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Xie Beijing¹

China University of Mining and Technology(Beijing)

Zhang Ben¹

BQT2210103031@student.cumtb.edu.cn

China University of Mining and Technology(Beijing)

Zhao Shunkun²

Guizhou University

Wei Shanyang²

Guizhou University

Wu Xingjie²

China University of Mining and Technology(Beijing)

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Microscopic fatigue damage behaviour due to dry and wet cycling on the deterioration law of mechanical properties of coal bodies with different water saturation levels

Xie Beijing¹ Zhang Ben¹ * Zhao Shunkun² Wei Shanyang² Wu Xingjie²

1. School of Emergency Management and Safety Engineering, China University of Mining and Technology(Beijing), Beijing 100083, China;

2. School of Mining, Guizhou University, Guiyang 550025, China

Abstract: Dynamic disasters are significant factors that limit the efficient and safe extraction of coal in mines. Dry-wet cycles, as a common natural phenomenon, are commonly encountered in engineering sites. To investigate the effects of dry-wet cycles on the microstructure and mechanical properties of coal seams, macro-micro experiments were conducted based on Computed Tomography (CT) three-dimensional reconstruction technology, Brunauer-Emmett-Teller (BET) nitrogen adsorption, and triaxial Hopkinson pressure bar. The impact of dry-wet cycles on the porosity structure, connectivity, deterioration mechanism, and mechanical properties of coal samples was qualitatively and quantitatively evaluated and analyzed. The results show that an increase in the number of dry-wet cycles leads to a rise in the number of coal sample pore cracks, while the connectivity, cumulative pore volume, and cumulative specific surface area first increase and then decrease. Dry-wet cycles weakened the peak strength of the coal samples, and the saturation water treatment further exacerbated the weakening effect, leading to a significant increase in the degree of coal sample damage. The weakening relationship is exponentially related to the number of cycles. The increase in pore water pressure, the reduction in shear strength, and the collapse of pore cracks, along with the dissolution of minerals, together contributed to the weakening of the coal sample's mechanical properties. Finally, the changes in the pore structure and mechanical properties of the coal seam were simulated. This joint analysis reveals the influence of dry and wet cycles on the microstructure and mechanical properties of coal, which provides a theoretical reference for the prevention and control of dynamic disasters in coal mines.

Keywords: Dry-wet cycles; CT 3D reconstruction; Triaxial loading; Numerical simulation; Deterioration mechanism

1. Introduction

As coal mining increasingly extends from shallow to deep layers, the problems of surrounding rock large deformation damage and dynamic disasters such as rock bursts during coal seam extraction in deep mines have become more prominent, making the situation increasingly severe. In the deep mining environment, the "three high" characteristics—high

ground stress, high ground temperature, and high pore pressure—are present. At the same time, strong mining-induced disturbances, intense rheological phenomena, and multi-physics field coupling occur, creating a highly challenging and complex geological and mechanical environment.[1-3].Building on this, the disturbances caused by coal seam extraction further exacerbate the complexity of the environment. Under the combined influence of these factors, significant changes occur in the stress field characteristics of deep coal seams, the fracturing properties of the coal-rock body, the movement of rock layers, and the accumulation and release patterns of energy.[4-7].In actual production processes, the natural environment in which coal seams are located is complex and variable, often affected by multiple cycles of dry-wet fluctuations, which in turn impact the microstructure of the coal-rock body and its macroscopic mechanical properties[8-14].In deep engineering, the mechanical properties of coal-rock bodies are influenced not only by their mineral composition, organizational structure, and loading conditions, but also by hydraulic factors, which cannot be overlooked. A significant body of research has revealed that water inside rocks plays a multidimensional role in the process of fracture propagation, primarily including the erosion of soluble substances within the rock, the increase in pore pressure, and the alteration of the micro-mechanism of internal fracture expansion. In deep, high-stress environments, water more easily infiltrates the pores of the coal-rock body. Therefore, research on the stability of coal-rock bodies in deep mines cannot bypass the impact of water. Continued research on the dynamic mechanical properties of coal-rock bodies under deep dry-wet cycle conditions is required, aiming to overcome the limitations of traditional mechanical property understanding in mining conditions, and to establish a new theoretical system for the mechanical properties of coal-rock bodies specifically tailored to dry-wet cycle coal seam extraction.

Since the concept of water-rock interaction (including coal) was proposed in the 1950s, it has attracted widespread attention[15-19].To gain a deeper understanding of the complex mechanisms behind the decline in the mechanical properties and structural instability of coal-rock systems, investigations are conducted from multiple dimensions. On one hand, the focus is placed on the microscopic changes in water-coal interactions, utilizing advanced microscopic observation technologies in an attempt to unveil the direct principles of interaction between water and coal-rock at the molecular and atomic levels. On the other hand, uniaxial, triaxial, and loading-unloading mechanical experiments are carried out to comprehensively capture the mechanical responses of coal-rock under various loading conditions.[20-24].The research found that the influence of water on crack propagation is primarily due to the difference in pore water pressure and the changes in the "resistance force" formed during crack propagation. The weakening of the dynamic mechanical strength of rocks is closely related to water absorption rate and absorption time. Therefore, static and dynamic loading tests were conducted on coal-rock samples with different water saturation times. The results showed that both the dynamic peak strength and elastic modulus of coal samples under dynamic and static loading conditions gradually decreased with increasing water saturation time, while the dynamic elastic modulus gradually increased. This led to the derivation of a fracture strength criterion for fractured rock masses under the influence of water. These findings make an important contribution to the mining of water-bearing coal seams.

With the deepening of research, extensive experimental and numerical studies have been conducted on the degradation and damage characteristics of coal-rock under multiple wet-dry cycles, focusing on the reservoir characteristics of water-bearing coal seams after experiencing numerous wet-dry cycles. These studies have yielded abundant research results.[14,25,26]From a fine microscopic perspective, various technical methods such as scanning electron microscopy (SEM)[27,28], low-field nuclear magnetic resonance (NMR) [29-31], and industrial CT [32,33]have been employed to deeply investigate the development and propagation direction of microcracks in coal-rock, as well as the underlying microscopic reaction mechanisms. These studies further elucidate the intrinsic relationship between coal-rock porosity and water content increase, and analyze the development of pore and crack structures. The results indicate that under the influence of wet-dry cycles, phenomena such as interfacial slippage, localized contact deformation, and mineral particle damage occur within the rock. These factors collectively induce plastic deformation and initial damage. By precisely quantifying the impact mechanisms of cyclic parameters on sandstone damage using porosity and T_2 spectrum variations, and qualitatively analyzing the microstructure and composition while introducing porosity parameters, the damage mechanisms of sandstone are revealed and characterized. Additionally, the evolution process of matrix particles in saturated and dried sandstone is demonstrated, ultimately leading to the construction of a W-D degradation model. Notably, through 3D reconstruction of CT scan images, precise, non-destructive detection was performed to deeply analyze the dynamic changes in parameters such as pore diameter, volume, porosity, and connectivity within sandstone. It was clearly observed that, with the gradual increase in the frequency of wet-dry cycles, the rock's porosity continuously increased, and the pore morphology became increasingly complex[34-36]. In the mechanical testing phase, coal-rock subjected to wet-dry cycles exhibited a downward trend in peak strength, with key mechanical strength indices—compressive, shear, and tensile strength—all showing an inverse correlation with the number of wet-dry cycles[37]. The mechanical parameters of sandstone were most significantly affected during the initial cycles, and the degradation effects induced by wet-dry cycles were observed to remain within certain limits. Using the acoustic emission (AE) system, the evolution of acoustic emission characteristic values during compression and impact loading tests under wet-dry cycles was deeply analyzed[38]. Based on monitoring results and the mechanical properties of coal-rock, mathematical analysis software such as MATLAB[39,40]was employed to collaboratively explore the differential variation characteristics of coal-rock failure modes driven by different wet-dry cycle conditions. This comprehensive approach provided a full-spectrum understanding of the performance of coal-rock under the influence of wet-dry cycles.

As described above, the microstructure and mechanical characteristics of coal-rock, such as porosity, permeability, peak strength, elastic modulus, and failure features, are all affected by wet-dry cycle treatment, leading to reduced coal-rock stability and inducing dynamic disasters in mines. Therefore, this study aims to investigate the effects and mechanisms of wet-dry cycles on the microstructure of coal during the wet-dry cycling process of coal seams. This is achieved through 3D reconstruction of CT scan images, combined with BET nitrogen adsorption and SEM analyses. Furthermore, based on the mining conditions of deep coal-rock subjected to pre-static three-dimensional stress and strong disturbances, triaxial Split

Hopkinson Pressure Bar (SHPB) testing equipment was used to examine the mechanical properties of coal samples under dry and saturated states after wet-dry cycling. Finally, using the geological conditions of the coal samples, a numerical model was established with COMSOL Multiphysics to simulate the microstructural changes and macroscopic mechanical behavior of coal during the wet-dry cycling process.

2.Sample Preparation and Pore Characteristics

2.1Sample Preparation

The coal samples used in the experiment were collected from the 19# coal seam at the 221908 mining face of the Shanjiaoshu Coal Mine, located 42 meters from the upper exit at a depth of 1268.3 meters. To ensure uniformity, all samples were taken from the same block of coal and subjected to longitudinal wave velocity testing prior to the experiment. Each coal sample was prepared with a height of 30 mm and a diameter of 50 mm, with end-face parallelism deviations of less than 0.02 mm. These specifications comply with the standards set by the International Society for Rock Mechanics (ISRM) for dynamic testing of rock samples.

The coal samples were subjected to different numbers of wet-dry cycles and divided into four groups corresponding to 0, 3, 6, and 9 cycles. A single wet-dry cycle involved vacuum-saturating the coal samples with water for 48 hours, followed by drying in a constant-temperature oven at 35°C for 24 hours. During the saturation and drying processes, the coal samples were weighed, and the cycle was considered complete when the weight stabilized, indicating full saturation or drying.

2.2Testing Methods

First, the coal samples were subjected to varying numbers of wet-dry cycles in the laboratory. Industrial rock CT scanning equipment was then used to scan the coal samples, capturing their pore and crack characteristics under different cycle conditions. The 3D pore and crack structures of the coal samples were reconstructed using AVIZO software. Additionally, the microstructural changes and mechanisms were analyzed and discussed using BET nitrogen adsorption and SEM techniques.

Finally, impact loading experiments were conducted using an improved Hopkinson bar system developed by China University of Mining and Technology (Beijing) to investigate the mechanical properties and failure characteristics of coal under different wet-dry cycles. The testing process is illustrated in Figure 1.

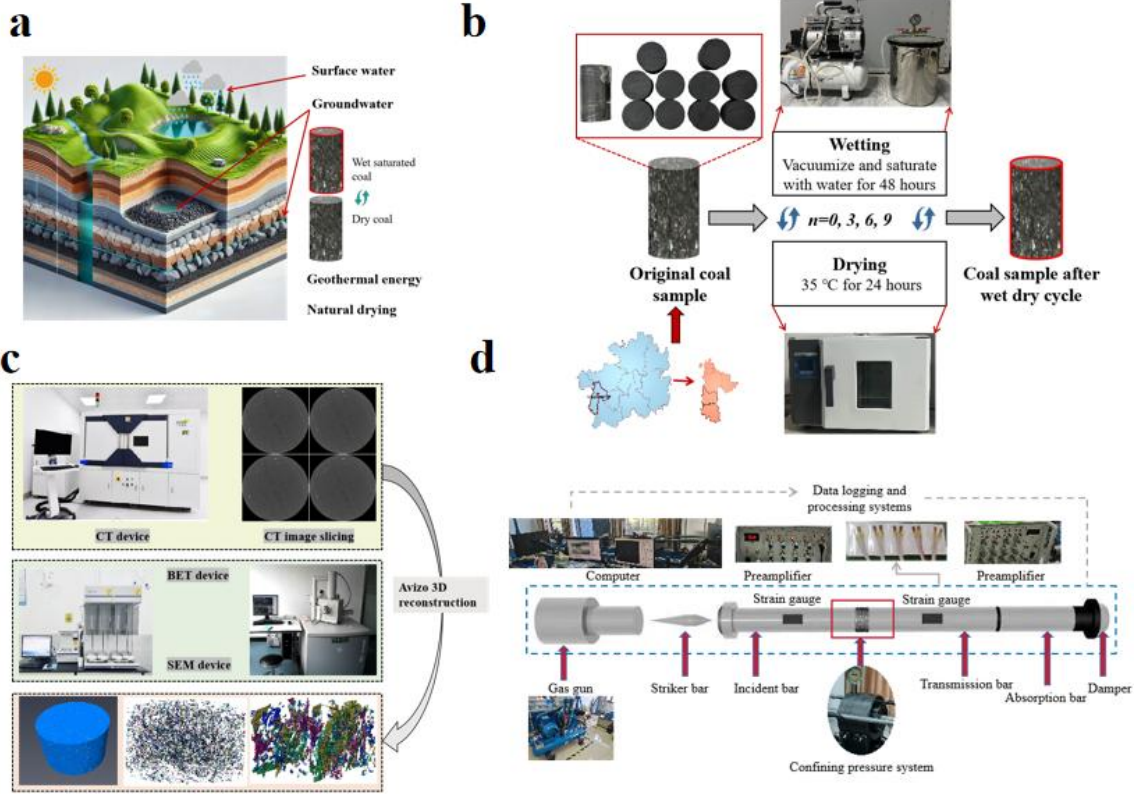


Figure 1. Schematic Diagram of Wet-Dry Cycle Coal Sample Preparation and Macro-Micro Experimental Process

2.3 Pore Characteristics

2.3.1 CT Scanning and 3D Reconstruction

CT scanning of coal sample pores and cracks is a non-destructive testing technique that ensures the continuity of research. With high spatial resolution, it clearly displays the size distribution of pores and cracks, enabling three-dimensional visualization for a more intuitive understanding of the changes in coal sample pores and cracks under the influence of wet-dry cycles. As shown in Figure 2a, in the CT grayscale images, the coal matrix region appears gray, the mineral matrix is brighter, and the pores and cracks are darker.

Currently, numerous numerical analysis software tools are available for the visualization and analysis of CT scan slices[41-43], such as Thermo Scientific Avizo, MATLAB, MIMICS, COMSOL, and VGStudio. In this study, AVIZO software was used to perform 3D reconstruction by overlaying grayscale slice images of the coal samples. Subsequently, quantitative analysis of the pores and cracks in the coal samples was conducted to further investigate the microstructural changes in pores and cracks of coal samples subjected to wet-dry cycles. After applying pore and crack threshold processing to the CT images, errors caused by limitations of CT scanning technology were minimized. Each layer of the coal sample was subjected to 3D reconstruction and quantitative analysis. Figure 2(b) shows the pore volume fraction (porosity) variation curves for different layers of the coal samples after various wet-dry cycle counts. According to the curve distribution, the porosity of each layer gradually increases with the number of wet-dry cycles. Notably, the porosity near the surface layers—at both the beginning and end—was higher than that of other layers, with porosity gradually decreasing from the surface toward the interior of the coal sample. Figure 2(c)

demonstrates the cumulative porosity, which similarly increases as the number of wet-dry cycles grows. Through the 3D reconstruction of the overall pore and crack structures in the coal samples, as shown in the 3D models in Figure 2(d), it was observed that new pores emerged and expanded between existing pores and cracks as the number of cycles increased. The pore density rose progressively, and the number of cracks also increased, appearing more densely distributed in the 3D models with higher cycle counts.

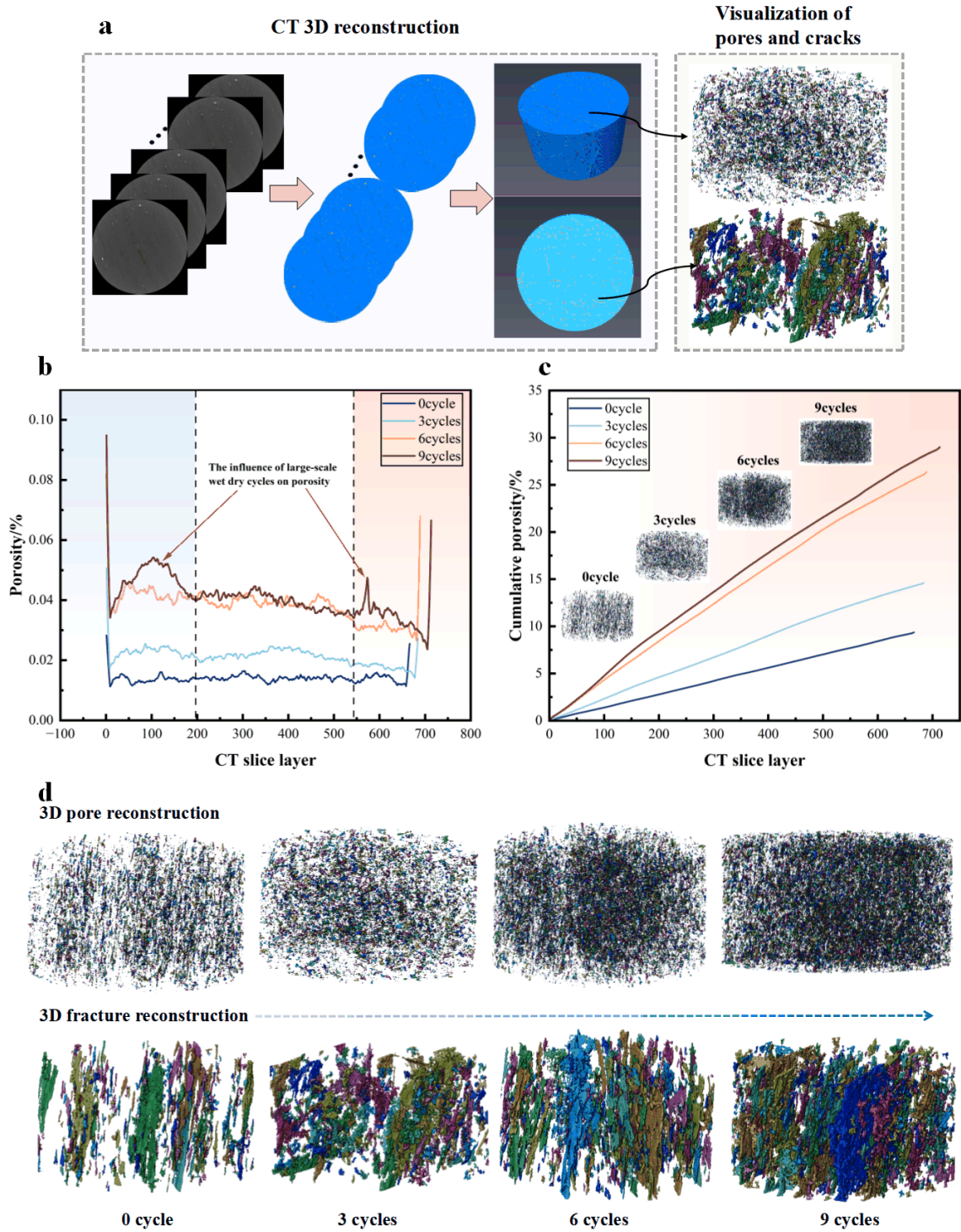


Figure 2. CT 3D Reconstruction and Quantitative Characterization of Pores and Cracks

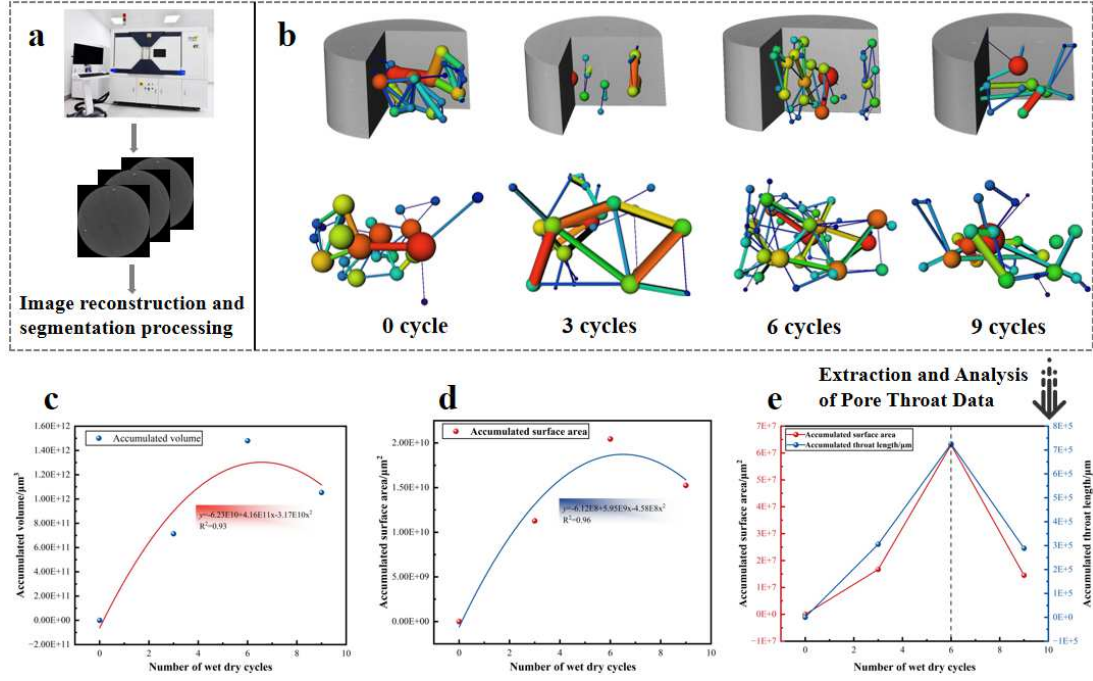


Figure 3. CT 3D Reconstruction of Pore Density and Connectivity

After conducting a quantitative analysis of the pores and cracks in coal samples subjected to wet-dry cycles, the surface area, volume, and length of the pores and throats were characterized based on the constructed 3D coal body. The results are shown in Figure 3. From Figure 3b, it can be observed that the density of the stick-ball model initially increases and then decreases as the number of wet-dry cycles increases. Figures 3(c), (d), and (e) respectively present the cumulative pore volume, cumulative pore surface area, and the quantitative characterizations of throat surface area and length.

The data among these groups exhibit quadratic relationships, showing an initial increase followed by a decline with the number of cycles. This trend is attributed to the pore water pressure generated by water absorption-induced swelling during the initial wet-dry cycles, as well as the erosion caused by the flow of water molecules between pores and cracks, which further expands and connects pre-existing pores and cracks. Some closed or smaller pores are opened, leading to an increase in pore surface area, volume, and throat length.

However, with further increases in the number of cycles, the coal matrix particles undergo migration and reorganization due to repeated swelling and contraction. Over time, the prolonged wet-dry cycling destabilizes the internal structure, causing some pores and throats to collapse, while the accumulation of precipitated minerals clogs pores and throats. As a result, the surface area, volume, and length of pores and throats gradually decrease.

2.3.2 BET Low-Temperature Nitrogen Adsorption Test

Low-temperature nitrogen adsorption (LT-N₂) behavior can characterize the pore structure of coal samples without damaging their structure. This method effectively prevents the damage to coal pore structures caused by high-pressure conditions in the mercury intrusion method.

As shown in Figure 4, under high pressure, nitrogen adsorption increases continuously with the number of wet-dry cycles. However, the calculations of cumulative pore volume and cumulative specific surface area reveal that when the number of cycles reaches a certain

threshold, the pore structure of the coal sample becomes unstable and collapses. During repeated wet-dry cycles, original micropores and small pores expand and fail, eventually forming smaller or even non-porous structures, resulting in a decrease in pore volume. Consequently, cumulative pore volume and cumulative specific surface area show a trend of initially increasing and then decreasing with the number of cycles.

It is noteworthy that total pore volume increases with the number of wet-dry cycles. This occurs because, despite the instability and damage to the pore structure, the total number of pores created increases, and the average pore diameter decreases. This result aligns with the findings from CT 3D reconstruction. Additionally, the relationships between total pore volume, average pore diameter, and the number of cycles can be described using an exponential function (1) and a linear function (2), respectively.

$$y = 5.503e^{(-x/2.409)} + 4.133, R^2 = 0.99 \quad (1)$$

$$y = 0.0134 + 0.00142x, R^2 = 0.96 \quad (2)$$

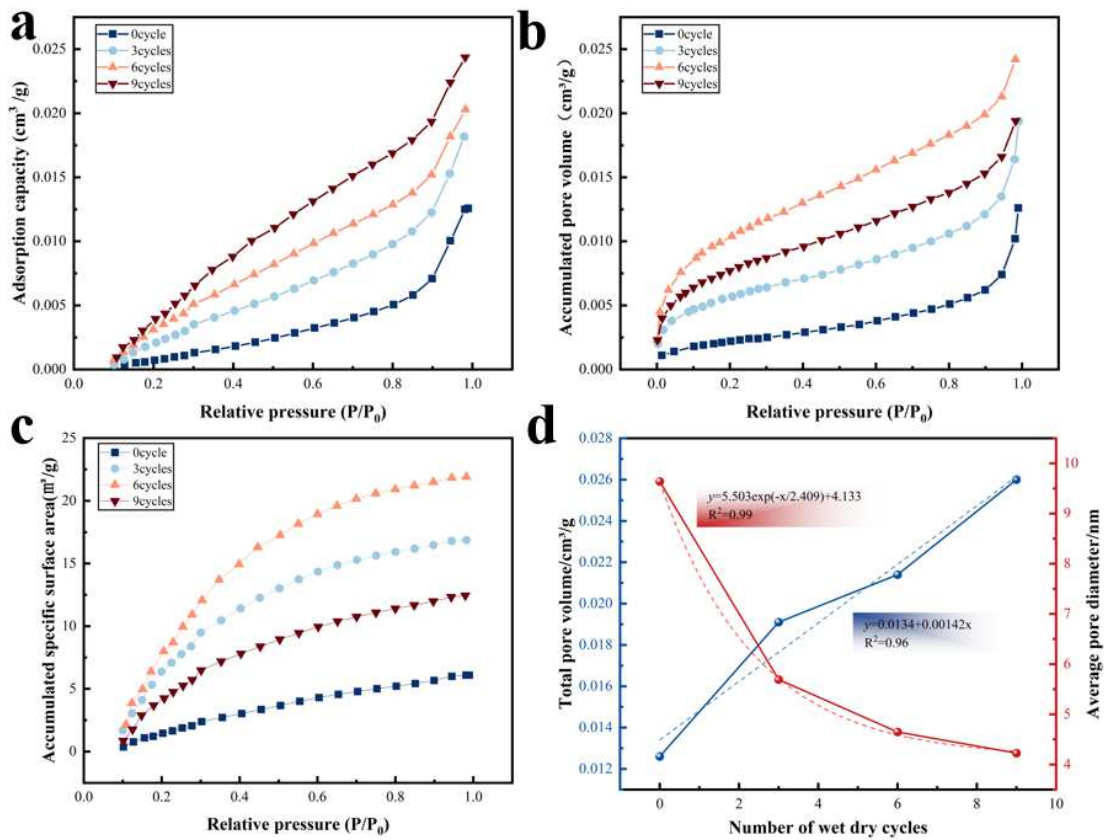


Figure 4. BET Nitrogen Adsorption: Adsorption Amount (a), Cumulative Pore Volume (b), Cumulative Specific Surface Area (c), and Relationships Between Total Pore Volume, Average Diameter, and Number of Cycles (d)

3.SHPB Experimental Analysis

This experiment utilized a Split Hopkinson Pressure Bar (SHPB) triaxial dynamic-static combined testing system. Compared with conventional Hopkinson bar systems, this system allows the addition of circumferential active confining pressure and axial pre-stress. The lengths of the striker, incident bar, and transmission bar were 400 mm, 3000 mm, and 2500 mm, respectively, with a diameter of 50 mm. The bars have an elastic modulus of 206 GPa, a

density of 7.74 g/cm³, and a longitudinal wave propagation velocity of 5159 m/s. The strain signals were further processed and calculated using a high-speed dynamic strain recorder and data processing system.

During the experiment, the axial pressure was set to 25 MPa, the confining pressure to 30 MPa, and the loading velocity to 7 m/s. To validate the reliability of the experimental data, the stress uniformity assumption was tested using Equation (3), which states that the sum of the reflected strain and incident strain equals the transmitted strain. The results of the three-wave test are shown in the waveform diagram in Figure 5a.

$$\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t) \quad (3)$$

Figures 5b and 5c present the stress-strain curves of coal samples in dry and saturated states under different numbers of wet-dry cycles. The results indicate that the peak strength of the coal samples decreases continuously with an increasing number of wet-dry cycles. Comparing the peak strength of dry and saturated coal samples reveals that saturation significantly reduces the peak strength of the coal samples.

Moreover, as the number of cycles increases, the strain experienced by the coal samples increases, indicating greater macroscopic damage to the samples. On a microscopic level, the pores and cracks in the coal are compressed under impact loading, resulting in larger strains. With increasing cycles, the porosity continuously grows, leading to rapid closure of compressed pores. This reduces the elastic space within the coal samples, altering their deformation mode. The reduction in elastic space limits the ability of the coal samples to accommodate larger strains, which, combined with increased porosity, results in lower strength, reduced strain, and greater overall damage as the number of cycles increases.

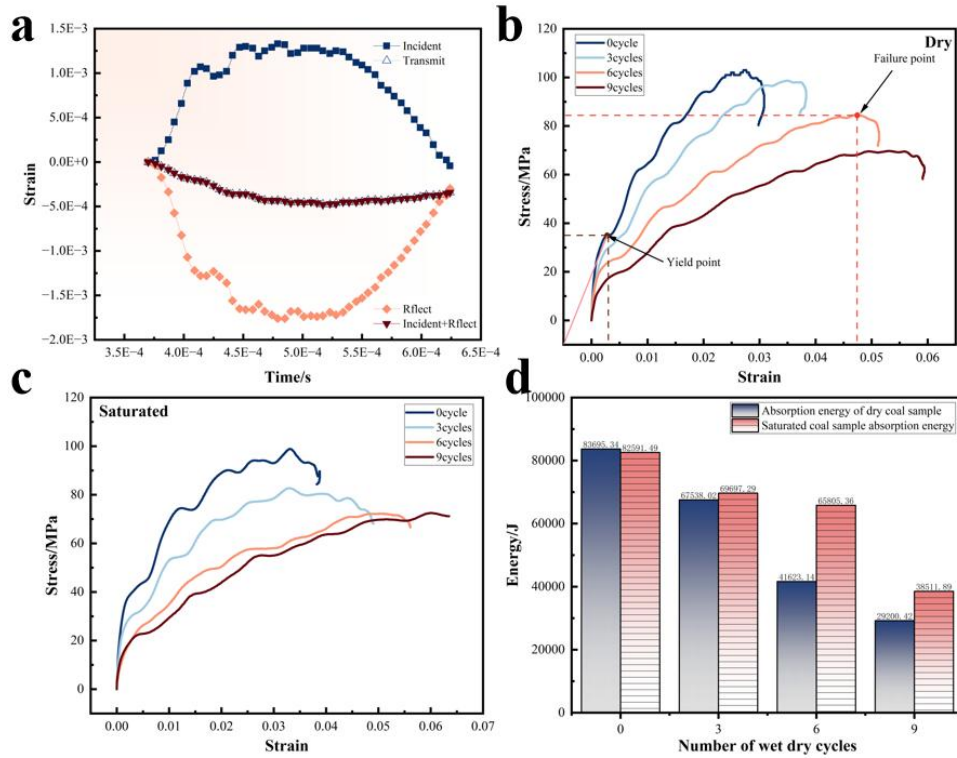


Figure 5. SHPB Test: Three-Wave Equilibrium (a), Stress-Strain Curves (b, c), and Energy Dissipation (d)

The failure of coal is essentially a process of energy release and dissipation within the coal body, encompassing energy absorption, conversion, and release. In practical engineering applications, the energy absorbed during coal-rock fracturing can be used to represent the difficulty of coal-rock failure.

As shown in Figure 5d, the energy absorption of coal samples decreases with an increasing number of wet-dry cycles. This is due to the increased porosity of the coal samples, which reduces the energy required for failure and, correspondingly, lowers the peak strength of the samples. However, after saturation treatment, the absorbed energy of the coal samples is generally higher than that of the dry samples. This is because dry samples primarily absorb incident energy through their deformation and the generation and propagation of internal microcracks.

In contrast, saturated samples, due to reduced strength and elastic modulus, enter the yield stage earlier under impact loading, resulting in more plastic deformation and higher energy dissipation. Additionally, during impact loading, a "water wedge" effect occurs between water and pores/cracks. When coal samples are subjected to impact, the water in the pores exerts additional pressure on coal particles, promoting further crack propagation between coal particles, which consumes additional energy.

Furthermore, as stress waves propagate through the coal-water interface, reflection and refraction occur, leading to energy redistribution. This also contributes to the higher energy absorption of saturated coal samples compared to dry ones.

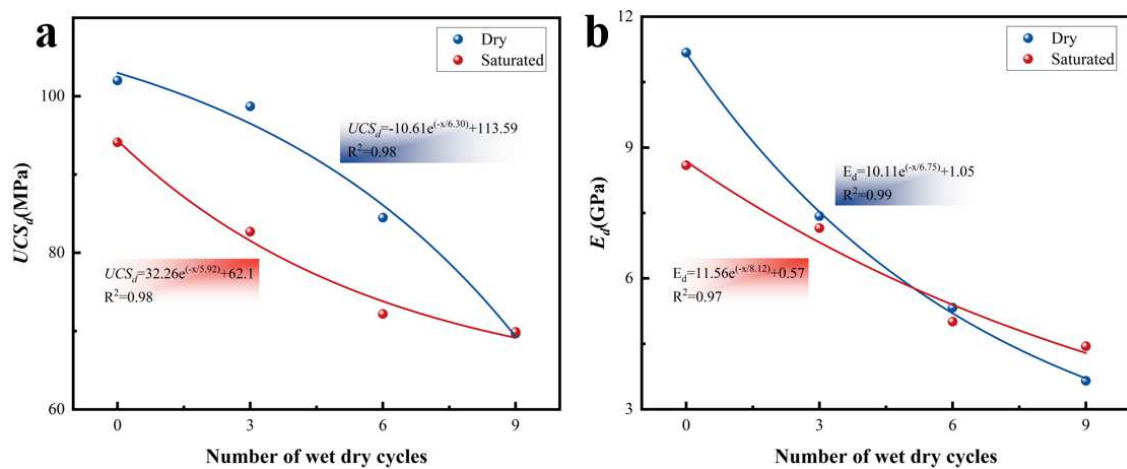


Figure 6. Relationships Between Peak Strength (UCS_d) (a) and Dynamic Elastic Modulus (E_d) (b) and the Number of Cycles

The peak compressive strength of the coal sample is defined as UCS_d , and the slope of the two-point line at 0% and 50% of the peak stress is defined as the dynamic elastic modulus E_d . These parameters are used to evaluate the effects of wet-dry cycles and saturation on the dynamic properties of sandstone.

Figure 6 illustrates the relationships between UCS_d and E_d and the number of cycles for both dry and saturated coal samples. As the number of wet-dry cycles increases, both UCS_d and E_d exhibit a gradual decline. When the number of cycles increases from 0 to 9, the coal sample strength decreases from 102.1 MPa to 69.7 MPa, while the dynamic elastic modulus drops from 11.178 GPa to 3.654 GPa. The relationships between UCS_d and E_d and the number of cycles n can be effectively described using exponential functions (Equations 4 and

5):

$$UCS_d = 113.59 - 10.61epx(-x/6.3) \quad (4)$$

$$E_d = 1.05 + 10.11epx(-x/6.75) \quad (5)$$

The same trend is observed in saturated samples. As the number of cycles increases from 0 to 9, the coal sample strength decreases from 94.1 MPa to 69.9 MPa, and the dynamic elastic modulus decreases from 8.593 GPa to 4.446 GPa. The relationships are described by the following exponential functions (Equations 6 and 7):

$$UCS_d = 62.1 + 32.26epx(-x/5.92) \quad (6)$$

$$E_d = 0.57 + 11.56epx(-x/8.12) \quad (7)$$

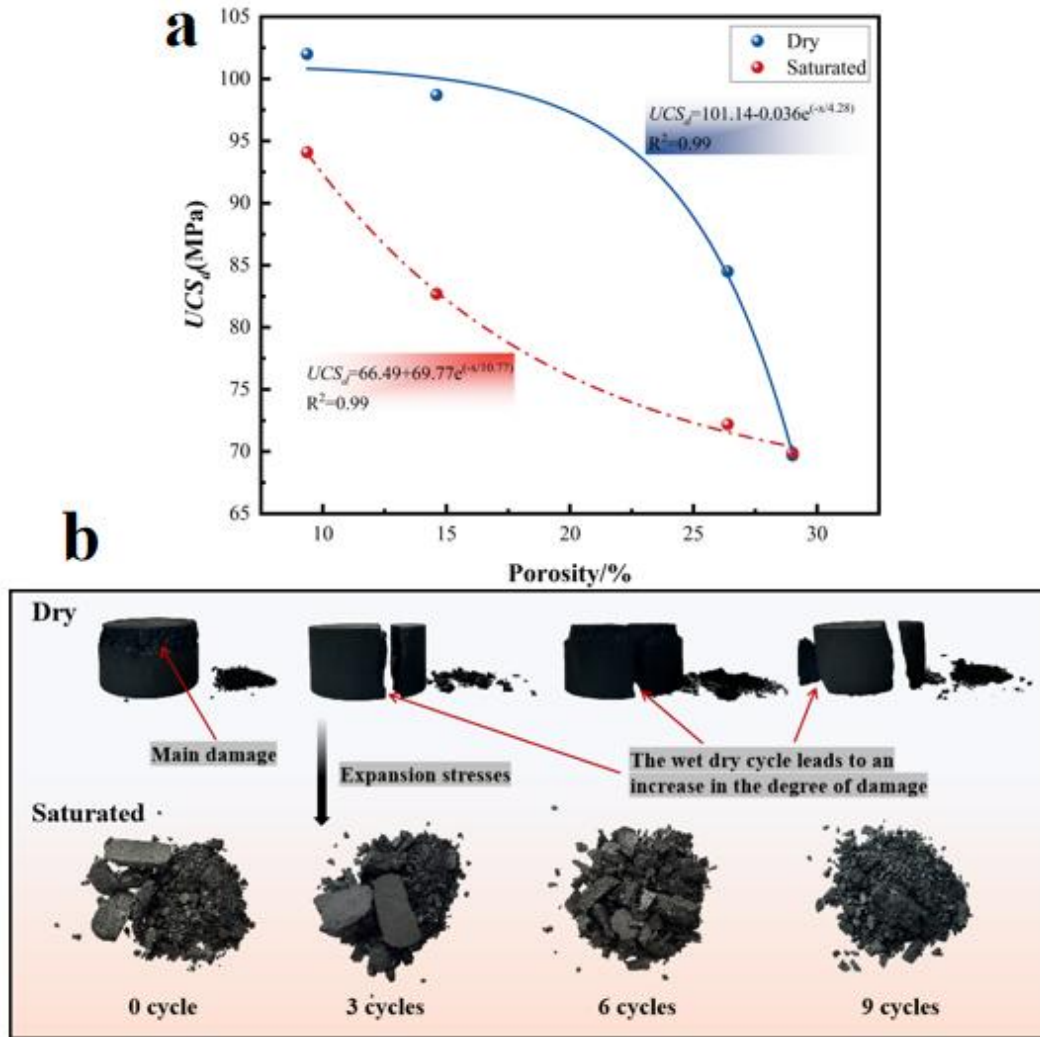


Figure 7. Relationships Between Peak Strength (UCS_d) and Dynamic Elastic Modulus (E_d) and Porosity (a) and Coal Sample Failure Images (b)

The wet-dry cycle treatment significantly affects the microstructure of coal samples. By analyzing the relationship between the cumulative porosity and peak strength of the coal samples, the influence of microstructural changes induced by wet-dry cycles on macroscopic mechanical properties can be further characterized.

In Figure 7a, as the porosity of the coal samples increases, the peak strength gradually weakens. Figure 7b shows that with an increasing number of wet-dry cycles, the extent and degree of coal sample failure also increase. Moreover, saturated coal samples exhibit more

severe damage compared to dry samples. Saturation leads to a swelling phenomenon in coal samples, generating expansion stress within the sample. When this expansion stress exceeds the strength limit of the coal, internal microcracks propagate further. As these microcracks expand and connect, the structural instability of the coal samples becomes more pronounced, leading to increased damage severity.

The relationship between porosity and peak strength for dry and saturated coal samples follows the equations below (Equation 8 for dry samples, Equation 9 for saturated samples):

$$UCS_d = 101.14 + 0.036epx(-x/4.28) \quad (8)$$

$$UCS_d = 66.49 + 69.77epx(-x/10.77) \quad (9)$$

4. COMSOL numerical simulation

To further explore the changes in pore structure and mechanical characteristics of coal seams subjected to wet-dry cycles, a model was constructed based on the geological structural layers of the sampled coal. Considering that deep coal seams are subjected to dynamic loading under static stress conditions, resulting in a dynamic-static coupled stress state, a 3D environment was employed to address this issue.

During the modeling process, the CDA import module was utilized. The constructed model and the mesh division are shown in Figure 8.

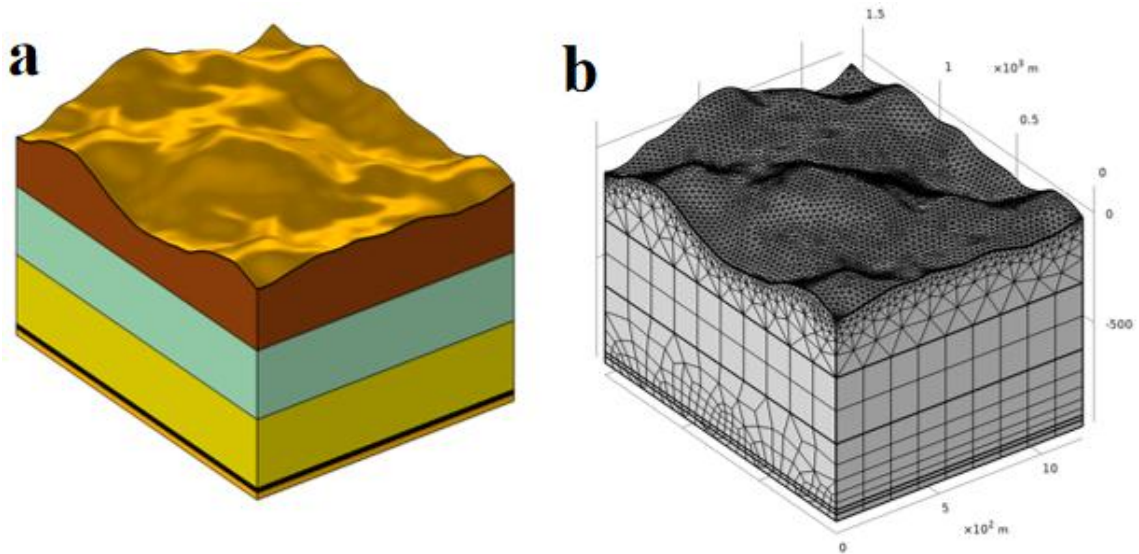


Figure 8. COMSOL Coal Seam Structural Model and Mesh Division

To implement the wet-dry cycle preprocessing for the coal seam, the Groundwater Flow module in COMSOL Multiphysics was employed, with the wet-dry cycles of the coal seam controlled using the Richards equation[44,45]. Since coal is a heterogeneous porous medium, the coal seam was divided into two components: the fluid flow region and the porous medium matrix, governed by the following distinct equations.

$$\frac{c_m}{g} \frac{\partial p}{\partial t} + \nabla(\rho u) = Q_m \quad (10)$$

$$u = -\frac{k}{\rho g} \nabla p \quad (11)$$

Equations (10) and (11) describe the behavior of unsaturated porous media:

The first term represents the rate of change in fluid mass due to pressure variations. $\nabla(\rho u)$ is the divergence of the mass flux q , which indicates the mass flow per unit area. Q_m denotes the rate of fluid mass generation or consumption per unit volume. v is the seepage velocity of the fluid within the porous medium. k is the permeability, representing the ability of the porous medium to allow fluid flow. ρ is the fluid density, g is the gravitational acceleration, and ∇P is the pressure gradient.

$$\rho = \rho(P_A), Xf = \frac{1}{\rho} \frac{\partial \rho}{\partial P_A} \quad (12)$$

$$k = K_s k_r(S_e) \quad (13)$$

Equation (12) (Fluid): ρ denotes the fluid density, which is a function of a specific pressure parameter $\rho(P_A)$. This relationship reflects the compressibility of the fluid.

Formula (13) in porous matrix: K_s is the hydraulic conductivity of $2.94e4 \times 1.5m/s$, $k_r(S_e)$ is the relative permeability, which is a function of saturation S_e .

In the water retention model, the soil water characteristic curve is commonly used to describe the relationship between matric suction and water content. Among these models, the Van Genuchten model is widely used as it effectively fits the water retention properties of soil across the entire range of water content[46,47]. Its expression is given by Equation (14):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \quad (14)$$

The soil water characteristic curve describes the relationship between matric suction and water content, expressed as follows: θ : Volumetric water content; θ_s : Saturated water content; θ_r : Residual water content; h : Matric suction; n , m , α : Model parameters, with values of 1.35, 0.5, and 2.382, respectively.

The wet-dry cycle information for the coal seam controlled by the above equations is shown in Figure 9. In Figure 9a, a complete wet-dry cycle is achieved when the coal seam's water content changes from 0.0 to 1.0. In Figure 9b, after 9 cycles, the coal seam's porosity increased from an initial 9.361% to 29.002%, showing a growth trend that matches the model predictions.

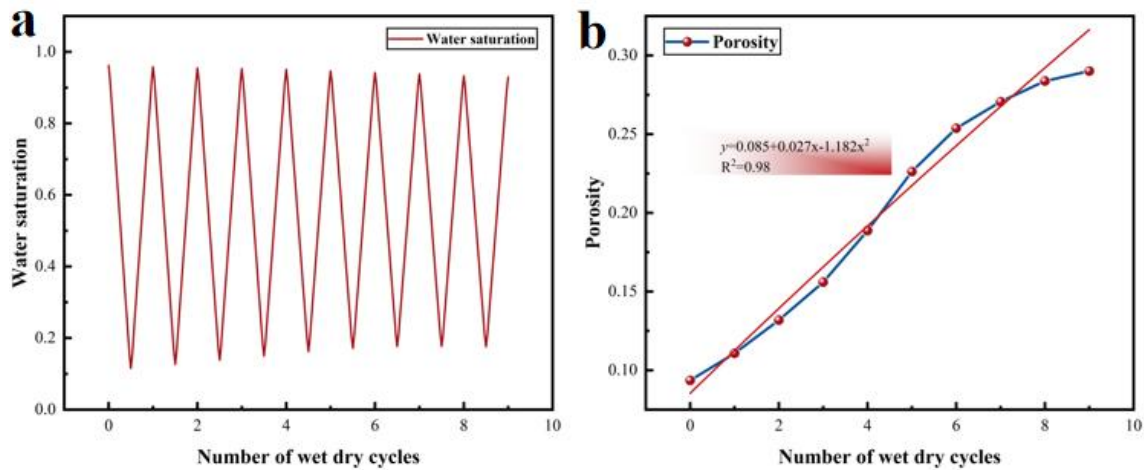


Figure 9. Wet-Dry Cycle Control Method and Coal Seam Porosity

In addition, to study the changes in the mechanical properties of coal seams under the influence of wet-dry cycles, the Structural Mechanics module was used to investigate the peak stress that coal seams can withstand under different numbers of wet-dry cycles. The

process was governed by the following equations:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} + \rho \mathbf{a} \mathbf{f} = \nabla \mathbf{S} + \mathbf{F} \mathbf{v} \quad (15)$$

Formula (15) is the dynamic equilibrium equation in Solid Mechanics: $\rho \frac{\partial^2 \mathbf{u}}{\partial t^2}$ is the inertial force, where ρ is the density; $\mathbf{u}$ is the displacement vector; $\mathbf{a} \mathbf{f}$ is acceleration; $\frac{\partial^2 \mathbf{u}}{\partial t^2}$ physical acceleration; $\nabla \mathbf{S}$ represents the divergence of the stress tensor, corresponding to the internal force inside the object; $\mathbf{F} \mathbf{v}$ is the external force acting on the volume of the object.

$$\mathbf{S} = \mathbf{S}_{\text{inel}} + \mathbf{S}_{\text{el}}, \quad \epsilon_{\text{el}} = \epsilon - \epsilon_{\text{inel}} \quad (16)$$

Stress strain decomposition equation (16): $\mathbf{S}_{\text{inel}}$ inelastic stress, $\mathbf{S}_{\text{el}}$ elastic stress, ϵ_{el} elastic strain, ϵ_{inel} inelastic strain, ϵ is the total strain.

$$\epsilon_{\text{inel}} = \epsilon_0 + \epsilon_{\text{ext}} + \epsilon_{\text{th}} + \epsilon_{\text{hs}} + \epsilon_{\text{pl}} + \epsilon_{\text{cr}} + \epsilon_{\text{vp}} + \epsilon_{\text{ve}} \quad (17)$$

Equation (17): Inelastic Strain Decomposition: ϵ_0 :Initial Strain, ϵ_{ext} :External Strain, ϵ_{hs} :Hardening Strain, ϵ_{pl} :Plastic Strain, ϵ_{cr} :Creep Strain, ϵ_{vp} :Viscoplastic Strain, ϵ_{ve} :Viscoelastic Strain.

$$\mathbf{S}_{\text{el}} = \mathbf{C} : \epsilon_{\text{el}} \quad (18)$$

Equation (18): Elastic Stress-Strain Relationship Where $\mathbf{C}$ is a fourth-order elastic stiffness tensor.

$$\epsilon = \frac{1}{2} [(\nabla \mathbf{u})^T + \nabla \mathbf{u}] \quad (19)$$

Equation (19): Strain-Displacement Relationship Where $\nabla \mathbf{u}$ represents the gradient of the displacement vector $\mathbf{u}$.

$$\mathbf{C} = c(\mathbf{E} : \mathbf{v}) \quad (20)$$

Equation (20): Relationship Between Elastic Stiffness Tensor and Material Parameters: $\mathbf{E}$:Young's modulus., $\mathbf{v}$:Poisson's ratio.

As the number of wet-dry cycles increases, the porosity of the coal seam also increases. Under this condition, an external stress is applied to the coal seam to simulate mining-induced disturbances. Using the aforementioned equations, the mechanical behavior of the coal seam after different numbers of wet-dry cycles was obtained, as shown in Figure 10.

The stress cloud maps in the figure demonstrate that as the number of cycles increases, the stress the coal seam can withstand gradually decreases, and the range of peak stress it can endure narrows. This indicates that after undergoing multiple wet-dry cycles, mining disturbances more easily affect the stability of the coal seam.

Furthermore, to describe the relationship between peak stress and the number of wet-dry cycles n , exponential equations (21) and (22) were proposed. These equations exhibit a high degree of fit ($R^2=0.99$), showing strong consistency with the weakening trend of peak strength observed in the experiments.

$$y = 70.65 - 1.79 \exp(-x/-3.43) \quad (21)$$

$$y = 30.49 - 0.85 \exp(-x/-3.11) \quad (22)$$

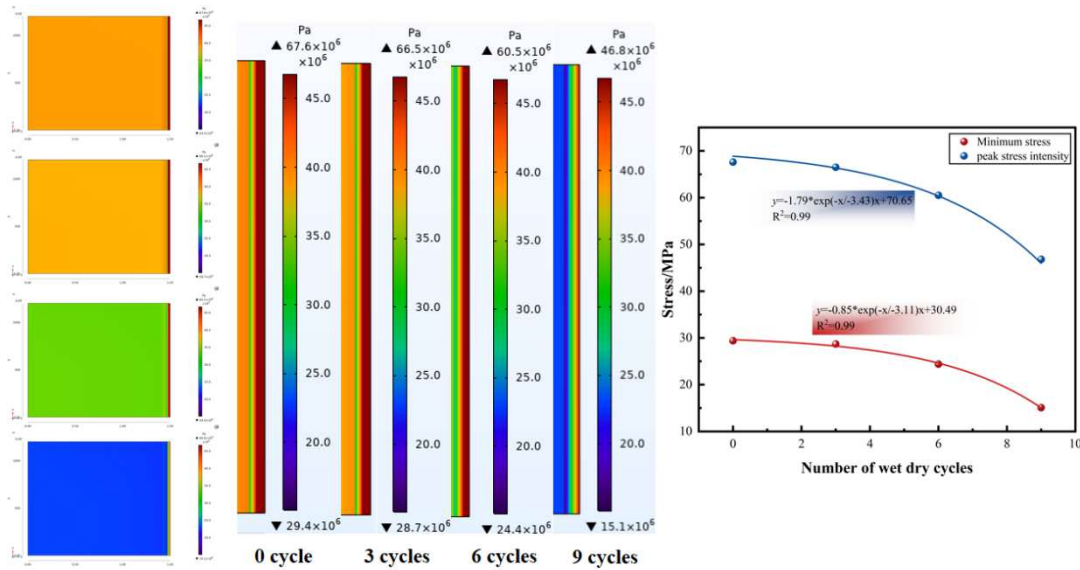


Figure 10. Peak Stress Intensity and Weakening Trend of Coal Seam Under Load

5. Discussion on Deterioration Mechanism and Engineering Applications

5.1 Mechanism of Strength Weakening Due to Water Saturation

Coal is a heterogeneous porous medium, with its surface and interior containing various types of pores—ranging from micropores to macroscopic fractures—formed by organic and mineral components. The pore structure is highly complex. During the water saturation process, the pores and cracks are filled with water, compressing and displacing the air originally present in the coal sample, as illustrated in the transition from Figure a to b.

Subsequently, as shown in Figure c, when axial and confining preloading is applied to the saturated coal sample, the incompressibility of water causes changes in the coal sample's volume and internal pore structure. Under the pressure exerted by water, the original cracks in the coal begin to propagate, leading to greater damage to the coal sample under impact loading.

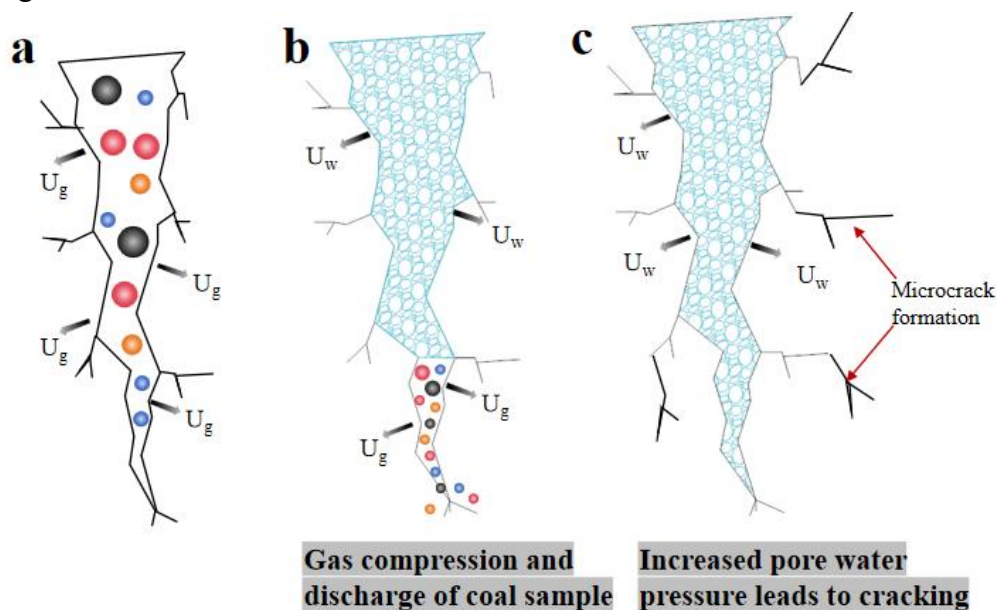


Figure 11. Schematic Diagram of Structural Deterioration in Coal Samples During Water Saturation

The pore pressure (Figure 11) is represented by u , indicating the pressure exerted by fluids within the coal seam. In the case of gradual water saturation, U_w represents the water pore pressure, while U_g denotes the gas pore pressure when the soil is also gas-saturated. The presence of fluids in the pore spaces alters the physical and mechanical properties of the coal seam and affects the net normal stress. This can be expressed as:

$$\sigma' = \sigma - U_t \quad (23)$$

Where, σ : Total normal stress; U_t : Fluid Pore Pressure. Considering the difference between the pore gas pressure (U_g) and the pore water pressure (U_w), the suction power of the coal matrix is:

$$S = U_g - U_w \quad (24)$$

Volumetric weight is defined as the weight of an object per unit volume, and the formula for calculating the unit weight of volume (γ_{bulk}) is:

$$\gamma_{bulk} = \gamma_w(G_s + eS)/1 + e \quad (25)$$

When all the voids in the coal are filled with water and the saturation degree S is 1, the expressions for the saturated unit weight (γ_{sat}) and dry density (γ_{dry}) are:

$$\gamma_{sat} = \gamma_w(G_s + e)/1 + e \quad (26)$$

$$\gamma_{dry} = \gamma_w G_s / 1 + e \quad (27)$$

Where, γ_w : Unit weight of saturated water. G_s : Specific gravity of coal. e : Void ratio of coal.

Assuming the coal seam is horizontal, with linear superposition between layers, considering the saturation of the voids by the fluid, the vertical stress formula can be expressed as:

$$\sigma_{sat} = \gamma_{sat}Z + \Delta\sigma_s \quad (28)$$

When the coal sample is in a dry state, $U_t = U_g$; when in a water-saturated state, $U_t = U_w$. Substituting the unit saturation values of water and gas into Equations (26), (27), and (28), the effective stress equation for coal is derived as Equation (29):

$$\sigma' = \sigma - (U_g + U_w) \quad (29)$$

Therefore, when a coal seam is at a certain burial depth, it is subjected to the overburden pressure (total stress). In an unsaturated state, the pore water pressure is relatively low, resulting in higher effective stress, which allows the coal sample to maintain a certain degree of strength and stability[48]. However, once the coal becomes saturated with water, the pore water pressure increases, and the effective stress decreases, leading to a reduction in the shear strength of the coal sample. This reduction in shear strength makes the coal sample more susceptible to shear failure under relatively small external forces, thereby weakening its mechanical properties.

5.2 Deterioration Mechanism of Wet-Dry Cycles

To further understand the changes in the microstructure of coal samples, SEM analysis was conducted to examine the micro-morphology of samples subjected to different numbers of wet-dry cycles (as shown in Figure 12). Comparative observations revealed that during the wet-dry cycling process, the porous medium structure of the coal allowed water to penetrate the pores and cracks, causing swelling. With an increasing number of wet-dry cycles, this repeated swelling and shrinkage behavior led to micro-damage fatigue in the coal samples, resulting in the continuous expansion of existing micro-pores and cracks and the formation of

new cracks, as evidenced by the newly developed pore-crack features shown in Figure 12b.

Moreover, as the number of wet-dry cycles increased, the repeated transitions between saturated and dry states weakened the connectivity between micro-particles in the coal samples. The mineral matrix within the coal also reacted with water, leading to structural transformations. The originally multilayered structure evolved into the discontinuous and isolated state depicted in Figure 12d[49].

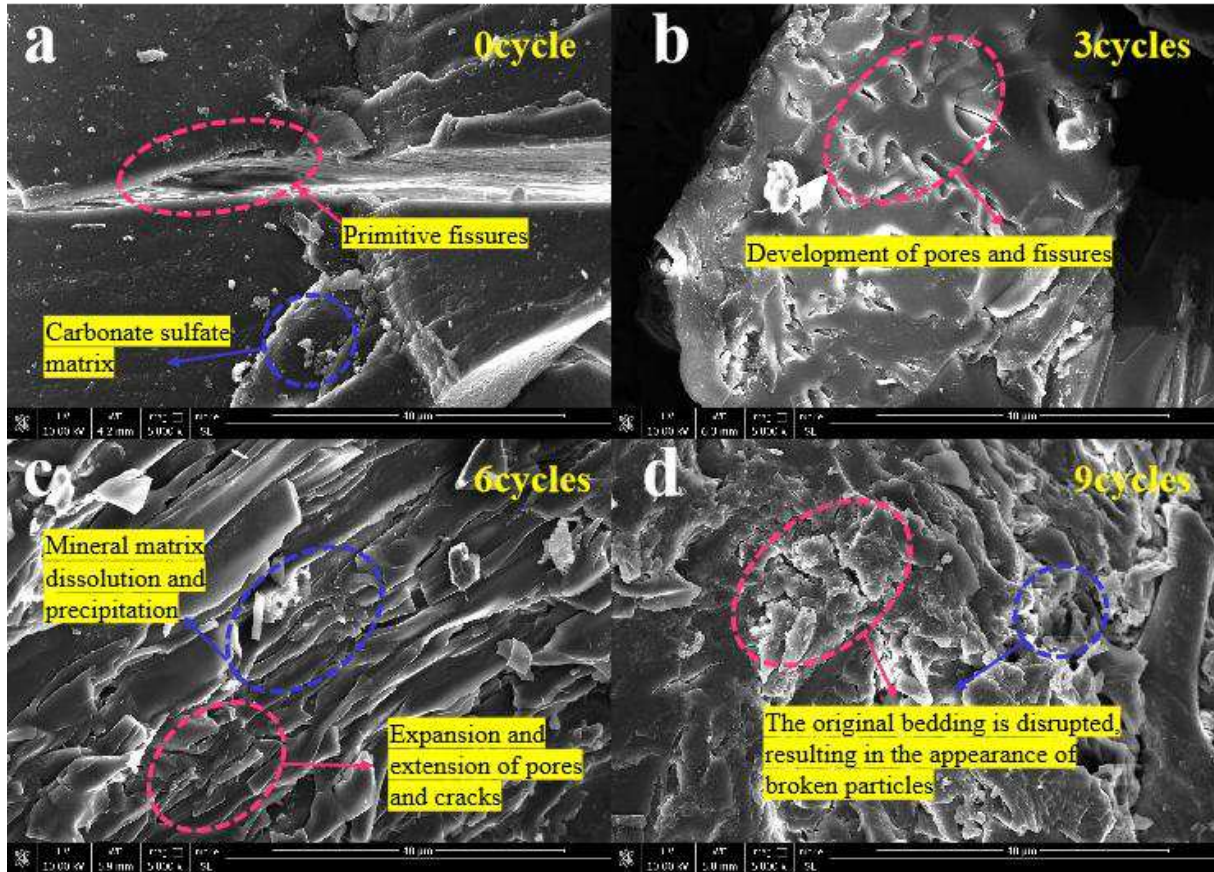


Figure 12. Microstructural Changes in Coal Samples Under Different Numbers of Wet-Dry Cycles

In addition, coal contains various minerals, such as carbonates (e.g., calcite) and sulfates (e.g., gypsum). Under repeated wet-dry cycles, some minerals undergo dissolution reactions. Taking calcite as an example, its dissolution reaction is shown in Equation (30).



As shown in Figure 13, such chemical reactions weaken the cementation between mineral particles in the coal samples. Meanwhile, under certain conditions, the dissolved ions precipitate to form new mineral phases. The formation of these new mineral phases generates expansion stress, further disrupting the internal structure of the coal samples.

Moreover, the presence of water promotes redox reactions within the coal, leading to the formation of oxygen-containing functional groups such as hydroxyl (-OH) and carboxyl (-COOH). These functional groups alter the chemical structure of the coal, enhancing its hydrophilicity and loosening its macromolecular structure. This ultimately reduces the strength and stability of the coal samples.

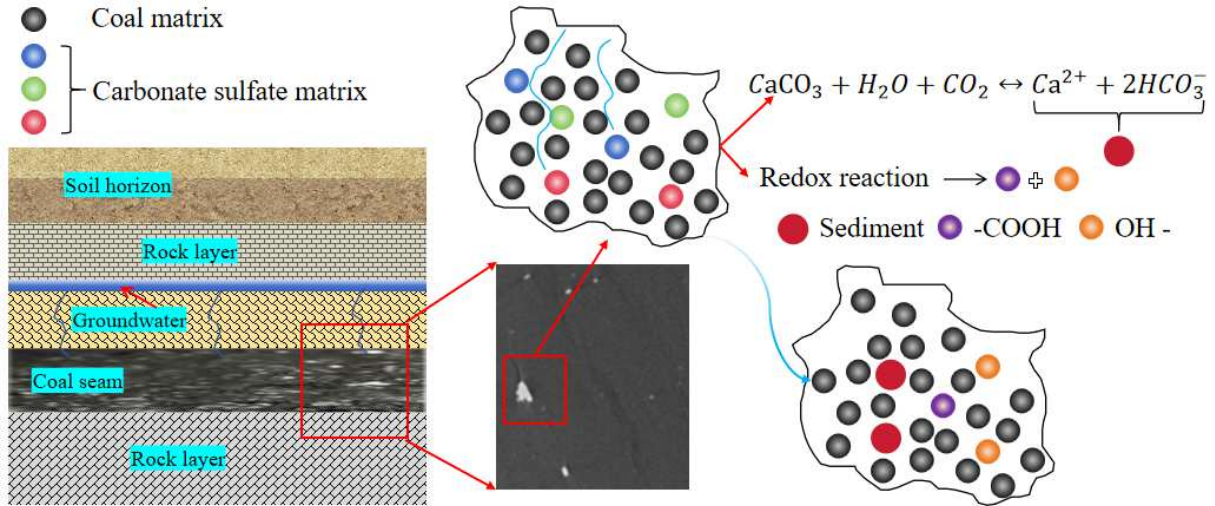


Figure 13. Schematic Diagram of Chemical Reactions in Coal Samples Under Wet-Dry Cycles

5.3 Engineering Application Analysis

The coal mining environment is complex and variable, with wet-dry cycles being a common natural phenomenon widely present at mining sites. From the stability of roadway surrounding rocks to the operating conditions of mining equipment, wet-dry cycles play a crucial role that cannot be overlooked. Figure 14 illustrates the depositional conditions of a localized coal-rock formation in a specific coal mine.



Figure 14. Schematic Diagram of Different Wet-Dry Environments at the Engineering Site

The physical and chemical effects mentioned in the above deterioration mechanisms, such as the weakening of inter-particle bonding and the accelerated dissolution of calcium carbonate, can easily lead to spalling phenomena on roadway walls, reducing coal-rock strength and increasing the difficulty of roadway support. Based on the findings of this study, the following recommendations are proposed for mining areas with coal seams subjected to wet-dry cycles:

1.Enhance drainage efforts: Lower the groundwater level to reduce the soaking time of the roadway surrounding rock, maintaining its relative stability and creating favorable conditions for mining.

2.Adopt combined support methods: Utilize anchor bolt reinforcement for the surrounding rock and apply shotcrete to form a sealing layer, isolating the wet-dry cycling medium from the surrounding rock.

6. Conclusion

Wet-dry cycles have a significant impact on the microstructure and mechanical behavior of coal. Through 3D reconstruction of CT scan images and BET nitrogen adsorption experiments, the mechanism by which wet-dry cycles affect the micro-pore and crack structure of coal samples was revealed. Additionally, triaxial impact loading tests were conducted using a Hopkinson pressure bar, and combined with simulations in COMSOL Multiphysics, the weakening effects of wet-dry cycles on the macroscopic mechanical properties of coal were explored and validated.

Based on the results of macro- and micro-scale experiments, the deterioration mechanism of wet-dry cycles on coal structures was comprehensively discussed. Practical recommendations were proposed to meet engineering site requirements, providing theoretical support for the prevention and control of coal mine dynamic disasters. The following conclusions were drawn:

1.The influence of wet-dry cycles on the porosity of coal samples progresses from the surface to the interior. As the number of wet-dry cycles increases, the porosity and connectivity of the coal samples initially increase and then decrease. The collapse of pores and cracks results in a gradual reduction in the average pore size, while the total pore volume exhibits an opposite trend. Both parameters demonstrate a strong functional relationship with the number of wet-dry cycles.

2.Under triaxial impact loading conditions, the number of wet-dry cycles weakens the peak strength of coal samples. Saturation treatment further exacerbates this weakening effect, significantly increasing the degree of coal sample damage. The peak strength (UCSd) and dynamic elastic modulus (Ed) exhibit an exponential relationship with the number of cycles (n), a result validated by numerical simulations

3.After water saturation, the pore water pressure in coal samples increases, effective stress decreases, and the degree of damage intensifies. With the increase in the number of wet-dry cycles, the repeated swelling and shrinkage behavior induces micro-damage fatigue in the coal samples, leading to internal structural collapse. Additionally, the chemical dissolution and precipitation of the mineral matrix jointly cause the number, size, and volume of pores and cracks to initially increase and then decrease.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The datasets used and/or analysed during the current study are available from the

corresponding author on reasonable request.

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