Mechanical Properties and Acoustic Emission Characteristics of Water-Bearing Coal Specimens under a Coupled Compression–Shear Load

Lan Wang 1, Peng Wu 2, Ming Li 2,*, Xianbiao Mao 2 and Liang Chen 3,4

Abstract: The construction of an underground coal mine reservoir plays an essential role in the ecological environment of arid areas. The moisture content and loading angle inclination significantly impact the strength and stability of the safety coal pillar of underground reservoirs. Water-bearing coal was investigated under a coupled compression–shear load using inclined uniaxial compression tests on coal samples with varying water contents ($\omega = 0\%$, 2.42%, 5.53%, 7.55%, and 10.08%) and acoustic emission (AE) technology. The weakening mechanism of the mechanical property parameters and the crack evolution law, combined with the characteristics of the stress–strain curve, the cumulative AE count, and the cumulative AE energy methods, were used. Therefore, the evolution law of the coal’s crack closure (CC) threshold, crack initiation (CI) threshold, and crack damage (CD) threshold was analyzed. The results indicate that coal samples’ peak stress and elastic modulus decreased when the water content or inclination angle increased. Peak shear stress decreased as the water content rose, and the overall characteristics gradually rose as the inclination angle increased. The exception was when the ratio was 10.08%; when the inclination angle was 0°, the failure mode of the coal sample progressively changed from tension failure ($\omega = 0\%$, 2.42%) to tension–shear composite failure ($\omega = 5.53\%$), and finally to shear failure ($\omega = 7.55\%$, 10.08%). When the inclination angle was 5° and 10°, the coal specimens showed shear failure at any moisture content. When the water content or inclination angle increased, the crack closure threshold, crack initiation threshold, and damage threshold of the coal samples decreased. Therefore, these results show that their peak stress ratio does not depend on the water content or inclination angle.

Keywords: water-bearing coal specimen; inclination angle; mechanical characteristics; AE characteristics; crack evolution

1. Introduction

Northwest China is an arid or semi-arid region with abundant underground coal resources but scarce water resources. Underground coal mining deforms the aquifer, and the water-conducting crack zone formed by the collapse of the overlying rock gradually develops into the aquifer, forming a water-conducting channel. This results in water inrush into the coal mine and poses a significant threat to coal mine production safety. In addition, if the mine water is discharged to the outside, it will cause salinization of the surface land and seriously damage the surface ecology [1,2].
The idea of underground reservoir construction provides a new idea for solving this problem [3], bringing new problems. As shown in Figure 1, first of all, for the most important part of the underground reservoir, the safety coal pillar, its moisture content will have an important impact on its stability. Due to the uneven distribution of the water content in the coal pillar, the physical and mechanical properties of coal in different water-bearing areas are significantly different. Secondly, due to the complexity of in situ stress, such as gravity and tectonic stress generated by the overlying strata, the direction of the maximum principal stress on the coal pillar is often distributed at a certain angle in the coal pillar’s axial direction [4], as shown in Figure 2. At this time, the coal pillar will be affected by both compression and shear loads. A large number of experiments have shown that the mechanical properties of coal and rock masses under the combined action of compression and shear loads are significantly different from those under conventional uniaxial compression [5–7]. Therefore, clarifying the mechanical properties of water-bearing coal specimens under a coupled compression–shear load can effectively ensure the safety and stability of an underground reservoir and provide the necessary mechanical parameters for the size design of the safety coal pillar in the underground reservoir.

![Figure 1. Structural diagram of an underground reservoir in a coal mine.](image)

![Figure 2. Pillar under combined compression and shear loading: (a) when the ore body is inclined, the maximum principal stress is vertical; (b) when the ore body is horizontal, the maximum principal stress is inclined.](image)

The water environment is one of the basic environments faced by coal and rock masses in nature [8]. Coal and rock masses weather or decompose when exposed to the air for a long time, resulting in changes in physical and mechanical properties, and they are stable in the short term. However, when the coal rock mass is submerged or saturated in water, the clay mineral particles dissolve, resulting in a change in the internal structure of the coal rock mass. As a result, this affects the macro-physical and mechanical characteristics of rocks, mainly sedimentary rocks such as coal masses [9,10]. At present, there are abundant research results on the static mechanical properties of water-bearing coal and rocks. Scholars have conducted uniaxial compression tests [11,12], triaxial compression tests [13,14], and shear tests [15–17] on various types of water-bearing coal and rocks. They investigated the
variation characteristics of mechanical characteristic parameters such as failure strength, elastic modulus, and macrofailure characteristics and discussed the relationship between mechanical characteristic parameters and moisture content. However, the effect of a coupled compression–shear load was not considered in the above research results.

Understanding the physical and mechanical properties of materials under various complex loads is the premise and basis for engineering practice. In recent years, scholars have carried out a significant amount of research on the mechanical properties of materials under coupled compression–shear loads. Many researchers mainly focused on two aspects: first, the use of the split Hopkinson pressure bar (SHPB) to develop borosilicate glass [18], inorganic glass [19], granite [20], sandstone [21], honeycomb [22], polymer-bonded explosives [23], and other materials, and to explore the mechanical properties of materials under dynamic compressive shear loads; second, the use of a material testing system (MTS) and an auxiliary loading device to carry out static coupled compression–shear loading tests of materials such as granite [24], coal [25], honeycomb [26,27], polymethyl methacrylate [28,29], and expanded polystyrene [30]. The above studies show that the peak strength and elastic modulus of the material decrease as the loading angle rises, and the macroscopic failure mode is also very different from the way it would be in uniaxial compression. However, research on the microfracture process of materials (including the evolution characteristics of tensile and shear cracks, the CC threshold, the CI threshold, and the CD threshold) combined with the AE characteristics of water-bearing coal specimens under a coupled compression–shear load was not involved in the above researchers’ studies. Therefore, those properties are considered in this paper.

This paper used an improved combined compression–shear test (C-CAST) and an AE acquisition device to systematically study the mechanical properties and AE characteristics of water-bearing coal samples under coupled compression–shear stress. The variation law of the mechanical parameters and macroscopic fracture characteristics of the coal samples with the loading dip and water content were analyzed. We investigated the crack evolution law and the variable characteristics of the crack closure threshold, crack initiation threshold, and damage threshold of water-bearing coal specimens subjected to coupled compression–shear stress. This study provides reasonable mechanical parameters for determining the safe size of coal pillars in underground reservoirs.

2. Materials and Methods

2.1. Specimen Preparation

The coal specimens were taken from the Daliuta coal mine in Yulin City, Shaanxi Province, China. The coal specimens were processed into a cylinder with a diameter of 50 mm and a height of 100 mm [31]. The p-wave velocity and density of coal rocks are closely related to their strength [1,32,33]. This test selected coal specimens with a wave velocity between 1820 m/s and 1850 m/s and a density between 1360 kg/m$^3$ and 1380 kg/m$^3$. Through the uniaxial compression test, the basic mechanical parameters of natural coal specimens were obtained, as follows: average peak strength of 22.95 MPa, average elastic modulus of 1.92 GPa, and average Poisson’s ratio of 0.32.

Water is one of the most important indexes affecting the mechanical properties of coal [2,34]. Coal specimens with different moisture contents were prepared, as shown in Figure 3. The saturated moisture content of coal specimens selected in this paper was about 10.02%. According to the test scheme, preparing saturated coal specimens with a moisture content of 0%, 2.5%, 5.0%, and 7.5% was necessary. However, due to the difference in the internal pore structure of coal specimens, the prepared moisture content deviated slightly from the set value. The actually prepared moisture contents were 0%, 2.42%, 5.53%, 7.55%, and 10.08%. We wrapped the prepared coal specimens with different moisture contents in fresh-keeping film, sealed them with sealing bags, put them into the incubator, and used them during the test.
In the process of loading, the crack initiation, expansion, and penetration of coal release energy and generate elastic waves, which can be collected by AE equipment to realize the dynamic monitoring of the coal fracture evolution. This test collected the AE

The test included five moisture contents ($\omega = 0\%, 2.42\%, 5.53\%, 7.55\%$, and $10.08\%$). In order to study the variation in the mechanical properties of sub-horizontal coal specimens and the ore body with four inclination angles ($\theta = 0°, 5°, 10°$, and $15°$), cross-combinations for a total of 20 test groups were set up. Each test group was repeated five times, with the maximum and minimum values of each data group excluded and the remaining data used for further analysis.

2.3. AE Techniques

In the process of loading, the crack initiation, expansion, and penetration of coal release energy and generate elastic waves, which can be collected by AE equipment to realize the dynamic monitoring of the coal fracture evolution. This test collected the AE

Figure 3. Preparation flow chart of coal specimens with different moisture contents.

Figure 4 shows the test procedure and related equipment. The main tools used in the test loading process were an electro-hydraulic servo universal testing machine, a C-CAST system, and an AE monitoring system. The universal testing machine provides axial pressure; the C-CAST system realizes variable angle adjustment; the AE monitoring system collects AE signals during coal specimen loading. During the test, two RS-54A AE probes were arranged symmetrically, 25 mm from the end of the coal sample, and the sampling frequency was 3 MHz. The AE probes were affixed to the surface of the specimen with hot-melt adhesive. The loading rate was set to 1 mm/min.
count, AE energy, duration, rise time, and amplitude. The typical characterization method of AE parameters is shown in Figure 5a.

**Figure 5.** Schematic diagram of AE characteristic parameters and crack mode: (a) AE parameters; (b) characterization method of crack mode.

At present, in the fields of civil engineering [35], materials science [36], and mining engineering [37,38], many scholars use AE waveform analysis to study the crack mode of materials. It is primarily defined by its average frequency (AF) and rising angle (RA), where RA represents the ratio of rising time to amplitude, and AF represents the ratio of AE count to duration [37,38]. In this paper, the ratio of RA to AF was mainly used to analyze the crack mode. Figure 5b shows that shear failure occurs when RA/AF is greater than 1; tensile failure occurs when RA/AF is less than 1 [25].

In addition, scholars determine the characteristic thresholds of coal and rock specimens through stress–strain curves and AE parameters (counts or energy), including the CC threshold, CI threshold, CD threshold, and peak stress. The CC threshold and peak stress can be obtained from the stress–strain curve [1,2]. In contrast, the CI threshold and CD threshold can be obtained from the slope of the “cumulative AE parameter–axial stress” curve [37,39] or the slope of the “accumulated AE parameter–time” curve [1,2], as shown in Figure 6. Figure 6 shows the variation characteristics of stress, AE parameters, and accumulated AE parameters with time, according to the sudden change point of the slope of the “accumulated AE parameter–time” curve, which is used to determine the CI and the CD threshold. The four feature thresholds divide the coal loading process into five stages: the compaction stage (I), approximate linear elastic stage (II), stable crack growth stage (III), unstable crack growth stage (IV), and post-peak breakthrough stage (V) [40–42].

**Figure 6.** Schematic diagram of the determination method of feature threshold during loading.

3. Results and Discussion

3.1. Variation Law of Mechanical Characteristic Parameters

Through the inclined UCS test of water-bearing coal specimens, the variation laws of the coal specimens’ peak stress and elastic modulus under different moisture contents and
inclusion angles were obtained, as shown in Figure 7a,b. The average peak shear stress variation characteristics with the moisture content and inclination angle were obtained using the method described in the literature [6], as shown in Figure 7c. The fitting equation for each curve is also presented in Figure 7.

Figure 7. Variation law of mechanical characteristic parameters of water-bearing coal specimens with the inclination angle: (a) peak stress $\sigma_c$; (b) modulus of elasticity $E$; (c) peak shear stress $\tau_c$.

(1) Peak stress $\sigma_c$

The peak stress decreased linearly with the increase in the inclination angle. The inclination angle increased from 0° to 15°, and the peak stress at each moisture content decreased by 14.27% (21.33 MPa-18.29 Mpa, for $\omega = 0\%$), 18.21% (18.63 Mpa-15.24 Mpa, for $\omega = 2.42\%$), 32.86% (15.58 Mpa-10.46 Mpa, for $\omega = 5.53\%$), 50.67% (14.17 Mpa-6.99 Mpa, for $\omega = 7.55\%$), and 79.11% (13.50 MPa-2.82 MPa, for $\omega = 10.08\%$). The higher the moisture content, the larger the absolute value of the linear slope, which indicates that the characteristic of gradually decreasing peak stress is more sensitive to a high moisture content. The main reasons for this result are as follows: When the coal specimen contains water, the bound water will erode and dissolve the mineral particles and the cementing materials between the particles, resulting in an increase in the number and size of pores and fissures in the coal specimen and the initial damage of the coal specimen. Under the action of an external load, the free water inside the coal specimen will produce large pore pressure at the crack and pore tip, which further promotes the initiation and propagation of microcracks, leading to secondary damage in the loading process of the coal specimen. With the increase in the moisture content, the initial damage caused by bound water and the secondary damage caused by free water gradually increase, the lubrication between
mineral particles increases, and the frictional resistance decreases; smaller shear stress can lead to coal specimen damage; the higher the moisture content, the smaller the frictional resistance between the mineral particles, and the more the specimen is damaged under a lower load. Therefore, the high moisture content aggravates the weakening effect of the dip angle on the strength of the coal specimen.

The peak stress decreased nonlinearly with the increase in the moisture content. The moisture content increased from 0% to 10.08%, and the peak stress under the inclination angle of each specimen decreased by 36.72% (21.33 MPa-13.50 MPa, for $\theta = 0^\circ$), 47.22% (20.23 MPa-10.68 MPa, for $\theta = 5^\circ$), 62.46% (19.34 MPa-7.26 MPa, for $\theta = 10^\circ$), and 84.58% (18.29 MPa-2.82 MPa, for $\theta = 15^\circ$); the greater the inclination angle, the greater the decrease in the amplitude of the peak stress. The main reasons for this result are that the increase in the inclination angle leads to an increase in additional shear stress in the coal specimen, which promotes the development and extension of internal cracks in the coal specimen and further aggravates the weakening effect of the moisture content on the strength of the coal specimen.

(2) Elastic modulus $E$

The variation in the elastic modulus with the inclination angle is consistent with the peak stress. The inclination angle increased from $0^\circ$ to $15^\circ$, and the elastic modulus decreased by 14.33% (1.85 GPa-1.58 GPa, for $\omega = 0\%$), 8.41% (1.37 GPa-1.25 GPa, for $\omega = 2.42\%$), 14.97% (1.17 GPa-1.00 GPa, for $\omega = 5.53\%$), 42.69% (1.13 GPa-0.65 GPa, for $\omega = 7.55\%$), and 73.74% (1.08 GPa-0.28 GPa, for $\omega = 10.08\%$). In addition, the elastic modulus decreased nonlinearly with the increase in the moisture content.

The main reasons for the above results are as follows: The value of the elastic modulus depends on the friction resistance between mineral particles or microcracks [43]. The greater the inclination angle, the greater the additional shear stress component in the coal specimen. The additional shear stress intensifies the sliding between microcracks in the specimen, reduces the friction resistance, and reduces the elastic modulus of the coal specimen. In addition, the bound water attached to the soluble mineral particles and the cement between mineral particles plays a role in lubrication and reduces friction resistance. The greater the water content of the coal sample, the lower the frictional resistance and the smaller the restraint of the movement of mineral particles or microcracks, resulting in a lower elastic modulus [44].

(3) Peak shear stress $\tau_c$

When the moisture content was in the range of 0~7.55%, the peak shear stress increased gradually with the increase in the specimen inclination angle. The increase in peak shear stress under each moisture content was 192.09% (1.77 MPa-5.17 MPa, for $\omega = 0\%$), 170.51% (1.56 MPa-4.22 MPa, for $\omega = 2.42\%$), 134.68% (1.24 MPa-2.91 MPa, for $\omega = 5.53\%$), and 85.85% (1.06 MPa-1.97 MPa, for $\omega = 7.55\%$), and the increasing amplitude gradually decreased. When the moisture content $\omega = 10.08\%$, the peak shear stress increased first and then decreased until it reached its maximum when the inclination angle $\theta = 10^\circ$, and the maximum peak shear stress $\tau_c = 1.27$ MPa. In summary, the peak shear stress of coal specimens showed the characteristics of a rapid increase at a low moisture content and a slow increase or even a decrease at a high moisture content because shear stress has a negative effect on the strength of the specimen. In addition, the peak shear stress decreased linearly with the increase in the moisture content, and the greater the inclination angle, the greater the decrease in the peak shear stress. The features indicating that the peak shear stress decreases are more sensitive to large inclination angles.

3.2. Macroscopic Failure Characteristics

The initiation, expansion, and penetration of cracks are followed by the loading process of coal and rocks. Their macrofracture mode is closely related to the material’s mechanical properties and is significantly affected by the external loading conditions. In the traditional uniaxial compression test, the macrofracture modes of coal and rock masses mainly include
tension failure, shear failure, and tension–shear composite failure, but the dominant failure modes of coal and rock masses are different under different loading conditions. In terms of the moisture content and inclination angle, the macrofracture mode of the coal specimen showed obvious moisture content and inclination angle effects, as shown in Figure 8.

Figure 8. Different moisture contents and inclination angles. Macroscopic failure characteristics of lower coal specimens: (a) \( \omega = 0 \% \); (b) \( \omega = 2.42 \% \); (c) \( \omega = 5.53 \% \); (d) \( \omega = 7.55 \% \); (e) \( \omega = 10.08 \% \).
Figure 8 shows the physical diagram and schematic diagram of the macro-damage of coal specimens under different moisture contents and inclinations. Figure 8 shows that when the inclination angle increased, the macroscopic fracture mode of the coal specimens under different moisture contents was slightly different. Under a low moisture content (for \( \omega = 0\% \) and 2.42\%), the macrofracture mode of the coal specimen gradually changed from tensile failure to shear failure. When the inclination \( \theta = 0^\circ \), the coal specimen showed obvious tensile failure, with multiple tensile cracks penetrating each other, accompanied by a small number of shear cracks. When the inclination \( \theta = 5^\circ \), not only the main shear cracks penetrating the upper and lower end faces but also a large number of tensile cracks appeared on most coal specimens, and the coal specimens mainly showed tensile–shear composite failure. When the inclination \( \theta = 10^\circ \) and 15\°, the shear failure trend of coal specimens increased, and most coal specimens showed inclined shear failure, accompanied by a small number of tensile cracks locally. Bieniawski [45] pointed out that the propagation direction of the internal crack of the specimen is consistent with the direction of the maximum principal stress; the specimen mainly presents tensile splitting failure under conventional uniaxial compression; as the inclination angle increases, the direction of the highest primary stress deviates from the specimen’s axial direction. Therefore, the specimen shows shear failure. At a medium moisture content (for \( \omega = 5.53\% \)), there were a large number of tension and shear cracks in the coal specimens at any inclination angle, but the larger the inclination angle, the more obvious the shear failure trend of the coal specimens. Under a high moisture content (for \( \omega = 7.55\% \) and 10.08\%), the coal specimens showed shear failure at all inclination angles, but the integrity of the damaged coal specimens was better than that of low-moisture-content coal specimens.

With the increase in the moisture content, the failure forms of coal specimens under different inclination angles showed obvious differences. When the inclination angle \( \theta = 0^\circ \), under a low moisture content (for \( \omega = 0\% \) and 2.42\%), the coal specimen mainly showed the characteristics of tensile failure. The integrity of the specimen was damaged, showing the characteristics of burst, and a large number of stripped fragments could be seen around the coal specimen. Under a medium moisture content (\( \omega = 5.53\% \)), the integrity of the coal specimen was poor after damage, and a large number of shear and tension cracks could be seen on the surface. Under a high moisture content (\( \omega = 7.55\% \) and 10.08\%), coal specimens mainly underwent shear failure. When the inclination angle \( \theta = 5^\circ \), under any moisture content, the failure mode of the coal specimen was mainly tension–shear composite failure. The higher the moisture content, the more obvious the shear failure trend. When the inclination angle \( \theta = 10^\circ \) and 15\°, the coal specimens exhibited shear failure at any moisture content. In addition, the higher the moisture content, the better the integrity of the coal specimen when it is damaged. The main reasons for this result are as follows: After water is immersed in the coal body, the internal cracks of the coal specimen expand, the volume expands, and the plasticity is enhanced. The higher the moisture content, the stronger the plasticity and the lower the macrofracture degree of the coal specimen.

The higher the moisture content, the more obvious the shear failure trend of the coal specimens. The following explanation is given: The macrofracture characteristics of coal specimens are closely related to the frictional resistance between mineral particles or microcracks. 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 between particles. When the coal specimen contains water, the water plays the role of lubrication and reduces the friction resistance. The greater the moisture content of the coal specimen, the smaller the friction resistance, and the smaller the constraint of mineral particle or microcrack movement, increasing the trend of shear failure of the coal specimen [44,46,47]. In addition, under an external load, the water in pores and fractures will produce pore pressure, and there will be tensile stress concentration areas at the tips of pores and fractures, resulting in the tensile failure of coal specimens.

In summary, the macrofracture mode of coal specimens is closely related to their properties. Under the condition of moisture content, whether the coal specimen undergoes
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, under a low moisture content, the coal sample was mainly damaged by tensile failure, which means the effect of pore water pressure is greater than that of water lubrication. Meanwhile, shear failure was dominant at a high moisture content, meaning that the lubricating effect of water is greater than that of the pore water pressure.

To summarize, the macrofracture mode of coal and rocks is not an essential characteristic but is strongly dependent on the loading direction and the external environment. Under a high moisture content and a high inclination angle, coal specimens mainly show shear failure; under a low moisture content and a low inclination angle, coal specimens mainly show tensile failure.

4. Analysis of AE Behavior

4.1. Crack Evolution Law

In order to analyze the influence of the inclination angle on the evolution law of tensile–shear cracks, according to the method described in Section 2.3, the RA–AF relationship curve of coal samples under different inclination angles during the loading process was created. To simplify the analysis, the moisture content considered in this section was 2.42% and 7.55%. After that, the effect of the inclination angle on the fracture mode of a coal specimen was analyzed.

Figure 9 shows the variation law of the RA–AF relationship curve with the inclination angle when the moisture content was 2.42%. As shown in Figure 9, the cracks were concentrated near the RA and AF axes when $\theta = 0^\circ$ and $5^\circ$, and the number of cracks near the AF axis was significantly greater than that near the RA axis. As the inclination angle increased to $10^\circ$ and $15^\circ$, the distribution of cracks gradually shifted from the AF axis to the vicinity of the RA axis, indicating that the shear failure of the specimen tended to increase gradually with the inclination angle. Figure 9e shows the ratio of tensile and shear cracks to the total number of cracks at $\omega = 2.42\%$ at different inclination angles. It can be seen from Figure 9e that at $\theta = 0^\circ$, the proportion of tensile cracks was 64.54%, which is more than 50%, indicating that the failure of coal is mainly tensile failure under this condition. When the inclination angle $\theta = 5^\circ$, the proportion of tensile cracks was 48.92%, and the proportion of shear cracks was 51.08%. The specimen mainly presented tensile–shear composite failure. When the inclination angle increased from $10^\circ$ to $15^\circ$, the proportion of tensile cracks was less than 50%, decreasing from 34.28% to 28.91%, while the proportion of shear cracks was more than 50%, increasing from 65.72% to 71.09%. This indicates that shear failure was the main cause of coal specimen failure. This law is basically consistent with the macroscopic fracture mode of coal specimens described in Section 3.2.

Figure 10 shows the law of the RA–AF relation curve changing with the inclination angle when the moisture content $\omega = 7.55\%$. Figure 10e shows the ratio of tensile and shear cracks to the total number of cracks at different inclination angles when $\omega = 7.55\%$. It can be seen from Figure 10e that when the moisture content was 7.55%, the proportion of shear cracks was greater than that of tensile cracks at any inclination angle. The specimens mainly showed shear failure, and the proportion of shear cracks gradually increased with the increase in the moisture content. For example, the inclination angle increased from $0^\circ$ to $15^\circ$, and the proportion of shear cracks increased from 63.28% to 74.85%. It should be pointed out that the increase in the moisture content led to a gradual reduction in the number of cracks produced by the coal specimen during loading. From the macroscopic point of view, the macrocracks produced during specimen failure were reduced, which is the main reason for the good integrity of the specimen at a high moisture content.
Figure 9. Evolution law of tension–shear crack of coal specimens under different inclination angles ($\omega = 2.42\%$). (a) $\theta = 0^{\circ}$; (b) $\theta = 5^{\circ}$; (c) $\theta = 10^{\circ}$; (d) $\theta = 15^{\circ}$; (e) The proportion of tension–shear cracks in coal specimens under different inclination angles.
cracks was greater than that of tensile cracks at any inclination angle. The specimens mainly showed shear failure, and the proportion of shear cracks gradually increased with the increase in the moisture content. For example, the inclination angle increased from 0° to 15°, and the proportion of shear cracks increased from 63.28% to 74.85%. It should be pointed out that the increase in the moisture content led to a gradual reduction in the number of cracks produced by the coal specimen during loading. From the macroscopic point of view, the macrocracks produced during specimen failure were reduced, which is the main reason for the good integrity of the specimen at a high moisture content.

Figure 10. Tensile–shear crack evolution law of coal specimens under different inclination angles (ω = 7.55%). (a) θ = 0°; (b) θ = 5°; (c) θ = 10°; (d) θ = 15°; (e) The proportion of tension–shear cracks in coal specimens under different inclination angles.

In order to simplify the analysis process, the inclination angles of 0° and 10° were taken to study the influence of the moisture content on the crack mode of the coal samples. Figure 11 shows the variation law of the RA–AF relationship curve with the moisture content when the inclination angle was 0°. Figure 11f shows the ratio of the number of tensile and shear cracks to the total number of cracks under different moisture contents when the inclination angle was 0°. As shown in Figure 11f, when the moisture content was 0% and 2.42%, the cracks were mainly concentrated near the AF axis, indicating that the proportion of tension cracks was higher than that of shear cracks. When the
moisture content was 5.53%, the tensile and shear crack proportions were 50.42% and 49.58%, respectively, and the specimens mainly showed composite tensile–shear failure. When the moisture content exceeded 7.55%, shear cracks accounted for more than 50% of the specimen’s shear failure. Overall, the higher the moisture content, the more obvious the shear failure trend, which is basically consistent with the macrofracture mode of coal and rocks described in Section 3.2.

**Figure 11.** Evolution of tension–shear cracks in coal specimens at different inclination angles ($\theta = 0^\circ$).

(a) $\omega = 0\%$; (b) $\omega = 2.42\%$; (c) $\omega = 5.53\%$; (d) $\omega = 7.55\%$; (e) $\omega = 10.08\%$; (f) The ratio of tensile and shear cracks in coal specimens under different moisture contents.
Figure 12 shows the variation rule of the RA–AF relationship curve with the moisture content when the inclination angle was 10°. Figure 12f shows the ratio of the number of tensile and shear cracks to the total number of cracks when the inclination angle was 10°. At any moisture content, the proportion of shear cracks was greater than 50%, and with the increase in the moisture content, the shear failure trend gradually increased, and the sample mainly exhibited shear failure, as shown in Figure 12f.

Figure 12. Evolution of tension–shear cracks in coal specimens at different inclination angles (θ = 10°). (a) ω = 0%; (b) ω = 2.42%; (c) ω = 5.53%; (d) ω = 7.55%; (e) ω = 10.08%; (f) The ratio of tensile and shear cracks in coal specimens under different moisture contents.
4.2. Evolution Law of CC Threshold, CI Threshold, and CD Threshold

Based on the method described in Section 2.3, the AE parameters (ringing count and energy), cumulative AE parameters (ringing count and energy), CC threshold, CI threshold, and CD threshold of coal specimens under different inclination angles and moisture contents were obtained.

In order to simplify the analysis process, the AE characteristics of coal specimens with a moisture content of 7.55% at different inclination angles were selected for analysis. Figure 13 shows the relationship between stress, AE parameters, cumulative AE parameters, and time at different inclination angles. Figure 14 shows the variation in the CC threshold, CI threshold, and CD threshold and their ratios ($\sigma_{CC}/\sigma_{C}$, $\sigma_{CI}/\sigma_{C}$, $\sigma_{CD}/\sigma_{C}$) with the inclination angle. Table 1 shows the specific values. The main conclusions are as follows.

**Figure 13.** Curves of cumulative AE parameters (counts and energy) versus time at different inclination angles when the moisture content was 7.55%: (a) $\theta = 0^\circ$; (b) $\theta = 5^\circ$; (c) $\theta = 10^\circ$; (d) $\theta = 15^\circ$.
Table 1. Values of $\sigma_{CC}$, $\sigma_{CI}$, and $\sigma_{CD}$ at various inclination angles for $\omega = 7.55\%$.

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<th>Inclination Angle (°)</th>
<th>$\sigma_{CC}$ (MPa)/Ratio(1)</th>
<th>$\sigma_{CI}$ (MPa)/Ratio(1)</th>
<th>$\sigma_{CD}$ (MPa)/Ratio(1)</th>
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</table>

Under a fixed inclination angle, the AE parameters were small in the initial loading stage, and the slope of the relationship between “accumulated AE parameters and time” was low. The coal specimen had only a few AE events at this stage, corresponding to the I and II stages. As the load increased, when the CI threshold was reached, the number of AE events increased, and the slope of the curve of the relationship between “accumulated AE parameters and time” increased, indicating that new cracks were generated at this stage and expanded slowly, corresponding to stage III. AE events increased significantly when the load reached the CD threshold. The accumulated AE parameters and time rose quickly, and the internal cracks of the coal specimen penetrated each other, which is shown as stage IV.

The CC threshold, CI threshold, and CD threshold of coal specimens decreased with the increase in the inclination angle, which is basically consistent with the changing trend of the peak stress with the inclination angle. When the inclination angle was $0^\circ$, the CC threshold, CI threshold, and CD threshold were 3.52 MPa, 5.97 MPa, and 11.91 MPa, respectively. Compared with the inclination angle of $0^\circ$, the CC threshold decreased by 24.15% ($\theta = 5^\circ$), 34.94% ($\theta = 10^\circ$), and 51.99% ($\theta = 15^\circ$). The CI threshold decreased by 24.56% ($\theta = 5^\circ$), 38.87% ($\theta = 10^\circ$), and 51.34% ($\theta = 15^\circ$). However, the ratios of the CC threshold, CI threshold, and CD threshold to the peak stress were in the range of 0.22–0.24, 0.35–0.41, and 0.71–0.83, respectively, and basically did not change with the inclination angle. Therefore,
the CC threshold, CI threshold, and CD threshold of cracks can be predicted by the peak stress of the coal pillar.

The characteristics of the CI threshold and CD threshold which decreased with the increase in the inclination angle are explained as follows: The increase in shear stress is conducive to the reopening of the internal cracks and the formation of new cracks after the elastic stage \([7,48]\). The increase in the inclination angle leads to an increase in the additional shear stress component inside the specimen, which accelerates the initiation and propagation of cracks in the coal specimen, resulting in a decrease in the CI threshold with the increase in the inclination angle. In addition, when the load is close to the peak stress of the specimen, the microcracks are dominated by shear failure, which dominates the expansion and intersection of microcracks \([39,49]\). In the uniaxial compression test, the shear stress inside the specimen is indirectly induced by the compressive stress. Thus, a strong axial load is required to promote the shear failure of the microcracks. However, under oblique loading, the additional shear stress aggravates the shear stress concentration at the tip of the microcrack, resulting in the failure of the specimen at lower loads. Therefore, the CD threshold decreases as the inclination angle increases.

In order to facilitate the analysis process, a 10° inclination angle was used to determine the AE characteristics of coal specimens at different moisture contents. Figure 15 shows the relationship between stress, AE parameters, cumulative AE parameters, and time at different moisture contents. Figure 16 shows the variation in the CC threshold, CI threshold, and CD threshold and their ratios \((σ_{CC}/σ_C, σ_{CI}/σ_C, σ_{CD}/σ_C)\) with the moisture content. Table 2 shows the specific values. The main conclusions are as follows.

![Figure 15. Cont.](image-url)
Figure 15. Curves of cumulative AE parameters (counts and energy) versus time at different moisture contents when the inclination angle was 10°: (a) \(\omega = 0\%\); (b) \(\omega = 2.42\%\); (c) \(\omega = 5.53\%\); (d) \(\omega = 7.55\%\); (e) \(\omega = 10.08\%\).

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>0</th>
<th>2.42</th>
<th>5.53</th>
<th>7.55</th>
<th>10.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{CC} \text{ (MPa)/Ratio(1)})</td>
<td>Cumulative AE count</td>
<td>4.33/0.24</td>
<td>3.48/0.23</td>
<td>2.52/0.24</td>
<td>1.69/0.24</td>
</tr>
<tr>
<td></td>
<td>Cumulative AE energy</td>
<td>4.33/0.24</td>
<td>3.48/0.23</td>
<td>2.52/0.24</td>
<td>1.69/0.24</td>
</tr>
<tr>
<td></td>
<td>Average value</td>
<td>4.33/0.24</td>
<td>3.48/0.23</td>
<td>2.52/0.24</td>
<td>1.69/0.24</td>
</tr>
<tr>
<td></td>
<td>Cumulative AE count</td>
<td>7.08/0.39</td>
<td>5.58/0.36</td>
<td>4.08/0.39</td>
<td>2.88/0.41</td>
</tr>
<tr>
<td>(\sigma_{CI} \text{ (MPa)/Ratio(1)})</td>
<td>Cumulative AE energy</td>
<td>7.01/0.38</td>
<td>5.55/0.36</td>
<td>3.96/0.38</td>
<td>2.85/0.41</td>
</tr>
<tr>
<td></td>
<td>Average value</td>
<td>7.05/0.38</td>
<td>5.57/0.36</td>
<td>4.02/0.39</td>
<td>2.87/0.41</td>
</tr>
<tr>
<td></td>
<td>Cumulative AE count</td>
<td>14.49/0.79</td>
<td>12.12/0.79</td>
<td>8.83/0.85</td>
<td>5.84/0.83</td>
</tr>
<tr>
<td>(\sigma_{CD} \text{ (MPa)/Ratio(1)})</td>
<td>Cumulative AE energy</td>
<td>14.27/0.78</td>
<td>12.21/0.79</td>
<td>8.76/0.85</td>
<td>5.75/0.82</td>
</tr>
<tr>
<td></td>
<td>Average value</td>
<td>14.38/0.78</td>
<td>12.17/0.79</td>
<td>8.80/0.85</td>
<td>5.80/0.83</td>
</tr>
</tbody>
</table>
Figure 15. Curves of cumulative AE parameters (counts and energy) versus time at different moisture contents when the inclination angle was 10°: (a) the CC threshold, CI threshold, and CD threshold; (b) the ratio of the CC threshold, CI threshold, and CD threshold to $\sigma_c$ varied with the moisture content.

Under a fixed moisture content, the variation characteristics of the slope of the “accumulated AE parameters–time” curve of coal specimens were consistent with the slope characteristics of the “accumulated AE parameters–time” curve at any inclination angle, indicating that the evolution law of the AE parameters has nothing to do with the moisture content.

The CC threshold, CI threshold, and CD threshold of coal specimens decreased with the increase in the moisture content, which is basically consistent with the changing trend of the peak stress with the moisture content. When the moisture content was 0%, the CC threshold, CI threshold, and CD threshold were 4.33 MPa, 7.05 MPa, and 14.38 MPa, respectively. Compared with the moisture content of 0%, the CC threshold decreased by 19.63% ($\omega = 2.42\%$), 41.80% ($\omega = 5.53\%$), 60.97% ($\omega = 7.55\%$), and 85.22% ($\omega = 10.08\%$). The CI threshold decreased by 21.06% ($\omega = 2.42\%$), 42.98% ($\omega = 5.53\%$), 59.36% ($\omega = 7.55\%$), and 84.54% ($\omega = 10.08\%$). The CD threshold decreased by 15.40% ($\omega = 2.42\%$), 38.84% ($\omega = 5.53\%$), 59.70% ($\omega = 7.55\%$), and 84.63% ($\omega = 10.08\%$). However, the ratios of the CC threshold, CI threshold, and CD threshold to peak stress were 0.23–0.24, 0.36–0.41, and 0.78–0.85, respectively, and did not change with the moisture content. Therefore, the CC threshold, CI threshold, and CD threshold of cracks can be predicted by the peak stress of the coal pillar.

In view of the characteristics that the crack CI threshold and CD threshold decrease with the increase in the moisture content, the increase in the moisture content leads to the dissolution of soluble mineral particles in the coal specimen, which increases the lubrication effect of water on cracks [1], resulting in the initiation and propagation of internal cracks in coal specimens under small loads. Therefore, the CI threshold gradually decreases since shear failure dominates the expansion and intersection of microscopic cracks [39,49]. With the increase in the moisture content, the proportion of shear cracks gradually increases, indicating that the proportion of internal shear stress components in the coal specimen also increases. This increases the concentration of shear stress at the crack tips, resulting in damage and destruction of coal specimens at lower loads, as shown in Section 4.1. Therefore, the CD threshold decreases with the increase in the moisture content.

5. Conclusions

This paper used C-CAST and AE monitoring systems to analyze the mechanical properties and microfracture characteristics of water-bearing coal specimens under a cou-
pled compression–shear load. According to the test results, the following conclusions can be drawn:

(1) When the moisture content was less than 7.55%, the peak shear stress increased according to the inclination angle. Still, when the moisture content was 10.08%, the peak shear stress first increased and then decreased according to the inclination angle. The stress showed an obvious moisture content weakening effect; the peak stress and elastic modulus of coal specimens showed significant moisture content and inclination angle weakening effects. The progressive decrease in the peak stress and elastic modulus was especially susceptible to a high moisture content and a considerable inclination angle.

(2) Microcrack expansion and penetration in the coal specimens were controlled by shear cracks. Under a low moisture content ($\omega = 0\%, 2.42\%$), the macroscopic fracture mode of the coal specimens progressively shifted from tensile to shear failure as the loading inclination increased. At a medium moisture content ($\omega = 5.53\%$), the coal specimen mostly showed a combination of tension and shear failures. At a high moisture content ($\omega = 7.55\%, 10.08\%$), the coal specimen mostly showed a shear-based failure. The higher the ratio, the better the integrity of the coal specimen when it is damaged. The crack mode indicated by the AE characteristic parameters was consistent with the coal specimen’s macroscopic damage characteristics.

(3) When the moisture content was 7.55%, the CC threshold, CI threshold, and CD threshold decreased as the angle of inclination increased, but their ratio to the peak stress stayed in the range of 0.22–0.24, 0.35–0.41, and 0.71–0.83, respectively. This means that they did not change with the angle of inclination. At a 10° inclination angle, the CC threshold, CI threshold, and CD threshold all decreased with increasing moisture content, but their ratios to the peak stress remained constant in the range of 0.23–0.24, 0.36–0.41, and 0.78–0.85, respectively.

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References


33. Choens, R.C.; Chester, F.M. Characterizing Damage Evolution and Yield in Sandstone under Triaxial Loading as a Function of Changing Effective Pressure; Texas A & M University: College Station, TX, USA, 2011.


47. Zong, Y.; Han, L.; Wei, J.; Wen, S. Mechanical and damage evolution properties of sandstone under triaxial compression. *Int. J. Min. Sci. Technol.* 2016, 26, 601–607. [CrossRef]
