failure with a cumulative acoustic emission count of N_m , the acoustic emission per unit area is expressed as

$$n_v = \frac{N_m}{A} \quad (10)$$

When the microdefect area reaches A_d , the cumulative acoustic emission count can be expressed as:

$$N = n_v \cdot A_d = \frac{N_m}{A} \cdot A_d \quad (11)$$

Based on Equations (9) and (10), the relationship between the damage variable and acoustic emission can be expressed as:

$$D_s(t) = \frac{N(t)}{N_m} \quad (12)$$

According to Equation (12), the acoustic emission characteristics of the specimen are consistent with its damage evolution. Assuming that reduction in acoustic emission counts is solely attributed to water-rock interaction effects, a prolonged immersion duration leads to increased damage accumulation. By combining with Equation (6), the relationship between the damage variable and acoustic emission counts at different immersion times can be established as

$$D_s(t) = \frac{A \exp(-Bt) + C}{N_m} \quad (13)$$

When the microdefect area A_d equals the cross-sectional area A , the damage variable reaches its maximum value $D_s=1$. Consequently, the time-dependent damage variable $D_s'(t)$ induced by the water immersion can be expressed by the following Equation:

$$D_s'(t) = 1 - D_s(t) \quad (14)$$

Combining with Equation (13), the expression can be rewritten as:

$$D_s'(t) = 1 - \frac{A \exp(-Bt) + C}{N_m} \quad (15)$$

Here, $D_s'(t)$ is defined as a function of immersion time t . Based on the cumulative acoustic emission counts of the coal and sandstone specimens under different immersion durations, the relationship between the damage variable $D_s'(t)$ and immersion time can be established, as illustrated in Figure 12.

Based on the fitted curve, the quantitative relationship between the damage variable and immersion time can be expressed as follows:

$$D_s'(t) = A' \exp(B't) + C' \quad (16)$$

The relationship between the damage variable and the immersion time for coal samples is given by:

$$D_s'(t) = -0.691 \exp(-0.071t) + 0.521 \quad (17)$$

The relationship between the damage variable and immersion time for sandstone samples is given by

$$D_s'(t) = -0.680 \exp(-0.071t) + 0.436 \quad (18)$$

As evidenced by Figure 12, the damage variables of both coal and sandstone specimens exhibit a progressive increase with prolonged immersion time. When the coal sample is immersed in water for 10 days, the damage variable is 0.18; the damage variable was 0.35 at 20 days of immersion, which increased by 94.44 %; The damage variable was 0.44 at 30 days of immersion, which increased by 25.71 %; The damage variable was 0.48 at 40 days of immersion, which increased by 9.09 %; When immersed in water for 50 days, the damage variable was 0.50, which increased by 4.17 %; The damage variable was 0.51 at 60 days of immersion, an increase of 2.00 %. When the sandstone sample is immersed in water for 10 days, the damage variable is 0.10; the damage variable was 0.28 at 20 days of immersion, which increased by 180 %; The damage variable was 0.35 at 30 days of immersion, which increased by 25 %; The damage variable was 0.39 at 40 days of immersion, which increased by 11.43 %; The damage variable was 0.42 at 50 days of immersion, which increased by 7.69 %; The damage variable was 0.43 at 60 days of immersion, an increase of 2.38 %. It can be seen that the damage variables of coal rock soaked for 10d, 20d and 30d increase greatly, and the damage variables of soaked for 40d, 50d and 60d decrease. With the increase of soaking time, the damage variables of coal samples increased by 94.44 %, 25.71 %, 9.09 %, 4.17 % and 2.00 % respectively, and the cumulative number of acoustic emissions of sandstone decreased by 180 %, 25 %, 11.43 %, 7.69 % and 2.38 % respectively, as shown in Figure 13.

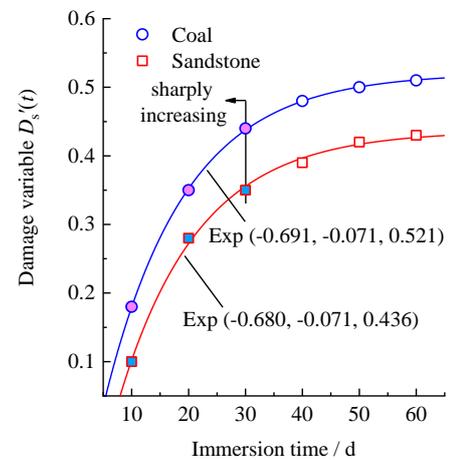


Fig. 12 Time-dependent evolution of damage variable in coal and sandstone specimens subjected to water immersion.

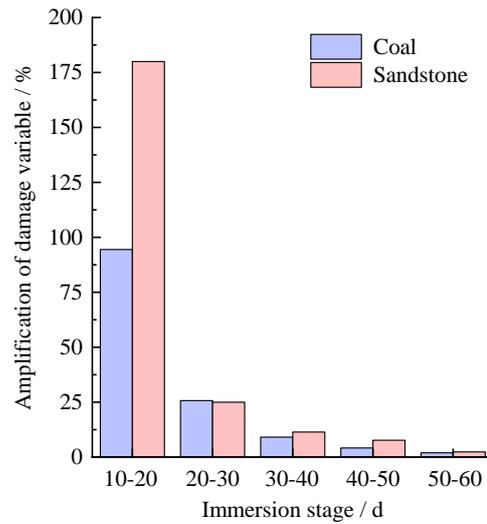


Fig. 13 Reduction amplitude of cumulative acoustic emission counts in specimens at different water immersion stages.

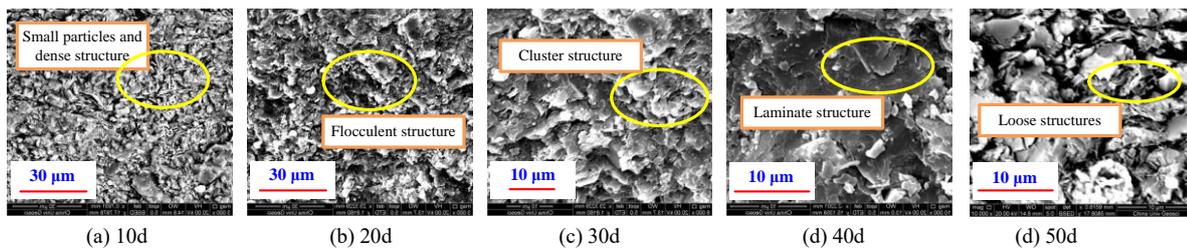


Fig. 14 SEM images of coal specimens under different immersion time.

With prolonged water immersion time, the degree of damage of coal rock increases gradually, the mechanical properties such as strength gradually deteriorate, and the stability gradually decreases, which easily induces instability and failure. This is also the reason why the surrounding rock system in a long-term water-rich environment should be drained in time and the support should be strengthened. In addition, it was found that the damage variable of coal samples is larger than that of sandstone samples under the same soaking time, which indicates that the soaking time has a stronger deterioration effect on coal samples. This is because coal is a natural porous material, and its internal cracks are all channels of water-rock interaction. Under the action of water-rock, the internal primary cracks continue to expand and penetrate, which significantly deteriorates the mechanical properties of coal. In contrast, the rock has a dense structure, fewer internal primary cracks, good homogeneity, small water-rock interaction area, and weak rock deterioration.

6. MICROSCOPIC ANALYSIS OF COAL - ROCK DAMAGE AND DETERIORATION UNDER WATER-ROCK INTERACTION

6.1. EVOLUTION OF MESO-STRUCTURE OF COAL AND ROCK UNDER WATER-ROCK INTERACTION

Experimental Results: The tests demonstrated significant degradation in the compressive strength and elastic modulus of both coal and sandstone under water-rock interaction. This deterioration primarily results from coupled physical, chemical, and mechanical processes between water and coal-rock masses, manifesting macroscopically as mechanical property degradation. The underlying mechanisms were analyzed as follows.

Coal and rock materials are mainly composed of various types of mineral particles of different sizes under certain conditions of cementation. Therefore, coal and rock materials have strong heterogeneity and multiple defects, with numerous internal voids and fractures, and this property is particularly evident in coal. Under the action of water-rock interaction, water penetrates the voids and fractures, playing a role in lubricates and softens the mineral particles, and reduces the frictional effect between the particles. When the specimen was loaded, the closure and slippage of the voids and fractures in the coal and rock were affected. Figure 14 shows the SEM images of the

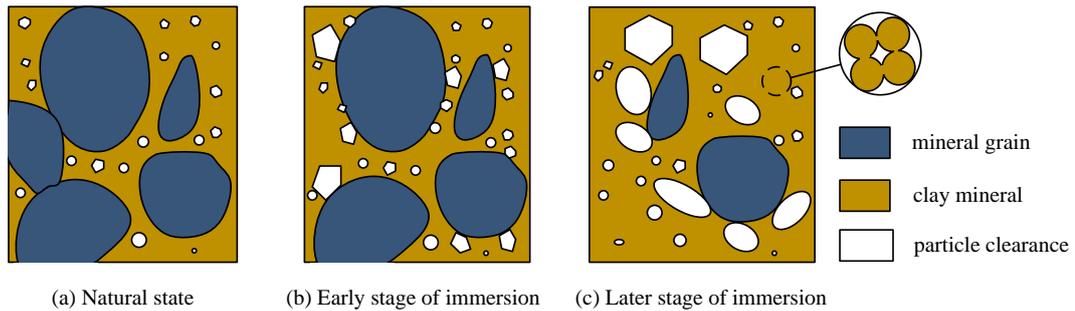


Fig. 15 Evolution model of particle cementation of coal and rock materials under the water-rock interaction.

coal specimens with different immersion time. After soaking for 10 d, the mineral particles in the specimen were smaller and the structure was denser. With the increase in soaking time, flocculent, agglomerate, and flake structures appear in turn. After soaking for 50 days, a loose structure appeared, and there were many large voids between particles, which led to the deterioration of the strength of the specimen. With increasing soaking time, the original dense structure with strong internal cementation and low porosity gradually evolved into a loose and weak structure with weak cementation and high porosity, which also revealed the softening effect of water on the coal rock.

Coal and rock materials contain large amounts of clay mineral components, such as montmorillonite and chlorite. These mineral components undergo chemical reactions, such as dissolution and alteration, when they come into contact with water. This changes the mineral composition of the coal and rock as well as the internal structure of the coal and rock. This also leads to degradation of the mechanical properties of coal and sandstone to varying degrees under the action of water-rock interactions.

6.2. MECHANISM OF DETERIORATION OF MECHANICAL PROPERTIES OF COAL AND ROCK UNDER WATER-ROCK INTERACTION

The test results show that the compressive strength and impact energy index of coal and sandstone samples have obvious deterioration effects under the water-rock interaction, and the deterioration rate is also different with different immersion times. Macroscopically, the deterioration of mechanical properties and the evolution of failure modes of coal and rock samples are essentially the external manifestations of the physical and chemical effects of coal and rock under the water-rock interaction. The deterioration mechanism of mechanical properties of coal and rock is discussed and analyzed as follows.

1. As natural materials, coal and rock materials have formed many primary defects such as voids and fissures in the coal and rock owing to their own factors and external factors during the formation process. During the immersion process, water entered the samples along the original crack of the samples, which had a certain lubrication effect and reduced the internal friction force of the

samples, resulting in a reduction in the compressive strength. With an increase in immersion time, the effect of lubrication becomes more obvious. Because the original defects, such as voids, inside the coal samples are greater than those of the sandstone samples, the lubrication effect inside the samples is stronger, and the compressive strength of the coal samples decreases faster.

2. The internal structure of the coal and rock samples mainly included mineral particles, clay minerals, and interspaces between particles, as shown in Figure 15. The mineral particles inside the samples were wrapped by clay minerals and, thus had a certain degree of cementation force. These clay minerals are easily dissolved in water. Clay minerals are dissolved in water under the water-rock interaction, and mineral particles are gradually exposed due to the loss of clay minerals. The cementation between mineral particles is weakened, gradually and the weakening of the cementation inside the sample leads to the decrease of the macroscopic compressive strength of the sample. In addition, the dissolved clay minerals are gradually brought out under the action of water flow, and the space of clay minerals is occupied by water after dissolution, which also broadens the channel of water-rock interaction, increases the area of water-rock interaction, and further improves the speed of water-rock interaction.
3. The clay minerals inside the coal and rock are easily corroded by water. In addition, the clay minerals are also expanded by water easily. The clay minerals wrapped around the mineral particles expand with water, and stress concentration occurs at the tip of the original crack, which promotes the further expansion of the original crack and increases the length and width of the original crack. Secondly, under the physical expansion of clay minerals, new cracks will also initiate in areas without original cracks, which increases the number of cracks, and these cracks will further expand under expansion. Under the expansion of clay minerals, the propagation and initiation of cracks are repeated, resulting in an increase in the length, width and

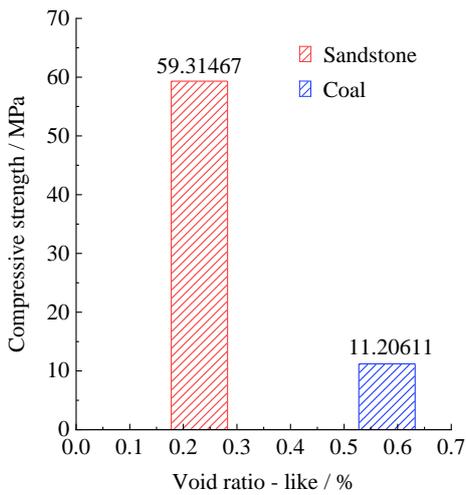


Fig.16 Relationship between void ratio and compressive strength of coal rock samples.

number of cracks, which not only broadens the water-rock interaction channel, but also aggravates the internal damage of the sample, which is also one of the reasons for the decrease of the compressive strength of the sample.

4. The essence of water-rock interaction is the combination of physical and chemical interaction between water and coal, but the time periods of physical and chemical interaction are different. In the early stage of soaking, the main physical interaction between water and rock is mainly physical adsorption. With the increase of immersion time, the physical effect gradually weakened, and the chemical effect gradually increased, and gradually occupied the dominant position. For these two effects, it is worth noting that the physical effect is stronger than the chemical reaction in terms of both the rate of action and the efficiency of action. Therefore, the rate of deterioration of compressive strength at the initial stage of immersion is faster, and the rate of deterioration of compressive strength at the later stage of immersion slows down gradually and tends to be stable. The difference of action rate and efficiency of these two effects determines the non-uniformity of deterioration effect of mechanical properties of samples. The above analysis explains the phenomenon that with the increase of water-rock interaction time, the deterioration effect of mechanical properties of samples weakens gradually.
5. The macroscopic failure of the sample is the result of continuous accumulation at the micro level. The samples cause microscopic damage under physical and chemical effects. With the progress of water-rock interaction, the damage accumulates continuously. When it reaches a certain level, it leads to macroscopic damage of the sample. From this point of view, the deterioration effect of the mechanical properties

of the samples under the water-rock interaction is the result of the gradual accumulation of internal damage of the sample under the water-rock interaction.

7. DISCUSSION

7.1. DISCUSSION ON RELATIONSHIP BETWEEN VOID RATIO AND COMPRESSIVE STRENGTH OF COAL ROCK

There are a large number of small voids in the coal rock, which are closed and dislocated under the action of an external force and are destroyed along the weak cracks, resulting in the gradual instability of the coal rock. To analyze the influence of water-rock interaction on compressive strength, the influence of internal voids of coal rock on compressive strength under a saturated state was analyzed.

The quality of the sample selected for the test was good, and there were few water-absorbing minerals, such as clay. To a certain extent, the water absorption of the sample was considered equivalent to the water absorption of the gap. When the sample reached saturation, the volume of absorbed water was equal to the void volume. Therefore, the void ratio K is defined as the ratio of the volume of inhaled water to the volume of the sample under the saturated state of the sample:

$$K = \frac{V_s}{V} \quad (19)$$

where,

V_s - the volume of water absorbed by the sample in saturated state;

V - the Volume of sample.

V_s can be obtained by Equation (20):

$$V_s = \frac{m_b - m_a}{\rho_s} \quad (20)$$

where,

m_b - sample's quality after absorbing water in saturated state;

m_a - the quality of the sample before water absorption;

ρ_s - density of water.

Therefore, the void ratio can be solved using by Equation (21).

$$K = \frac{m_b - m_a}{\rho_s \cdot V} \quad (21)$$

It can be seen from the test results that the coal and sandstone samples have basically reached saturation state after soaking for 50 days. The corresponding relationship between void ratio and compressive strength of coal rock is shown in Figure 16. As shown in the figure, the void ratio of the coal sample was 0.58 %, and the compressive strength was 11.21 MPa. The void ratio of the sandstone sample was 0.23 %, and the compressive strength was 59.31 MPa. Porosity ratio: sandstone sample < coal sample, compressive strength: coal sample < sandstone sample. This shows that the greater the void ratio, the smaller the compressive strength. This is because the more voids there are in the sample, the

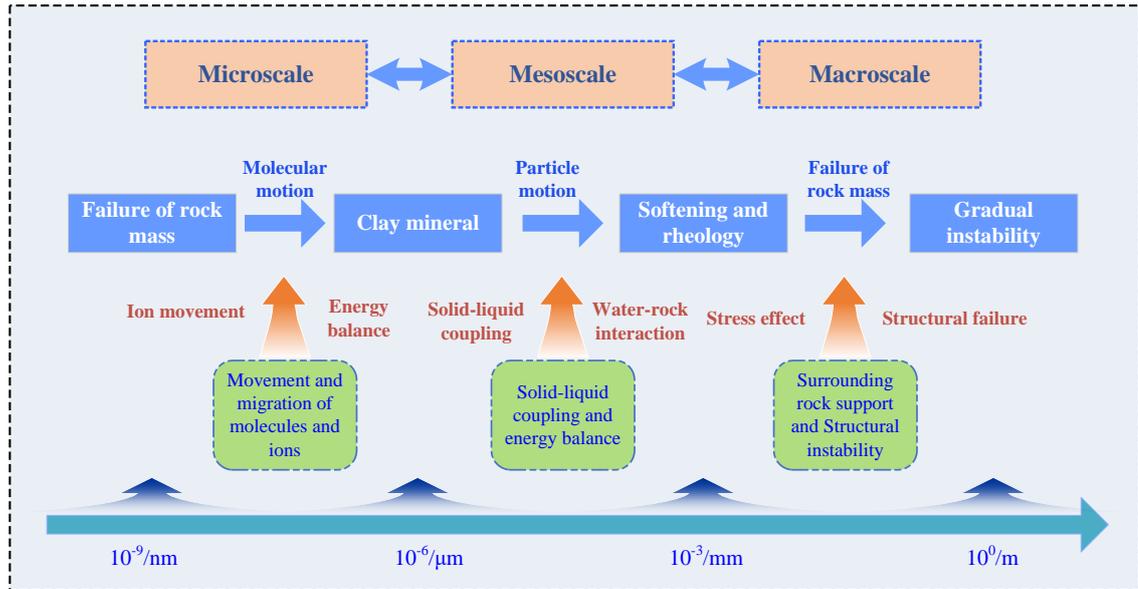


Fig. 17 Multi-scale system of coal-rock structure under water-rock interaction.

easier it is to penetrate under the action of external force. The small cracks continued to expand and penetrate, forming larger cracks and further forming weak areas or structural planes. These weak areas or weak structural planes have a linkage effect under load, which reduces the strength of the sample, weakens the mechanical properties of the sample, and accelerates the failure of the sample.

7.2. MULTI-SCALE ANALYSIS OF COAL AND ROCK STRUCTURE DETERIORATION UNDER WATER-ROCK INTERACTION

In engineering practice, the interaction layer between coal and various rock phases constitutes the coal-rock system in a coal mine. In the mining work of large water mines and under water-rich conditions, the coal-rock system is immersed in water for a long time, resulting in the deterioration of mechanical properties such as cohesion and compressive strength, resulting in the gradual loss of bearing capacity of the coal-rock system and instability failure. The deterioration effect of coal and rock under the water-rock interaction has a significant influence on the coal-rock system, but this deterioration effect lasts for a long time and the deterioration speed is relatively slow. Because the deterioration effect of coal-rock system under the action of water-rock is gradual, there are often slight slag fall, spalling and other behaviors in coal mine roadway, finally, it is gradually evolved into roadway collapse. According to the self-built multi-scale system of coal-rock structure under water-rock interaction (Fig. 17), the progressive failure mechanism of multi-scale coal-rock structure under water-rock interaction is analyzed.

Coal mass and rock mass is immersed in groundwater for a long time, water molecules first enter the gap between coal-rock particles, and form

osmotic repulsion through the diffusion double layer (Kuang et al., 2013; Gao, 2017). Under the action of hydration, water molecules form a weak bond on the surface of the unit cell and between the crystal layers of the unit cell. At this stage, the energy of the unit cell decreases and a significant expansion occurs in the stacking direction (Li et al., 2015). In addition, hydration produces some energy, and the interlayer cations migrate under the drive of these energy. On the mesoscopic scale, the hydration of water molecules and clay minerals makes the diameter of clay particles larger and the cementation between mineral particles weaker (Sun, 2019). On the macro scale, the internal structure of coal and rock has an expansion effect under the action of water rock. Stress concentration occurs near the internal cracks of coal and rock, and the cracks continue to expand and develop. In addition, the friction force inside the coal and rock decreases, and the lubrication effect is more obvious. Under the combined action of multi-directional stress of surrounding rock, these changes are more rapid, macroscopically showing the characteristics of coal and rock softening with water, such as roadway spalling and slag falling.

The water-rock interaction of coal and rock is mainly manifested in three scales: micro-scale, meso-scale and macro-scale. These three scales are interrelated, mutually influential and mutually reinforcing, and jointly promote the deterioration effect of coal and rock. The hydration of water molecules on the micro scale weakens the cementation between mineral particles in coal and rock, and further promotes the expansion and initiation of cracks and fissures in coal and rock samples. The macroscopic crack propagation and initiation of the samples also further broadens the water-rock interaction channel and accelerates the water-rock interaction rate, which

also promotes the hydration of water molecules at the microscopic level and promotes the weakening of cementation between mineral particles at the microscopic level. From this point of view, water-rock interaction on three scales is interrelated, influence each other and promote each other. Especially under high stress conditions, this effect is more significant, and the coal-rock structure is further deteriorated, which eventually leads to system instability.

8. CONCLUSION

1. With the prolongation of immersion time, the water content of coal and rock samples increased in varying degrees, and finally gradually stabilized; the compressive strength of coal and rock decreases gradually, and the compressive strength of coal samples decreases more, and the deterioration effect is more obvious than that of sandstone samples; the impact energy index of coal samples and sandstone samples decreased to varying degrees, and the impact tendency gradually weakened.
2. The immersion time and coal and rock materials have a significant influence on the failure characteristics of the specimen, mainly in terms of the crack length, crack initiation position, angle between the crack and axial direction of the specimen, number of cracks and the type of failure.
3. With an increase in immersion time, the cumulative number of acoustic emissions of the coal and sandstone samples decreased significantly. The longer the soaking time, the more severe the damage to the sample. A damage model based on immersion time was constructed. The model shows that as the immersion time increases, the degree of damage of the sample increases, and the strength and stability decrease.
4. Under the water-rock interaction, the physical and chemical actions inside the coal and rock samples cause microscopic damage. The deterioration of the mechanical properties of coal and rock results from the gradual accumulation of internal damage. A multi-scale system of coal and rock structure under water-rock interaction is constructed, and the water-rock interaction is analyzed at micro-scale, meso-scale, and macro-scale.

Water-rock interaction has long been a prominent research topic in academia and engineering practice. Prolonged water immersion induces continuous deterioration of rock mechanical properties, prompting this study to explore the deterioration effects and underlying mechanisms of coal-rock under varying water immersion durations. In actual engineering scenarios, some rock masses are not fully submerged but partially immersed in water, making the mechanical responses of rocks under different water immersion depths a key area requiring intensive research. Furthermore, many reservoirs

implement regular water storage and release operations, exposing their bank rock slopes to saturated-dry cyclic water-rock interaction. Consequently, the mechanical behaviors of rocks under such cyclic water-rock interaction will be prioritized in subsequent studies.

FUNDING

This research was supported by the National Natural Science Foundation of China (52304142, 52464014), Natural Science Foundation of Inner Mongolia Autonomous Region of China (2025YQ011, 2022MS05037), Basic Scientific Research Fees of Colleges and Universities directly under the Inner Mongolia Autonomous region (2023QNJS108, 2023QNJS089), and the Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region (NJYT22073).

DATA AVAILABILITY

The data used to support the findings of this study have been included within this article.

DISCLOSURE STATEMENT

The authors declare they have no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AUTHOR CONTRIBUTIONS STATEMENT

Guangbo Chen: conception and design, the drafting of the paper;

Wei Tang: analysis and interpretation of the data;

Tan Li: conception and design, revising it critically for intellectual content;

Eryu Wang: revising it critically for intellectual content;

Chuangye Wang: revising it critically for intellectual content;

Yejiào Liu: revising it critically for intellectual content.

All authors agree to be accountable for all aspects of the work.

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