INTRODUCTION

Groundwater reservoir technology is a scheme proposed to protect groundwater resources in the context of the widespread shortage of water and ecological damage in China's ecologically fragile mining areas. The strategic center of coal resources in China has shifted to the ecologically fragile mining areas in the central and western regions. In 2018, the total output of raw coal in the five provinces of Inner Mongolia, Shanxi, Shaanxi, Xinjiang, and Ningxia accounted for 76.2% of the country's total coal production. However, water resources in these provinces are scarce, accounting for only 6.67% of the total reserves. Water has become the main reason for restricting the scale of coal mining to protect the ecology in the region, which can be damaged by large-scale, high-intensity mining (e.g., aquifuge rupture, groundwater loss, surface drought, and safety accidents). To alleviate the conflict between coal production and water conservation, water-retaining mining technology has been developed to protect aquifers, and underground reservoir technology has been proposed to store water in goafs. After an aquifer is destroyed, underground reservoir technology can protect water
resources by connecting safety coal and rock pillars in goafs via artificial dams to form a storage space (see Figure 1).

Water causes long-term damage to the mechanical properties of coal pillars. Other underground operations in water-rich environments also weaken coal and rock due to water erosion. Differences in the structural components of coal and rock masses lead to different regularities in the mechanical properties of coal and rock after water absorption. Water absorption increases the plastic yield and softening degree of rock\(^{10}\) and decreases the elastic modulus, stiffness, compressive strength, tensile strength,\(^{11-13}\) and brittleness of hard rock and the possibility of rock burst.\(^ {14}\)

Shear failure is a common failure form in engineering. A shear load can easily weaken the internal structure and break the interface between different media, thereby promoting the propagation of shear cracks and increasing the number of microcracks.\(^ {15}\) Acoustic emission (AE) technology has been used to nondestructively detect cracks and assess damage\(^ {16,17}\) and may be used to divide the crack development process in brittle materials into five stages: crack closure, elastic deformation, stable crack development, unstable crack development, and the postpeak stage.\(^ {18}\) This technology can also obtain the thresholds of each stage\(^ {19,20}\) and classify crack types.\(^ {21}\)

In addition, high-resolution three-dimensional (3D) X-ray microscopy (3D-XRM) or computed tomography of rock offers another route to study the internal pore and crack distribution in rock materials and solid waste.\(^ {22-25}\) Previous studies have investigated how macroscopic features, microscopic composition, and structure affect the shear behavior of rocks under compression.\(^ {26}\) However, few studies have investigated the mechanical properties and crack propagation of coal samples with different water content and under compression shear.

Figure 1 shows that the force on a coal pillar includes not only the overburden pressure but also the shear force formed by the lateral gangue pressure and water pressure in the coalbed-bedding direction. Shear force along a weak surface cannot be ignored, because the shear strength is less than the compressive strength. Therefore, to design the size of coal pillars in underground reservoirs and for other underground engineering problems involving water, the use of compression-shear tests provides important information about shear strength and crack propagation in coal samples with arbitrary water content.

2 | EXPERIMENT

2.1 | Selection and processing of coal samples

This study uses coal samples selected from the 3-1# coal seam in China’s Wulan Mulun coal mine as the research object. The mine is located in Ordos City in the Inner Mongolia Autonomous Region. To guarantee the integrity of the raw coal samples, they were processed according to the specifications of the International Society for Rock Mechanics and Rock Engineering\(^ {27}\) and the Chinese regulations for testing physical and mechanical properties of rock (DZ/T0276.25-2015).\(^ {28}\) Thirty-six standard cubic samples 50 mm × 50 mm × 50 mm in size were divided into four groups according to their water content, shear angle, and sequence (Table 1). For example, in group one, including

![FIGURE 1 Schematic diagram of underground reservoirs in a coal mine](image-url)
W1-1-2 ~ W3-3-3 (nine pieces in total), the label W1-2-3 indicates the third sample with a water content of 0% tested at an angle of 55°.

2.2 Test equipment and methods

The samples were dried using a thermostatic drier (101-2, Shanghai Laboratory Instrument Works, China). Following the requirements (DZ/T0276.25-2015), the samples were dried at 105°C, which is slightly above the evaporation point of water. The drying process did little damage to the internal structure of the samples, because free water inside the samples was evaporated, whereas combined water was not affected.

Figure 2 shows the testing apparatus. The dry samples absorbed moisture freely in the saturated humid environment created by the nondestructive immersion equipment. Had the samples been directly immersed in tap water (from the laboratory), they would have disintegrated due to water absorption by the internal clay minerals and subsequent expansion.

The compression-shear tests were applied to coal samples with different water content using a microcomputer-controlled electronic universal testing machine (CMT5305, Shenzhen Xinsansi Testing Instrument Co., Ltd., China). The force imposed on the coal samples by the clamps was decomposed into normal stress perpendicular to the shear plane and shear stress parallel to the shear plane. Upon increasing the loading stress to a certain point, the shear forces in the samples exceeded the sum of the cohesive force and internal friction, causing sample damage and/or failure. By changing the fixture angles, different mechanical parameters were obtained.

During the compression-shear tests, an AE system (PCI-2, Physical Acoustics, USA) was used to monitor AE signals inside the samples. Because the cubic coal samples had only two exposed faces (one in front and one behind), the AE sensors were attached to the centers of the two exposed faces. 3D-XRM (Carl Zeiss AG, Germany; operated at 70 kV, 86 μA) was used for three-dimensional nondestructive scanning imaging of the failed coal samples and analysis of the spatial distribution of minerals and pores in these sample fragments. The maximum scanning diameter was 54 mm, and the exposure time was 6 seconds. Each sample was scanned repeatedly to generate over 1000 images per sample.

| TABLE 1 | Definitions of sample labels |
|------------------------------------------|-----------------------------|
| Label 1 | W1 | W2 | W3 | W4 |
| Water content | 0.00% | 5.35% | 17.88% | 20.40% |
| Label 2 | W1-1 | W1-2 | W1-3 |
| Shear angle | 45° | 55° | 65° |
| Label 3 | W1-1-1 | W1-1-2 | W1-1-3 |
| Sequence | No. 1 | No. 2 | No. 3 |

2.3 Innovation

1. A self-developed, nondestructive, water immersion device was used to avoid disintegration and destruction of coal samples after water absorption.
2. The mechanical variation characteristics and crack development process of the samples could be systematically studied from the macroscopic and microscopic perspectives through microcomputer-controlled electronic universal testing, acoustic emission, and three-dimensional X-ray microscopy and processing systems.
3. The test data were combined with the three-dimensional structures of the samples for analysis of the characteristics of the failed samples.

3 Evolution of shear strength in water-bearing coal

3.1 Water absorption by coal samples

Figure 3 shows the relationship between the moisture content of coal samples and the water immersion duration. We divided the curve into four phases based on the slope: (I) rapid rise in the sample surface, (II) rapid rise in the sample bulk, (III) slow rise, and (IV) stable phase.

From 0 to 9 hours, water is rapidly absorbed onto the surfaces of initially dry samples, and the water content increases with the immersion duration. From 9 to 23 hours, water gradually penetrates into the sample interior, and the moisture content increases rapidly but at a slightly slower rate than in stage I. From 23 to 62 hours, relatively complete infiltration channels form inside the sample, which allows water to completely penetrate the coal sample. The water content continues to increase, although the rate of increase decreases. From 62 to 122 hours, the moisture content of the coal samples remains essentially constant, which means that the coal sample has reached a saturated, watery state. The water content at 0, 9, 23, and 62 hours was 0%, 5.35%, 17.88%, and 20.40%, respectively.

We fit the water content data to the exponential function.

\[ w = 0.2072 \left(1 - e^{-0.0994t} \right)^{2.4924}, \quad R^2 = 0.98, \quad (1) \]

where \( w \) is the moisture content (%), \( t \) (hours) is the humidification time (ie, the time interval during which the coal sample was immersed in water using the nondestructive water immersion equipment), and \( R^2 \) is the correlation coefficient for the fit.

Equation (1) provides an excellent fit to the water immersion curve and can quantify the dynamic water absorption by the coal samples. The formula is convenient for determining
the time interval during which the coal samples are immersed in water and for laying a foundation for subsequent tests.

3.2 | Shear stress and shear displacement

Figure 4 shows the shear stress-shear displacement curves for coal samples with different water content. Based on the variations in these curves, we divide the loading process of coal samples into five stages: crack closure, elastic deformation, stable crack development, unstable crack development, and the post-peak stage. In the crack closure stage, the primary cracks inside the coal samples are closed by pressure, and the shear stress increases slowly with increasing shear displacement. In the elastic deformation phase, the slope of the shear stress-shear displacement curve is smaller for larger water content; that is, the shear modulus decreases. Water weakens and damages the internal structure of the samples and changes the microscopic sample composition and structure, thus degrading the mechanical properties of the samples.29 The duration of stable and unstable crack development correlates negatively with the water content.

The degree of water damage to the coal samples depends mainly on their mineral compositions, structures, and stress states. The softening effect of water causes the sample shear strength to decrease significantly with the increasing water content. In the postpeak stage, the shear stress of the dry samples suddenly drops, and almost no residual strength remains. Strain softening means that a shear zone forms.30 When the moisture content increases from 0% to 20.40%, the shear strength decreases from 5.82 to 1.00 MPa (82.82%). Water infiltrates the original pores and cracks of the coal samples and generates hydrostatic pore pressure, which causes pore expansion when the samples are loaded and reduces their ability to resist shear damage.31 The corresponding shear displacement of the samples is reduced from 2.21 to 1.10 mm (50.23%). From the microscopic perspective, water changes the microstructure through complex physical and chemical interactions inside the samples and attenuates the cohesion and friction between the sample particles, thereby rendering them more prone to damage.
Based on many engineering problems and much practical experience, Coulomb believed that the failure type of brittle rock materials was mainly shear failure and that failure at the shear plane was determined by both normal and shear stress. In 1773, he proposed the Coulomb criterion. Mathematical calculations and experimental verification led to the following formula for calculating the shear strength of a brittle rock mass:

\[ \tau = c + \sigma \tan \varphi \]  \hspace{1cm} (2)

where \( \tau \) is the shear strength, \( \sigma \) is the normal strength, \( c \) is the cohesion, and \( \varphi \) is the internal friction angle.

In engineering practice, cohesion and the internal friction angle are important indicators for evaluating the shear resistance of coal and rock masses. The mutual attraction between molecules inside the materials (i.e., the cohesion) causes the molecules to coalesce into a whole. The internal friction angle is a comprehensive concept that combines sliding and occlusion friction. Therefore, during the sample failure process, cohesion is closely related to the appearance of fractures, whereas the internal friction angle is related to the expansion, dislocation, and destruction of fractures.

Both the sample cohesion and internal friction angles decrease with the increasing water content (see Figure 5). In the dry state, the cohesion and internal friction angle are 1.22 MPa and 40.7°, respectively, and reach 0.52 MPa and 37.95° in the saturated state, which represents decreases of 57.38% and 6.76%, respectively. This finding also indicates that water affects shear strength mainly by changing the cohesion and internal friction angles. These results lead to the following Mohr-Coulomb model for coal samples with an arbitrary water content:

\[ \tau = -0.03w + 1.22 + \sigma \tan (2.65 \times 0.83w + 38.04) \]  \hspace{1cm} (3)

When water molecules enter the internal lattice of coal samples, they form water films between particles, weaken the microstructural mechanical properties of the particles, and reduce cohesion and the initial shear force required to destroy the samples. Thus, a greater moisture content corresponds to lower cohesion. Water contains not only water molecules but also hydroxide and hydrogen ions. Under neutral conditions, the water-soluble functional groups and the metallic and nonmetallic ions in raw coal are partially dissolved in water, and slow chemical reactions occur; that is, the acidic ion groups react with the hydroxide ions, and the alkaline ion groups react with the hydrogen ions. This behavior strips off the material composition of the original structure and physically weakens it; this process can also change the original structural state through chemical reactions, causing chemical weakening. Under loading conditions, this process leads to a decrease in the internal friction force that must be overcome to cause damage. Therefore, on a microscopic level, an increase in the water content decreases the intermolecular and frictional forces that need to be overcome to damage the sample, whereas on the macroscopic level, the cohesion and internal friction angle of the coal sample decrease, which facilitates sample damage.

4 | CRACK PROPAGATION DUE TO WATER

4.1 | Influence of water on acoustic emission counts

As shown in Figure 6, the shear stress-shear displacement curves have several peaks. AE counts are relatively concentrated near the peak shear stress, and individual events with larger values occur. A very small number of AE data beyond 300 are not shown in the graph; they will...
be considered in the sample failure analysis. AE activity is affected by the internal particle size, primary fissures, and lattice structure of the samples. In the early stages of loading, AE events are caused mainly by closure, extrusion, and dislocation of original cracks and pores in the samples, and the AE signals are relatively stable. In the later stage of loading, AE events are due to continuous expansion, sliding friction, and failure due to penetrating cracks, and the number of intense AE events increases.

In the crack closure stage, the primary cracks and pores in the coal samples with different water content begin to close under the combined action of compressive and shear stresses. The asymmetric meshing of the crack edges and the reconstruction of the structure produce a small number of AE signals. In the elastic stage, the shear stress-shear displacement curve is almost linear, and the slope remains constant (i.e., the shear modulus is constant); then, the AE signals are detected. During the stable crack propagation stage, AE signals continue to be emitted, albeit at a lower rate than in the elastic stage, which indicates that the fractures propagate steadily without large variations in structure or stress.

The coal samples enter the unstable crack propagation stage when the first relatively noticeable peak appears in the shear stress-shear displacement curve. Next, several
small peaks appear at the point when the AE signals are significantly enhanced, and the AE counts are greater than those in the previous stage. Compared with those of the dry state, the AE frequency and counts are reduced in the same crack development stage. The maximum AE count in the dry (saturated) state is 3579 (152); therefore, the saturated state has only 4.24% of the counts of the dry state.

We attribute this result to water molecules entering the particle gaps in the coal samples and weakening both the connection capacity between particles and strength of the particle crystals through complex physical and chemical reactions. As a result, a small amount of energy can cause fractures to develop and samples to fail. Macroscopically, a small number of AE signals are detected, which indicates that a greater water content leads to greater weakening. The AE counts are consistent with the shear stress–shear displacement curve, which indirectly reflects the physics of internal crack development and energy release from the coal samples.\(^3\)\(^8\),\(^3\)\(^9\)

### 4.2 Effect of fracture on cumulative acoustic emission counts and shear stiffness

Figure 7A shows that the cumulative AE counts correlate well with the shear displacement-shear stress curves, which can help discern various stages during fracture evolution. This correlation plays an important role in understanding the mechanical properties involved in rock damage in underground engineering. The crack closure phase (from A to B) contains almost no cumulative AE counts. A small external loading force leads to an inconsistent crack surface, and AE activities are required to overcome friction and close the crack; therefore, a small number of AE signals are detected.

During the elastic phase [from B to C in Figure 7A], both the loading force and cumulative AE counts are linear during shear displacement, which means that the coal specimens store elastic energy. This stage is reversible.

During the stable crack development stage [from C to D in Figure 7A], the cumulative AE count curve continues to increase, and the shear displacement-shear stress curve is approximately linear, but its slope is greater than during the elastic phase.

During the unstable fracture development stage [from D to E in Figure 7A], the shear displacement-shear stress curve starts after a small peak and passes through several small peaks until it reaches the maximum. During this time, the cumulative AE counts increase rapidly with large fluctuations, which signify that the internal structure and stress distribution of the sample have changed dramatically. This stage is irreversible. When the coal sample fails, a very large sound is generated, and the cumulative AE counts rise dramatically.

To analyze the shear displacement-shear stress curve and more accurately describe the mechanical failure process of coal samples immersed in water, in Figure 7B we plot the shear stiffness before peak shear strength as a function of shear stress to help determine the stress threshold for fracturing. The formula for shear stiffness is

\[
k = \frac{\tau}{l},
\]

where \(k\) is the shear stiffness, \(\tau\) is the shear stress, and \(l\) is the shear displacement.

Figure 7B shows that during the fracture closure phase (from A to B), the shear stiffness-shear stress and shear displacement-shear stress curves both rise rapidly, but the slopes decrease gradually. From B to C, the shear stiffness curve is approximately linear. The coal sample completes internal crack closure and begins to enter the elastic phase. Point C demarks the end of the elastic phase and the start of the stable crack propagation stage, wherein the shear stiffness reaches
its maximum. This stage extends from point C to point D and is quite stable.

Point D marks the plastic yield point, following which time the shear stress continues to increase and the shear stiffness decreases with some fluctuations. Here, the coal sample enters the unstable crack propagation stage. These results demonstrate that shear stiffness near the peak shear stress is not the maximum stiffness; instead, the maximum stiffness is concentrated in the stable crack development stage, where the ability to resist deformation is strongest.

In the unstable fracture propagation stage, the damage is more severe, the through crack is obvious, and the shear stiffness decreases. At point E, indicating peak shear strength, the coal sample is mechanically ineffective, and shear stiffness is lowest. The shear stiffness–shear stress curve corresponds well with the shear displacement–shear stress curve, which shows every stage of crack development before the coal sample fails.19,20 With the help of the cumulative AE counts, these curves complement and confirm each other.

### 4.3 Stress thresholds for crack closure, initiation, and damage

Figure 8 shows that the stress threshold has an approximately linear relationship with the water content. The fits give the stress threshold of coal samples for different water content. Crack closure stress decreases with the increasing water content. When water enters the sample interior, it degrades the mechanical properties and reduces the shear modulus; thus, the samples occupy a lower stress state in the elastic phase, which eases their entry into the plastic phase. As the water content increases from 17.88% to 20.4%, the crack initiation stress decreases by 62% from 1 to 0.38 MPa.

As the water content increases, the crack damage stress decreases, which is contrary to the effect on the moisture content as a function of the immersion time (see Figure 3). From the dry state to the early water-containing state, the samples rapidly absorb moisture and are remarkably weakened. Lowering the loading stress makes the coal samples enter the unstable crack development stage, which indicates that water helps redistribute stress in the samples.

When samples reach the saturation stage, the crack damage threshold again decreases significantly. Figure 9 shows that the ratios of the crack closure, crack initiation, and crack damage stress to the peak shear stress remain approximately constant at 11.57%, 35.64%, and 68.87%, respectively. Thus, the stress thresholds are independent of the water content. Therefore, to determine the crack development stage of coal samples, the stress thresholds can be estimated by measuring the peak shear stress as a function of the water content. Among them, crack damage stress is discrete. Formation of the fracture structure further promotes the softening action of water and conduction of stress, and the unevenness of the internal structural surface. In addition, because coal samples have a non-uniform internal composition, the cracks cannot be accurately

![Figure 8](image)

**FIGURE 8** Stress threshold as a function of the water content

samples is the main cause of the difference in the crack damage stress threshold.

### 4.4 Crack type and spatial morphology

Cracks in coal or rock have been classified in terms of the rise time divided by the peak amplitude (RA) and the average frequency (AF).21 A low RA and high AF indicate tensile cracks, whereas a high RA and low AF indicate shear cracks. Figure 10 shows the AF as a function of the RA for coal samples with various water contents, with the color code indicating the relative density of the data points. Most data are concentrated in the range 0-100 ms/v and 50-200 kHz. In other words, the data are largely concentrated at a low RA and high AF. At a high RA and low AF, the data points are relatively sparse.

Most cracks in coal samples containing water are tensile cracks, although obvious shear cracks occur when samples are damaged. During loading, debris caving occurs, and the sound diminishes with an increasing water content. In the Griffith strength theory, the zone near a crack tip is susceptible to stress concentration, resulting in crack expansion or destruction. Coal samples have an anisotropic fracture distribution, and thus, tensile cracks are easily produced under loading conditions, and their sizes and shapes are related to the power released. At the microscopic level, rock particles are squeezed in one direction and stretched in other directions. A twisting effect occurs when the structure is asymmetrical.

Tensile cracks play an important role in the present study. The presence of many tensile cracks can change the stress in the internal structure of coal samples, which complicates the internal structural stress and recloses and expands the structural surface. In addition, because coal samples have a non-uniform internal composition, the cracks cannot be accurately
monitored or controlled. The increasing water content weakens the cementation state, surface state, and stress distribution among the microscopic coal particles, which increases the relative interval of plastic development and buffers the energy released by sample damage. Therefore, the lower probability density in Figure 10D is consistent with fewer microcracks.

Fracture development in the $x$-$y$, $x$-$z$, and $y$-$z$ planes is intercepted at the sample center. The $y$-$z$ plane is shown in Figure 11 for analysis. The pixel concentrations in the figure panels are related to the material density, with a higher density corresponding to a brighter color. Pore and crack densities are the lowest (shown in black), whereas the highest mineral density appears bright white, and the density of the coal matrix is medium (shown in gray).

The main shear crack in the $y$-$z$ plane of the dry sample exhibits a tree-like trend. More secondary cracks appear near the main shear crack running primarily in the same direction as the main crack. The vertical cracks are also relatively obvious. Under the shearing force, the internal particles of the samples

**FIGURE 9** Ratio of the stress threshold to shear strength

**FIGURE 10** Probability density map for AF versus RA. The color code indicates the relative density of the data points. The water content is (A) 0%, (B) 5.35%, (C) 17.88%, and (D) 20.40%
stagger and slip, and the fine particles that collapse fall between the cracks, preventing them from closing and promoting their expansion.

Figure 11B shows the sample with the 5.35% water content, in which the main shear crack is the clearest, and the secondary shear cracks are the least clear. Because the sample integrity is good, it remains in good condition after shear failure. Two large cracks run parallel to the main crack at the edge of the specimen and are accompanied by several small fissures perpendicular to the main crack. These cracks develop because shear stress is the main force.

Lateral expansion occurs in the direction of compressive stress and generates a complex stress state of tension, shear, and compression that damages the sample. Increasing the water content to 17.88% significantly increases the number of secondary cracks running parallel to the main fracture surface. The morphology of the secondary cracks is similar to that of the main crack, because water in coal samples promotes the redistribution of stress during loading.

The resulting morphology also reveals the layered structure of the coal sedimentary rock. In the saturated state, almost all cracks run parallel to the main crack but are few and small. The cracks connect to other structural cracks under pressure to form a macroscopic parallel pattern of cracks. The action of water disperses the loading stress in the coal sample, and the irregular cracks are reduced but still dominated by the preset shear pressure.

As the water content ranges from dry to saturation, a substantial difference appears in the crack size after failure. The shape of the main cracks changes from staggered to neat and flat. The secondary cracks are fewer and change from an irregular distribution with a transverse stagger to gradually become parallel to the main cracks. The AE corresponding to shear failure ranges from violent to slight. The crack distribution patterns in the samples with different water content indicate that moisture in the samples affects the development of fracture morphology. The distribution of internal stress in the samples is made uniform by the transfer of stress, which reduces the sudden release of energy caused by local stress concentration and disordered cracks.

Three-dimensional visualization software (ORS Visual SI, Canada) was used to further scan the samples and obtain 3D reconstructed images of their internal cracks. The blue portions in Figure 12 represent the spatial forms of cracks, and the elliptical regions denote the main shear cracks. Associated fractures appear on both sides of the main fracture surface. The small number of and least connected fractures occur in the saturated state. Cracks in the dry or partially hydrated state are relatively complete and offer good water conduction. After absorbing a certain amount of water, some cracks close, and the water-conducting channels diminish, which inhibits water penetration. In other words, brittle failure promotes the development of pores and fissures and enhances the connectivity between pores, whereas

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**FIGURE 11**  Planes of failed samples (four left panels) and a schematic diagram of the interception method prepared with the 3D-XRM system (right panel)

**FIGURE 12**  Three-dimensional reconstruction of cracks created using ORS Visual SI
plastic failure rearranges the structure of the coal and rock materials, enhances the homogeneity, and degrades the pore connectivity.

5 | CONCLUSIONS

The mechanical properties, AE characteristics, and crack evolution were studied in coal samples with differing water content using compression-shear test and AE tests. The results lead to the following conclusions.

1. The curve of water content versus immersion duration is approximately exponential. The water absorption curve is divided into four stages: a rapidly rising phase on the sample surface (0-9 hours), a rapidly rising phase in the bulk (9-23 hours), a slowly rising phase (23-62 hours), and a stable phase (62-122 hours).

2. The water content affects the shear stress-shear displacement curve. Shear strength and the corresponding shear displacement, cohesion, and internal friction angles decrease with the increasing water content, which is described by the Mohr-Coulomb model including moisture content.

3. The change in AE counts is consistent with shear stress. According to the relationships among the cumulative AE counts, shear stiffness, and shear stress, crack development is divided into five stages: crack closure, elastic deformation, stable crack development, unstable crack development, and the postpeak stage.

4. The stress thresholds for each stage of crack development decrease with the increasing water content, whereas the ratios of the crack closure, crack initiation, and crack damage stress to the peak shear stress remain basically constant at 11.57%, 35.64%, and 68.87%, respectively, which can help estimate the various stages of fracture development.

5. The sizes and shapes of cracks are closely related to the internal structure and water content of coal samples, and water weakens the internal cementation. Under the action of water, the RA remains low, and the AF distribution is relatively uniform. Tensile cracks are common during loading. The computed tomography results show that an increase in the water content can promote the development of parallel cracks in coal samples.

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