INTRODUCTION

The effect of water on the properties of various types of rocks could induce complex physical and chemical reactions.\(^1\)\(^-\)\(^3\) The presence of water is key cause of microstructural and macroscopic mechanical deterioration in a wide range of rocks.\(^4\)\(^-\)\(^8\) In recent years, the effect of water on coal mass or rock mass has been viewed as a key factor related to the stability of geotechnical engineering constructions, leading to a great deal of research on this topic.

Coal mines are divided into open-pit mining and underground mining. Among them, open-pit mining coal mines are susceptible to rainfall and other factors, whereas several coal mines are underground geotechnical engineering facilities...
that are affected by water, in the form of gob water, aquifer leakage, coal seam water injection, and the water content of the coal.

Cyclic wetting-drying is a well-known yet poorly understood weathering process. Many studies have been conducted on the effect of wetting-drying cycles on the physical and mechanical properties of rocks, concerning water adsorption,9 acoustic wave velocity,10 elastic modulus,11 tensile strength,12,13 and static uniaxial or triaxial compressive strength.14-16 The deterioration process of rock mechanical properties under cyclic wetting-drying could also be induced by original defects.17,18

After cyclic wetting-drying treatments, the mechanical properties of different rock samples deteriorate to various degrees (Table 1). Khanlari et al15 and Hale et al16 reported that the uniaxial compressive strength (UCS) of sandstone was not significantly reduced even after 40 or 50 wetting-drying cycles. However, recent studies by Huang et al11 and Hua et al12 showed that cyclic wetting-drying could induce significant deterioration in the sandstone's mechanical properties. These results are similar to those of Deng et al19 and Yao et al20. These studies all indicate that cyclic wetting-drying could influence the mechanical strength of sandstone, but the effect of cyclic wetting-drying on coal mass has not been widely investigated. In addition, Lin et al21 found that the uniaxial compressive strength of sandstone with 11% chlorite content significantly decreases under cyclic wetting-drying. This indicates that the composition of rock could influence its mechanical properties under wetting-drying.

The effect of cyclic wetting-drying induces mechanical property deterioration in various rocks, such as green andesites,19 Pierre shale,23 and mudstone.24 This indicates that wetting-drying cycles could cause deterioration in a rock's skeleton. As wetting-drying cycles could induce mechanical property deterioration via the original defects in a rock, the effect of wetting-drying on coal would be more complex because coal is a porous and low wettability material.25 In addition, there are usually various clay minerals inside coal mass,26 and so the water-coal interaction does not merely involve soaking and water adsorption.

Particular challenges concern the seasonal ground rainfall in certain mining areas, and the periodic rise and fall of groundwater levels. These phenomena could induce wetting-drying cycles in coal mass. Further, because of the effect of these various factors on coal mass, its instability could be due to a gradual weakening process, suggesting the possible complexity of water-coal interactions induced by wetting-drying cycles. The effect of wetting-drying cycles on coal's microstructure and mechanical properties is still not completely understood.

The strength and deformability are significant mechanical properties for underground engineering rock mass,27 which provide a necessary index for determining optimal support parameters and strategies.25,28-31 Previous studies on water-coal interaction focused on the mechanical properties of coal, which were induced by water intrusion. Gu et al32 studied the relationship between the dynamic response of coal and the effect of soaking times. Their results indicated that the compressive strength and Young's modulus both decreased gradually with increasing soaking time. Liu et al33 found that the effect of water injection could change the mechanical properties of coal specimens and that this effect varied with coal size. These works reveal that the effect of water on coal has a time-related component. Zhang et al34 found no significant changes in the maximum strain and crack propagation of coal after moisture absorption and that different water compositions have different effects on the structure and mechanical properties of coal. This indicates that the components of water and coal have different effects on water-coal interactions. Wang et al35 conducted a series of P-wave, water content, triaxial compression, and acoustic emission tests, to compare the mechanical properties of naturally saturated and forcedly saturated coal samples. Their findings suggested that the effect of forced saturation could significantly improve the water content of coal specimens by changing the coal microstructure and driving water into its micropores. The softening effect of water thus resulted in a significant deterioration of the coal's structural and mechanical properties. Yao et al36 found that the peak stress, postpeak modulus, strain-softening modulus, and elastic modulus decreased with increasing moisture content of coal specimens, while the peak strain increased. Their results reveal that changes in the water environment cause various changes in the structure and mechanical properties of coal, in agreement with various other studies.37,38

There are many differences between continuous wetting and cyclic wetting-drying of in situ rock engineering. Among them, the most significant is that cyclic wetting-drying causes the moisture of the rock to change periodically, and its water content is in a state of constant change. The effect of wetting-drying cycles could cause the original stress balance of coal mass to be broken, thus reducing its strength and bearing capacity, and destroying its structure. The results of these effects on coal integrity could have a disastrous impact within a coal mine. In addition, changes in coal microstructure could induce a deterioration of its mechanical properties. This is a macroscopic manifestation of structural change under water-coal interactions,11 indicating that we should also consider the influence of changing microstructure parameters on the macroscopic strength characteristics of coal under wetting-drying cycles. These factors necessitate a more complete understanding of the mechanisms by which the mechanical properties of coal are affected by environmental factors such as continuous wetting and cyclic wetting-drying.

There have been many developments in quantitative research methods used to describe geotechnical


**TABLE 1** Effect of cyclic wetting-drying on the mechanical properties of various rocks

| References       | Specimen type                               | Sample size (mm) | Rock sample preparation methods                                                                 | N<sub>max</sub> | Mechanical properties                                      |
|------------------|---------------------------------------------|------------------|--------------------------------------------------------------------------------------------------|-----------------|----------------------------------------------------------|
| Huang et al<sup>11</sup> | Sandstones and mudstones from Chongqing of China | Ф50 × 100        | Wetting method: submerged in water for 24 h Drying method: oven-dried at 110°C for 12 h and 20°C for 12 h | 40 and 12      | EM: both reduce gradually UCS: both reduce gradually     |
| Hua et al<sup>12</sup>  | Sandstones from Ziyang of China              | Φ75 × 25         | Wetting method: submerged in water for 48 h Drying method: oven-dried at 105°C for 24 h           | 7               | Ts: decrease obviously FT: decrease obviously           |
| Khanlari et al<sup>15</sup> | Red sandstones from Iran                     | Ф54 × 108        | Wetting method: submerged in water for 24 h Drying method: oven-dried at 110°C for 24 h           | 40              | UCS: decrease not obviously                             |
| Deng et al<sup>19</sup> | Sandstone from Three Gorges Reservoir Region of China | Ф50 × 100        | Wetting method: submerged in water from Yangtze river for 30 d Drying method: air-dried at room temperature for 5 d | 6               | UCS: decrease obviously EM: decrease obviously         |
| Yao et al<sup>20</sup>  | Red sandstone from China                     | Ф50 × 100        | Wetting method: forced saturation for 8 h, then immersed in water for 24 h Drying method: oven-dried at 105°C for 24 h, then cooled to room temperature | 8               | UCS: decrease obviously EM: decrease obviously         |
| Lin et al<sup>21</sup>  | Tertiary sandstones from Taiwan              | Ф55 × 125        | Wetting method: submerged in water for 24 h Drying method: not indicated                          | 60              | UCS: (sandstone with 11% chlorite) decrease obviously UCS: (sandstone with 1% chlorite) decrease not obviously |
| Hale et al<sup>16</sup>  | Different tape of sandstones from Ohio and Pennsylvania | Ф54 × 108        | Wetting method: submerged in water for 24 h Drying method: oven-dried at 110°C for 24 h           | 50              | UCS: decrease not obviously                             |
| Yavuz et al<sup>22</sup> | Green andesites from Buca(Izmir), of Turkey  | Cylindrical and prismatic samples | Not indicated                                                                                   | 80              | Durability: decrease not obviously                       |
| Schaefer et al<sup>23</sup> | Pierre Shale from USA                        | Two cubic-inch   | Wetting method: soaked for 1 h in the distilled water bath Drying method: vacuumed at 24-inch Hg (11.8 psi) for 1 h in the chamber; air-dry for 48 to 72 h after wetting | 5               | Residual friction angle: dropped obviously               |
| Bell et al<sup>24</sup>   | Mudstone from County Durham of UK             | Ф38 × 25         | Wetting method: saturated under vacuum until they achieved a constant weight more than 24 h Drying method: dried in a ventilated oven to a constant weight | No More than 4 times | Durability: decrease obviously and related to rock strength |

Abbreviations: EM, elastic modulus; FT, fracture toughness; TS, tensile strength; UCS, uniaxial compressive strength.
microstructures, due to increasing use of scanning electron microscopy (SEM), mercury intrusion, and image-processing software such as MATLAB and Image Pro Plus 6.0 (IPP 6.0). Among these methods, using SEM to study microstructure has become the most common geotechnical technique. In the current study, we consider the condition of short-term rainfall evaporation and underground water level variation in a coal mine. Various average microstructure parameters were extracted for coal after different cycles, using the IPP 6.0 software. This approach allows us to quantitatively evaluate the damage mechanisms of coal under different wetting-drying cycles, at the microscale, leading to an understanding of changes in various properties, such as uniaxial compressive strength and elastic modulus.

As there are few previous studies into the mechanical properties of coal under wetting-drying cycles, the current study focuses on the following three issues: (a) a comparison of the effects of continuous wetting and cyclic wetting-drying on the mechanical properties of coal; (b) the effect of cyclic wetting-drying on the microstructural parameters and mechanical properties of coal; and (c) the influence of microstructural parameter changes on the macroscopic strength characteristics of coal under wetting-drying cycles.

2 | EXPERIMENTAL METHOD

2.1 | Sample preparation

The uniaxial compression tests were designed to study the effect of wetting-drying cycles on the mechanical properties and microstructure of coal specimens. In addition, in order to avoid the issues related to anisotropy and heterogeneity of coal and to ensure experimental reliability and comparability, the large coal blocks (of vitrain) were all extracted from the same position on the working face. These were all extracted from Daizhuang coal mine, no.3 coal seam, of the Shandong Energy Zibo Mining Group in Shandong province, China.

The blocks were then cored to obtain \( \Phi 50 \) mm coal core logs and cut into 100 mm cylinders for testing. The coal specimens (\( \Phi 50 \) mm \( \times \) 100 mm) were then polished and prepared for testing, according to the procedures recommended by the International Society for Rock Mechanics. The coal sample preparation procedure is shown in Figure 1.

2.2 | Testing procedure

In this current study, two sets of environmental conditions are considered: continuous wetting and cyclic wetting-drying. Because many scholars focus on water-coal interactions induced by continuous wetting or water conditions, the water-coal interactions induced by cyclic wetting-drying remain unclear. Thus, in this work, we compare the difference between continuous wetting and cyclic wetting-drying on the coal’s water adsorption, uniaxial compressive strength, and elastic modulus. For the continuous wetting tests, the coal specimens were immersed in pure water for different times (1, 3, 6, and 10 weeks), then subject to uniaxial compression testing under wet conditions. It is of note that during testing, the coal specimens failed within few minutes of the load being applied. Therefore, we could assume that the water loss that occurred in coal specimens during testing due to either evaporation or expulsion was negligible. For the cyclic wetting-drying tests, the uniaxial compression tests are performed after the coal specimens experienced 1, 3, 6, and 10 wetting-drying cycles. This is used to observe the effects of cyclic wetting-drying on the mechanical properties and microstructural parameters of coal specimens.

Taking into account the wetting-drying cycles and continuous wetting phenomenon induced by rainfall, increased groundwater levels, and so on, the hydrostatic pressure of
water is so small that it can be ignored. Therefore, we used a natural saturation method to saturate the coal samples. In the uniaxial compression test under wetting-drying cycles, the coal specimens were first submerged in pure water for 24 hours. These were then cooled to a temperature of 20°C for 4 hours. Later, these specimens were dried in an electro-thermostatic blast oven at 95°C for 24 hours. Finally, to avoid the effect of sudden changes in temperature induced by the water immersion of the high-temperature coal sample, these specimens were again cooled to a temperature of 20°C for 4 hours. This whole process is regarded as a single wetting-drying cycle, as shown in Figure 2.

As is shown in Figure 3, before and after each wetting-drying cycle and each period of continuous wetting, there were two groups of reserved specimens (each group contained four coal specimens that were set aside for testing, where each specimen had undergone a different treatment). The two groups of reserved specimens were weighed and subject to SEM, in order to analyze changes in water adsorption and microstructure, respectively. Uniaxial compression mechanical tests were carried out on coal specimens after various numbers of wetting-drying cycles (N = 0, 1, 3, 6, and 10 cycles) and different continuous wetting times (T = 0, 1, 3, 6, and 10 weeks) using the MTS 815.03 electro-hydraulic
Servo-controlled Rock Mechanics Testing System. For this study, the loading mode was that of displacement loading, and the loading rate was 0.005 mm/s.

In addition, because of difficulties related to efficiently segmenting SEM images using general methods, the graphic analysis software Image Pro Plus 6.0 (IPP 6.0) was chosen to observe quantitative changes in coal specimen microstructure. Before extracting the microstructural parameters of the SEM images, it was necessary to process the images, in order to obtain accurate measurement results. Because the measurement characteristics of the specimens do not change, and that the measurement object can be highlighted by SEM and IPP operation, the picture of coal microstructure could be processed. In addition, the spatial scale of IPP was calibrated using the scale in the lower right corner of the SEM image. We then binarized the SEM images to extract the microstructural parameters of coal. To accurately determine the threshold of imaging method, we used the hue, saturation, intensity (HSI) column curve and repeatedly adjusting the hue, saturation, and intensity (H, S, and I respectively) data groups, to change the threshold and achieve the best segmentation effect.

The dark area of the IPP image represents pore distribution, as shown in Figure 3. According to the multiple-visual and original image-comparison methods, the threshold value of the image could be determined. In the current study, we selected SEM images with 1000 times magnification for microstructure analysis, and obtained the best segmentation effect at threshold was between 78 and 82. Due to the presence of areas with large errors for automatic recognition and segmentation, we used manual segmentation for further adjustments, in order to improve the accuracy of defect recognition. This approach allowed us to evaluate the relationship between the microstructural parameters of coal and both its mechanical properties and microstructural morphology.

3 | RESULTS AND ANALYSIS

3.1 | Water adsorption

Before uniaxial compressive testing, the water adsorption of each specimen was calculated according to the weight variations at different immersion times or number of wetting-drying cycles:

\[ \omega = \frac{m_w - m_d}{m_d} \times 100\%, \]  
\[ \omega = \frac{m_{\text{sub}(T+1)} - m_{\text{sub}(T)}}{m_{\text{sub}(T)}} \times 100\%, \]  

where \( \omega \) is the water adsorption of the coal specimen, \( m_w \) is the weight of the wetted specimen (for cyclic wetting-drying), \( m_d \) is the weight of oven-dried specimen (for cyclic wetting-drying); \( m_{\text{sub}(T)} \) is the weight of the continuous wetting specimen and the time \( T \) of parameter \( m_{\text{sub}(T)} \) is the value of the continuous wetting time, \( m_{\text{sub}(T+1)} \) is the weight of the “\( T + 1 \)” time for the continuous wetting specimen.

The water adsorption of coal could be obtained according to Equations (1) and (2); which was 0.24%, 1.06%, 2.37%, and 4.31% under continuous wetting, corresponding to values of \( T = 1, 3, 6, \) and 10 weeks, respectively. The water adsorption of coal under cyclic wetting-drying was 4.36%, 5.06%, 5.93%, and 7.38%, corresponding to values of \( N = 1, 3, 6, \) and 10, respectively. With increasing \( T \) or \( N \), the water adsorption of coal showed a gradual increase.

The water storage capacity depends on the porosity of the coal specimens, while water adsorption is an external manifestation of the size and distribution of cracks in the coal, and micro-pore structure also has a certain effect on seepage and water drive. An increase in the water adsorption of coal specimens indicates an increase and extension of cracks within the structure and an increase in fluid permeability in the coal. The curve of water adsorption under cyclic wetting-drying is shown in Figure 4. In the early part of this curve, the water adsorption rate increases gradually, before a gradual acceleration in the later part of the curve. As mentioned above, one of the major macroscopic manifestations of microstructural change is a water adsorption mass change after the wetting-drying cycles. Therefore, after repeated wetting-drying cycles, the damage to the coal mass in a changing water environment was mainly induced by the migration and diffusion of coal debris, and the dissolution and erosion of clay mineral. In addition, the physical and chemical effects of water altered...
the original physical composition and spatial structure of the coal, resulting in secondary porosity. After each cycle, it was found that the water adsorption mass of the coal increased to a different extent. These results indicate that cyclic wetting-drying could accelerate the formation of cracks in the coal mass, and generate secondary porosity. These effects could reduce the strength of the coal and affect its mechanical properties. The above results were verified by the experiments described in the following sections.

In addition, it was found that the rate of change for water adsorption under cyclic wetting-drying is greater than that of continuous wetting. This indicates that cyclic wetting-drying has a more complex impact on the deterioration of the structural properties of coal than continuous wetting. Each wetting-drying cycle also caused a certain degree of damage to the coal specimens’ structure. These findings suggest that understanding the effect of wetting-drying cycles on coal mass is necessary to expand our knowledge of fluid permeability in coal mines.

### 3.2 Stress-strain curves

Generally, the failure process for coal specimens has five stages: (a) The microcrack compaction stage: the coal is compacted in initial loading and the stress-strain curve should adopt a concave shape. This could be due to the closing of the microcracks inside the coal under an external force. (b) The elastic deformation stage: the stress-strain curve shows a nearly linear relationship between the outset of the curve up to the yield strength. (c) The yield stage: the microcracks

**FIGURE 5** Stress-strain curves and Stress-EM variation of coal specimens after continuous wetting
develop and gather together until the coal specimen has completely failed, while the strength reaches the peak strength. (d) The strain-softening stage: after the coal reaches its peak strength, the stress decreases with the rapidly increasing strain, and a macroscopic fracture surface is formed with the development of the microcracks. (e) The plastic flow stage: after the coal fails, it still has a bearing capacity; this is referred to as its residual strength.

Stress-strain relationships, uniaxial compressive strength, and elastic modulus were obtained for coal specimens under different continuous wetting times and numbers of wetting-drying cycles, using uniaxial compression experiments. The stress-strain curves under continuous wetting and cyclic wetting-drying are shown in Figures 5 and 6. The coal specimens were damaged before loading, due to the impact of continuous wetting and cyclic wetting-drying. Thus, these curves do not always follow the above five stages.

With increasing $T$ or $N$, the microcrack compaction stage (stage 1) became wider, the slope of the stress-strain curves in the elastic deformation stage (stage 2) was significantly reduced, and the postpeaks of the stress-strain curves showed a “stepped” fluctuation. In addition, the ductile failure characteristics of the coal specimens increased significantly, following a brittle-ductile transformation law. These changes in the coal specimens are mainly due to large local contact deformations and damage during the loading process together with internal microcracks that grow and expand during wetting-drying cycles. In addition, when the number

**FIGURE 6** Stress-strain curves and Stress-EM variation of coal specimens after wetting-drying cycles

(A) Group A of coal samples

(B) Group B of coal samples
of wetting-drying cycles reached ten, the plastic property of coal increased significantly, the yield platform was obvious, and the yield stage (stage 3) became longer. Therefore, UCS exhibits a decreasing trend with increasing $N$. These results indicate that each wetting-drying cycle could exacerbate the internal damage to coal specimens.

As shown in Figure 6, the peak strengths of coal specimens after cyclic wetting-drying and continuous wetting were all less than those of intact specimens. The elastic modulus of all coal specimens also decreased with increasing $T$ or $N$.

In addition, according to the above data, we found that the effect of continuous wetting on the stress-strain curves was not as significant as that of cyclic wetting-drying. This could be due to the fact that cyclic wetting-drying induced a larger change in the coal structure than continuous wetting. The microcracks and secondary pores thus expanded and increased more rapidly. Therefore, the coal specimens exhibit a higher degree of degradation under cyclic wetting-drying than under continuous wetting.

Although the above-mentioned two environmental conditions (continuous wetting and cyclic wetting-drying) both have an impact on the structure and strength of coal, the effect of wetting-drying cycles on coal mass is rather complex. We therefore evaluated the effect of changes in the water environment such as wetting-drying cycles on the microstructure and macroscopic strength of coal mass.

### 3.3 Uniaxial compressive strength

In order to avoid discreteness of the coal specimens, we normalized mechanical parameters of coal such as UCS and elastic modulus (EM). According to Figure 7, the UCS decreases with increasing $T$ or $N$.

In addition, the damage to a material such as coal under cyclic wetting-drying may be expressed as a degradation degree $D$, which could indicate changes in strength. Mechanical properties determined using $D$ have previously been used to measure changes in rock strength due to cyclic wetting-drying conditions, freeze-thaw conditions, and thermal treatment. $D$ was calculated here using the following formula:

$$D_{UCS} = (1 - \frac{UCS_N}{UCS_0}) \times 100\%, \quad (3)$$

where $D_{UCS}$ is the total degradation degree of UCS, $UCS_N$ is the compressive strength of specimens after $N$ wetting-drying cycles, and $UCS_0$ is the uniaxial compressive strength without a wetting-drying cycle.

According to our test results, UCS decreased with increasing $N$, for $N = 1, 3, 6, \text{and} 10$. The corresponding degradation degrees of the UCS were 2.84%, 29.22%, 33.14% and 47.28%, respectively. At the beginning of testing, the UCS degenerated significantly, and then with further wetting-drying cycles, the UCS degenerated more gradually. These results are similar to those of Perera et al.

According to Equation (3), the degradation degree of coal after continuous wetting may also be calculated. For $T = 1, 3, 6, \text{and} 10$ weeks, the corresponding degradation degrees of the UCS were 8.70%, 21.00%, 19.61%, and 32.05%, respectively. It is clear that the effect of continuous wetting on $D$ was not as significant as that of wetting-drying cycles. This because the wetting-drying cycles could result in coal specimens that are more broken, producing more micropores in the coal than continuous wetting.
3.4 | Elastic modulus

From Figures 5, 6, and 8, it can be seen that the EM of coal decreased gradually throughout the testing process, with increasing $T$ or $N$.

In addition, the degradation degree of the EM, $D_{EM}$ is defined by the following formula:

$$D_{EM} = (1 - EM_N/EM_0) \times 100\%,$$

(4)

where $D_{EM}$ is the total degradation degree of EM, $EM_N$ is the elastic modulus after $N$ wetting-drying cycles, and $EM_0$ is the elastic modulus of the intact specimen that was not subject to wetting-drying processes.

For $N = 1, 3, 6, 10$, the corresponding degradation degrees of coal’s EM were 7.46%, 35.14%, 43.34%, 35.38%, and 60.78%, respectively. It was also possible to calculate the $D_{EM}$ of coal after continuous wetting. For the corresponding values of $T = 1, 3, 6$, and 10 weeks, the degradation degrees of EM were 1.22%, 6.57%, 2.41%, and 16.16%, respectively. For the case of wetting-drying cycles, the EM of coal began to degenerate gradually at the first cycle, after which the EM decreased rapidly with increasing $N$. This is similar to the results of Perera et al.48

These changes to the $D_{EM}$ could indicate that the coal specimens undergo continuous but different amounts of degradation under cyclic wetting-drying and continuous wetting. In addition, these results suggest that cyclic wetting-drying has a more serious deterioration effect on coal than continuous wetting.

4 | DISCUSSION

4.1 | Comparison between cyclic wetting-drying and continuous wetting

According to the above results, both continuous wetting and cyclic wetting-drying degrade the strength of coal. The change in the water adsorption of coal indicates that both conditions further amplify the structural defects inside the coal.

The water adsorption of coal under continuous wetting is equivalent to 5.50%, 20.94%, 39.97%, and 58.40% of the water adsorption for an increasing number of wetting-drying cycles (up to 10 cycles). This water adsorption is the external manifestation of crack size and distribution within the coal.49

These results indicate that continuous wetting could induce structural changes and deterioration in the coal to various degrees. Further, the effect of continuous wetting on structural changes has a time-based component, while cyclic wetting-drying has a more significant impact on structure.

For the stress-strain curves, the wetting-drying cycles produce stress-strain curves with a more significant ductility compared to continuous wetting. Furthermore, the peak strength of all the coal specimens after continuous wetting and cyclic wetting-drying was less than those of intact specimens, with peak strength decreasing with increasing $N$ or $T$. These mechanical effects are due to microcrack incremental increase and expansion under water-coal interactions.

With regard, uniaxial compressive strength and elastic modulus, a more significant reduction in mechanical properties occurred during cyclic wetting-drying. Furthermore, Zhang et al34 researched the effect of water on the mechanical properties of brown coal, finding that uniaxial compressive strength was influenced by changes in the moisture content. Their work also highlighted structural changes in coal upon interaction with water molecules.50 Considering this study, it may be suggested that cyclic wetting-drying continuously changes the moisture condition of coal specimens. In short, cyclic wetting-drying could induce cyclic changes in the moisture content of coal, where these environmental conditions influence both the structure and mechanical properties of coal in a complex manner.

4.2 | Deterioration factors of coal under cyclic wetting-drying

As mentioned above, the degradation degrees of UCS and EM for the coal specimens are correlated with $T$ or $N$. However, in practical engineering applications, it is difficult to determine the specific value of $T$ or $N$. As water adsorption and porosity represent the volume of the voids in coal specimens, these microstructural parameters could be used to define the damage induced by wetting-drying cycles. In addition, the degradation of wetting-drying circulation is a complex process that could lead to the accumulation of irreversible
damage in the coal structure. At the macroscopic and microscopic scales, the laws related to the deterioration of coal's mechanical properties that are induced by cyclic wetting-drying may be analyzed in term of the following aspects.

### 4.2.1 Structural parameters of coal

As shown in Figure 9, there are many microfractures inside the coal. These microfractures provide the necessary conditions for water-coal interaction. In addition, there are riverbed-shaped structural defects inside the coal, as shown in Figure 10. Water could gradually enter the interior of the coal through these riverbed-shape structural defects.

Under cyclic wetting-drying, the clay minerals have a high swelling-shrinking capacity. Under frequent water adsorption and water loss, these minerals could induce microscale destruction of the coal specimens’ structure. As is shown in Figure 11, the distribution of the clay minerals inside the coal is characterized using the distribution of the clay minerals' main chemical constituent elements, such as O, Al, and Si. According to these results, the clay minerals are widely distributed and present in various forms. An inhomogeneity could be induced in the coal specimens, due to the structural parameters of coal and the distribution of clay minerals.

As shown in Figure 11D and E, coal specimens with N = 0 and N = 3 were analyzed to investigate the impact of clay minerals on coal structure. Within the areas containing clay minerals, the morphology of the coal surface after wetting-drying cycles shows a wide distribution of tiny cracks and fragments. However, within the other areas, the coal surface morphology shows high integrity and compactness. These indicate that the clay minerals promote the growth of internal fissures and the formation of flaky structures via interactions with water.

### 4.2.2 Water-coal interaction

It is known that cyclic wetting-drying can initiate water-coal interactions, which could result in interface slips and local contact deformation of the coal structure. These processes not only enhance the plasticity of the coal specimen, but also induce initial deformation of the coal specimen prior to loading. This greatly affects the mechanical properties of coal. During the water-coal interactions, the coal specimens under cyclic wetting-drying exhibit a higher damage rate than untreated coal specimens, indicating that cyclic wetting-drying leads to a complex deterioration effect. In addition, water is a polar molecule and a solvent, and coal mass contains complex soluble components such as clay minerals. These could increase the effect of water-coal interaction when in contact with water. After a coal specimen is immersed in water, the mineral ions in the coal specimen precipitate, the solution concentration increases until the solution is saturated, and the reaction tends to be dynamically balanced. In the case of cyclic wetting-drying, the external environment of the coal is continually changing, and thus, the above-mentioned dynamic balance is broken. Under this process, the water-coal interaction continues, the damage of coal intensifies, and the development law for microcracks becomes more complicated.

The liquid bridge force induced by water could alter the interparticle force of the clay mineral particles. When the relative humidity outside the coal was lower than that inside, the water molecules in the clay minerals began to evaporate, and the coal debris began to detach from the coal with the flushing action of the water. Under the interactions of the liquid bridge force and the interparticle force, clay mineral particles gather together, the clay minerals shrink and deform, and dry-shrinkage cracks are formed in coal specimens. This effect further promoted the internal damage to the coal. In addition, during the cyclic wetting-drying, the erosion of microcrack tips was accelerated due to the wedge pressure of water and the expansion pressure of the clay minerals. When the expansion pressure exceeded a certain threshold, there was irreversible weakening of the internal structural connection. Thus, the cohesive force of coal and the adhesion between particles was reduced, the pores between coal particles were more noticeable, microscopic fissures were developed, and the coal integrity was weakened.

As shown in Figure 11, the coal microstructure within zones containing clay minerals was clearly damaged after cyclic wetting-drying. This is because the hydrophilic clay minerals frequently swelled and contracted under wetting-drying cycles, the intergranular connecting materials were dissolved, and connectivity was weakened, which led to a significant expansion of the coal structure and development of fissures. Thus, the coal specimen experienced serious damage during the above process. These results indicate that cyclic wetting-drying affects the mechanical properties of coal, mainly by changing its structure.

### 4.2.3 Cumulative damage induced by cyclic wetting-drying

The deterioration of coal induced by cyclic wetting-drying is a progressive failure process accompanied by significant
cumulative damage. Thus, coal damage was progressive with increasing $N$, until specimen failure. As shown in Figure 12, the coal particles were tightly cemented before cyclic wetting-drying. After the coal specimens were immersed in water, the water molecules penetrated the coal. This process lubricated and softened the coal skeleton, which resulted in dissolution of the clay mineral particles.\textsuperscript{65} Because of these effects, the integrity of coal was weakened. In the drying process, the water molecules inside the coal began to evaporate. This process promoted the outward migration of debris at microcrack fracture sections in the coal specimens. Furthermore, the mechanical effects induced by cyclic wetting-drying result in stress concentration at the tip of the microcrack.\textsuperscript{67} This, in turn, induces the development of microfractures.

These damage processes were repeated with increasing numbers of wetting-drying cycles. In these repeated processes, the number of secondary pores in the coal thus sharply increased and damage was accumulated in the coal structure. Further, the floc-shaped pores gradually became connected, and the microcracks were concentrated, expanded, and transformed into macroscale fractures. Therefore, the stages of...
The microstructural parameters of coal could reflect the internal defects and crack tip regions of the coal specimens, and are active zones of water-coal interaction. Thus, it is necessary to understand the influence of microstructural parameters on the macroscopic strength characteristics of coal under cyclic wetting-drying.

### 4.3 Influence of microstructural parameter changes on the macroscopic strength of coal under cyclic wetting-drying

Internal defects and crack tip regions of the coal specimens are active zones of water-coal interaction. Thus, it is necessary to understand the influence of microstructural parameters on the macroscopic strength characteristics of coal under cyclic wetting-drying.

#### 4.3.1 The quantitative analysis on microstructure parameters of coal under cyclic wetting-drying

The microstructural parameters of coal could reflect changes in internal defects. These parameters include porosity, pore diameter, pore circularity, anisotropy rate, and probability entropy. Porosity describes the density of pores, the pore diameter and pore circularity characterize the morphology of the pores, and the anisotropy rate and probability entropy characterize the pore unit body directivity. These structural parameters then reflect the pore shape, density, and arrangement characteristics of coal specimens, and are therefore correlated with the mechanical strength of coal.

The anisotropy rate $I_n$ could reflect the microstructure of coal. The value of $I_n$ varies from 0% to 100%. The larger the $I_n$, the more chaotic the corresponding coal structure, following the expression:

$$I_n = \frac{L - l}{L} \times 100\%,$$

where $L$ is the major axis length of the microstructure unit; $l$ is the minor axis length.

The probability entropy $H_m$ could reflect the order of the coal pore unit and is described by the formula:

$$H_m = - \sum_{i=1}^{n} F_i(\alpha) \log_n F_i(\alpha),$$

where $\alpha$ is the orientation angle of the pores, and $F_i(\alpha)$ is the occurrence rate of the pores in each orientation angle interval, $F_i(\alpha) = \frac{n_i}{n}$; $n_i$ is the number of pores unit and $n$ is the total number of pores unit in the directional angle in the interval $[\theta_i, \theta_{i+1}]$; where the orientation angle interval $\Delta \theta = 20^\circ$, this is the range of $H_m$ values. At $0 \leq H_m \leq 1$, the larger the $H_m$ value, the more disordered the pores of the internal unit body of the coal.

According to the results of processed SEM images using the IPP software, we obtained the average variations in the microstructural parameters of coal after cyclic wetting-drying, as shown in Table 2. These average variations in microstructural parameters confirm that cyclic wetting-drying has a significant influence on coal structure.

With increasing $N$, pores developed inside the coal, and the coal defects continued to expand. The porosity and pore diameters then increased further, and pore circularity gradually increased. These processes were all due to continuous erosion of the coal pore tips by water scouring, and changes in the microstructure of coal. Furthermore, microcracks expanded and developed, and the pore morphologies changed from their initial morphologies to similar round shapes. In addition, due to the influence of cyclic wetting-drying on coal structure, the directivity of the pore unit body increased, the rate of heterogeneity was enhanced and the tightness between coal particles was weakened.

### TABLE 2 Coal microstructure parameters under different number of wetting-drying cycles

|                  | $N = 0$ | $N = 1$ | $N = 3$ | $N = 6$ | $N = 10$ |
|------------------|--------|--------|--------|--------|--------|
| Porosity         | 0.503  | 0.567  | 0.634  | 0.697  | 0.768  |
| Pore circularity | 0.301  | 0.342  | 0.452  | 0.559  | 0.698  |
| Pore diameter (µm) | 4.723 | 5.324  | 7.035  | 8.872  | 10.478 |
| Anisotropy rate (%) | 49.2  | 54.1  | 64.8  | 65.8  | 71.3  |
| Probability entropy | 0.646 | 0.579  | 0.461  | 0.416  | 0.357  |
Finally, the integrity of coal was reduced, and its uniaxial compressive strength was also reduced. This resulted in an increase in the anisotropy rate and a decrease in the probability entropy.

### 4.3.2 Correlation between microstructural parameters and macroscopic mechanical strength under cyclic wetting-drying

The influence of each microstructural parameter on the macroscopic mechanical properties of coal vary, and most of these are correlated with mechanical strength and permeability. According to an analysis of the correlation coefficients (Pearson coefficient) between microstructural parameters, we examined the correlation between $N$, uniaxial compressive strength, porosity, and various other microstructural parameters of coal, following the expression:

$$
r = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}}.
$$

where $\bar{X}$ is the sample mean of sample $X_i$ and $\bar{Y}$ is the sample mean of sample $Y_i$. The value of $r$ is between $-1$ and $+1$. If $r > 0$, the two variables are positively correlated; if $r < 0$, the two variables are negatively correlated. The higher the absolute value of $r$, the stronger the correlation.

The higher the absolute value of the correlation coefficient, the stronger the correlation between the above-mentioned parameters. This analysis provided the correlation coefficients between microstructural parameters and uniaxial compressive strength under cyclic wetting-drying shown in Table 3.

According to these results, uniaxial compressive strength is significantly correlated with $N$, porosity, pore circularity, pore diameter, anisotropy rate, and probability entropy at the 1% level (a correct probability of 99%). Pore circularity is significantly correlated with porosity, pore diameter, and probability entropy at the 1% level, and is significantly correlated with the anisotropy rate at the 5% level (a correct probability of 95%). In addition, pore diameter is significantly correlated with pore circularity, porosity, and probability entropy at the 1% level, and significantly correlated with the anisotropy rate at the 5% level.

Overall, porosity, pore diameter, and pore circularity exhibit significant positive correlations with each other at the 1% level, and the three have multiple collinearity.

$$
P_D = 0.07I - 0.02, R^2 = 0.995
$$

where $O$ is porosity; $I$ is pore circularity; $P_D$ is pore diameter.

These results indicate that the circularity of the pores is highly correlated with uniaxial compressive strength. Furthermore, pore shape approaches a circular shape as $N$ increases. These effects are due to the water scouring that is induced by cyclic wetting-drying, an effect that also promotes the development of pores. Thus, the pore tip could be eroded continuously, the coal structure damaged, and its mechanical properties deteriorated.

The porosity changed with pore circularity and diameter, and these three parameters are interrelated. The variation of porosity is consistent with the uniaxial compressive strength, and so porosity could be selected as a significant variable for uniaxial compressive strength multiple regression analysis.

Furthermore, because the circularity and porosity of pores are significant variables that affect the uniaxial compressive strength of coal, an expression for its uniaxial compressive strength was thus established:

$$
\sigma_f = 54.36 - 1.24O - 51.84\Phi,
$$

where $\sigma_f$ is its uniaxial compressive strength, and $\Phi$ is the porosity.
The fitted value for the uniaxial compressive strength of coal could be obtained by substituting the measured values for pore circularity and porosity into the regression equation for uniaxial compressive strength (Equation 6). Comparisons between measured and fitted values for uniaxial compressive strength obtained in laboratory tests are shown in Table 4.

These results show that the regression-fitting results are generally consistent with the measured results for the samples and that the regression equation has a high fitting accuracy. Therefore, under the basis of eliminating the multiple collinearity of the different microstructural parameters, this regression equation could be used to reduce the dimensions of microstructural parameters and provide new insight into the process of the stress-crack-permeability evolution inside coal under wetting-drying cycles.75

According to the regression model of cyclic wetting-drying, porosity and pore circularity are the main significant correlation indicators associated with uniaxial compressive strength. These findings indicate that we should focus our further studies on the microcrack morphology of coal mass and its development in the coal mine.63 In this manner, we aim to estimate the mechanical strength of coal mass in order to avoid disasters induced by coal mass instability in coal mines.

5 | CONCLUSION

In the current work, we studied the variation of coal microstructure and strength after various continuous wetting times and numbers of wetting-drying cycles. We also studied several microstructural parameters, and their influence on the macroscopic mechanical strength and microstructure of coal, using IPP software. The main conclusions are as follows:

1. The water adsorption, uniaxial compressive strength elastic modulus, and stress-strain results indicate that cyclic wetting-drying has a more significant impact on the microstructure and macroscopic mechanical properties of coal than continuous wetting.
2. The effect of cyclic wetting-drying involves a process of cumulative damage to the microscopic pore structure, and a cumulative effect on macroscopic strength. The porosity of coal, its average pore diameter, and its circularity increased with increasing number of wetting-drying cycles, while the uniaxial compressive strength was reduced. In addition, the uniaxial compressive strength of coal follows a functional relationship to its porosity under the effect of wetting-drying cycles. Therefore, in case of a coal mine, we may estimate the deterioration degree of coal mass by observing its microstructure.
3. The cyclic wetting-drying of coal could result in a deterioration of macroscopic mechanical properties via three factors: the inherent coal structure, water-coal interactions, and cumulative damage to the coal structure. The coal structure could provide channels for water-coal interactions; the water adsorption-swelling behavior of the clay minerals inside coal could promote microcrack propagation, water dissolution, and a scouring effect due to the water-coal interaction; and cumulative damage accelerates the deterioration of the microstructural parameters and macroscopic mechanical properties of coal.
4. The wetting-drying cycles could induce progressive and irreversible damage to the coal structure. Thus, we should focus on reducing the risk of instability induced by changes in the water environment that is present in mining engineering applications.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously,
and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

ORCID

Tianqi Jiang https://orcid.org/0000-0003-3500-8435
Dawei Yin https://orcid.org/0000-0002-8846-2001

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