Experimental Study on the Mechanical Behavior of Coal Samples during Water Saturation

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ABSTRACT: When mining-induced fractures reach overlying aquifers, water enters the mining area and the coal is under different natural water saturation conditions, which significantly affect the mechanical behavior of the coal. In this study, uniaxial compression tests were conducted on dry, partially saturated, quasi-saturated, and fully saturated coal samples. The mechanical parameters, acoustic emission (AE) activities, and failure patterns of differently saturated coal samples were analyzed. The effect of water content on the behavior of coal and suggestions to ensure safe underground coal mining were discussed. The results indicate that the water content in coal increases nonlinearly with intrusion time and can be regarded as a logarithmic function. With increasing water saturation, the mechanical strength of the coal decreases on the whole and the AE activities, crack development, and burst severity are weakened significantly. The failure pattern of the coal samples changes from a dynamic type to a quasi-static one and from a compressive-shear type to a tensile one. Water content has four main effects on the mechanical behavior of the coal samples. These are a liquid bridge force, a water softening effect, a wedge effect, and a lubrication effect. With increasing water saturation, the effect of water gradually increases and predominates the coal failure, leading to a continuous decline in the strength of the coal samples. When the coal around the mining space is subjected to water, the high degree of water saturation in the coal decreases the risks of coal bursts significantly; however, it causes a large deformation and instability of the roadways. To ensure safe mining, more measures should be taken to decrease the amount of inrushing water, reduce the stress, and reinforce the anchor bolting support.

1. INTRODUCTION

In recent years, the intensive exploitation of coal resources in China has gradually transferred to west China and the coal mining depth has increased significantly (the maximum depth exceeds 1500 m).1 Meanwhile, dynamic disasters during underground coal mining, such as coal or rock bursts, have occurred more frequently.2 In contrast to the eastern regions of China, overlying confined aquifers are commonly present in the deep coal mines in west China.3

The Binchang mining area is located in a hilly and gully area of the Loess Plateau in Shaanxi Province, and it is the major coal extraction area of the Huanglong coal production base in west China. The Binchang mining area extends to about 46.0 km in the east–west direction and 36.5 km in the north–south direction. The proven coal reserves of the Binchang mining area are 7.6 billion tons. By the end of 2020, there were 12 coal mines under production and 1 coal mine under development; out of these, coal burst disasters occurred in 7 coal mines, as shown in Figure 1a. In the Binchang mining area, the no. 4 coal seam is the sole fully recoverable coal seam whose thickness ranges from 0.15 to 35.04 m with an average of 10.64 m. The depth of the no. 4 coal seam gradually deepens from the southeast to the northwest and ranges from about 400 to 1000 m. Above the no. 4 coal seam is the Cretaceous Luohe Formation aquifer (LHFA), which is rich in water, as shown in Figure 1a. Underground coal mining experience has indicated that the LHFA is the main source of water that rushes in from the mine roof and causes disasters in the mining area.4 Meanwhile, the LHFA has good recharge capability, and it is very difficult to thoroughly drain. In the Binchang mining area, the Gaojiapu coal mine is the deepest one, with a depth reaching 1000 m. At present, four panels, including 12 longwall working (LW) faces, have been developed and they all underlie the highly watery LHFA. During coal mining in LWs, the fully mechanized caving method was adopted and the mining height was about 7–10 m. The advancing speed of LWs was about 3.2–5.6 m. As shown in Figure 1b, the thickness of the LHFA is 330–450 m, and the distance between the no. 4 coal seam

Received: September 14, 2021
Accepted: November 17, 2021
Published: December 1, 2021
and the LHFA is 50−160 m. The overlying strata profile of a geological exploration borehole is shown in Figure 1c. The maximum water pressure in the LHFA reaches up to 7 MPa. A microseismic monitoring system (MS) has been used to capture the ruptures in the coal and rock mass, and the MS results in Figure 1d indicate that mining-induced fractures have reached the middle of the LHFA and formed many channels for the confined water to enter the mining gob. In addition, the maximum water inflow into the LW can reach up to 800 m^3/h, and this exceeds the capacity of the drainage pump station. The average water logging in the 0−100 m advanced gates can reach 0.4 m. In such a case, the coal mass surrounding the gob area is under different natural water saturation conditions.

The extrinsic stress environment and the intrinsic mechanical properties of the coal/rock are the two dominant factors leading to coal/rock dynamic disasters. It has been reported that many factors, including large buried depth, thick-hard roof, folds, faults, and magmatic intrusion, can lead to coal burst or rockburst by changing the extrinsic stress field. Moreover, mineral components, microstructure, and the temperature and water condition can change the intrinsic mechanical behaviors of coal and rocks significantly. The mechanical behavior of most coal/rocks is severely affected by the state of their water saturation. A deep understanding of water–coal/rock interactions is of significance to ensure the stability of underground engineering works.

The mechanical behavior of coal/rock with different water contents, including their mechanical parameters, crack development, and failure patterns, has been extensively studied. The water content in coal and rock heavily depends on the internal microstructures and the soaking time. The physical process of water imbibition in coal and rock samples has been reproduced using physical tests and numerical simulations. To obtain the mechanical parameters of coal and rocks with different water contents, a series of experiments including uniaxial compression/tensile tests, point-load tests, and triaxial compression tests have been conducted. These studies have shown that, with increasing water content, the uniaxial compressive strength (UCS), uniaxial tensile strength, shear strength, Young’s modulus, rigidity, and brittleness, friction angle, plastic deformability, accumulation energy, and burst propensity all decrease, but that the Poisson’s ratio increases. Moreover, acoustic emission (AE) tests on dry and saturated coal and rocks have been conducted and the results have shown that the AE activity of the saturated samples decreases while the crack initiation stress increases. Additionally, the crack development and failure modes of coal and rocks with different water contents have also been systematically investigated.

Coal and rocks in coal measure strata are porous media materials and their micropore structure significantly influences their physical and mechanical properties. The response of the micropore structure of coal and rocks to water has been detected and the micro mechanisms of water–coal/rock interactions have been analyzed comprehensively using scanning electron microscopy (SEM), micro-X-ray computed tomography, and nuclear magnetic resonance imaging.
tomography (μ-CT), nitrogen adsorption/desorption (NAD), mercury intrusion porosimetry (MIP), transmission electron microscopy (TEM), and nuclear magnetic resonance (NMR). It has been found that water treatment of coal and rocks can increase the pore size, permeability, and porosity, as well as change the mineral components. This microstructure exploration greatly helps understand the microscopic mechanical behaviors of coal and rocks.

However, in most studies on the effect of water on the mechanical behavior of coal/rock, only dry, natural, and fully saturated coal or rocks were considered and less unsaturated samples were rarely included. In practice, coal and rocks in underground coal mines are all under unsaturated conditions. The water saturation degree is a critical factor affecting the mechanical properties and the stability of coal and rock structures. Comprehensive experimental data on the mechanical behavior of coal or rocks during the saturation process is limited. Therefore, further studies on the mechanical behavior of coal or rocks during the saturation process need to be carried out.

In this study, uniaxial compression tests on coal samples during a water saturation process (i.e., dry, partially saturated, quasi-saturated, and fully saturated state) were performed, and then their stress-strain curves, mechanical parameters, AE activities, and failure patterns were analyzed. The microstructures of different saturated samples were detected. Finally, the effect of water content on the mechanical behavior of coal and its relevance to the safe underground mining of coal is discussed. This study is expected to provide a deeper understanding of the mechanical behavior of coal during the saturation process and guide the safe mining of coal.

2. EXPERIMENTAL SCHEME

2.1. Preparation of the Coal Samples. The preparation of the coal samples, the test apparatus, and the test procedure are illustrated in Figure 2. Coal blocks were derived from the LW 205 in the Gaojiapu coal mine, which is facing serious coal bursts and water hazards. The no. 4 coal seam in Gaojiapu coal mine is the low-rank bituminous coal. The raw coal ash content is 14.71%, the volatiles of floating coal is 29.00%, the sulfur content of raw coal is 0.96%, and the caloriﬁc capacity is 27.30 MJ/kg. Following the recommended shape and size by
ISRM, 12 cylinder coal samples of 50 mm diameter and 100 mm height were made using a coring machine and two ends of each sample were accurately ground. And the axial direction of the samples is vertical to the horizontal bedding in coal seam. Then, the coal samples were randomly divided into four groups (i.e., groups C1, C2, C3, and C4) and there were three samples in each group.

2.2. Experimental Apparatus. In the test, an MTS system, whose maximum load is 500 kN, was used for the uniaxial loading. An AE system, with eight AE sensors, was used for monitoring the AE signals; the sampling rate was 2 MHz, and the threshold value was 40 dB. A high-speed camera was used to record the deformation and failure patterns of the samples. The static resistance strain indicators with two digital strain gauges orthogonally attached to the surface of the coal samples were used to acquire the axial/circumferential strain of the samples. A scanning electron microscope (SEM) was used to detect the microprobe structures of different water-treated samples with a working current of 25 kV under the high vacuum + nonconductive mode. An X-ray diffractometer was used to test the mineral components in the coal.

2.3. Experimental Methods. When mining-induced fractures reach overlying or underlying aquifers, the coal masses around the mine opening are always under conditions of being naturally soaked by water. Therefore, in this study, the natural water soaking method was conducted to prepare different water-saturated coal samples. First, the coal samples were dried for 24 h in an electric drying oven at a temperature of 110 °C. The coal samples were weighed before and after being oven-dried to calculate their natural water content. Second, the group C4 samples were first totally immersed in water under room-temperature conditions. During the saturation process, they were weighed regularly to determine their water content. The group C4 samples were immersed for 50 h, and their water contents were as illustrated in Figure 3. Then, the group C2 and C3 samples were immersed in water for 3 and 12 h, respectively, to reach partial saturation and quasi-saturation. Finally, dry, partially saturated, quasi-saturated, and fully saturated coal samples were prepared. Here, partially saturated samples means the samples with a low moisture content and rising water absorption speed as well as quasi-saturated samples are the samples with high moisture and decreasing water absorption speed.

The water content of the fully saturated coal samples is illustrated in Figure 3, and it increases nonlinearly with the water intrusion time and finally converges to a certain value. The water saturation process of the coal samples can be divided into three stages, i.e., stage I—rapidly rising stage in the first 7 h, stage II—slowly rising stage from about 8 to 23 h, and stage III—stable stage after about over 23 h. In stage III, the water content remains stable and the weight of the coal sample varies within 0.01 g, meaning that the coal samples are fully saturated. In addition, the relationship between the real water content and the water intrusion time can be expressed by a logarithmic function as

\[ y = a + b \ln x \]  

(1)

where \( y \) is the real water content, \( x \) is the water intrusion time, \( h_1 \) and \( h_2 \) are constants related to the intrinsic property of the coal.

3.2. Stress–Strain Curves. The typical stress–strain curves of the different water-saturated coal samples are shown in Figure 4a. The stress–strain curves can be divided into four stages: the crack closure stage, the elastic deformation stage, the quasi-plastic deformation stage, and the post-peak stage. However, the stress–strain curves of the different saturated samples differ significantly. Compared to the dry samples, on the whole, the wet samples have a lower Young’s modulus, a lower peak stress and peak strain, a shorter elastic deformation stage, a longer post-peak stage, and a minor stress drop at the peak stress, especially the quasi-saturated and fully saturated samples. In the initial loading stage, the stress–strain curves of the partial and quasi-saturated samples are higher than those of the dry and fully saturated samples. The ratios of the post-peak stage, i.e., the ratio between the loading time after the peak stress and the entire loading time, are illustrated in Figure 4b. The ratios of the post-peak stage increase with the saturation degree, and this means that the high water content softens the coal and makes it more plastic. These changes indicate that the water saturation degree has a significant influence on the mechanical behavior of coal, including both the pre- and post-peak stress.
3.3. Mechanical Parameters. The uniaxial compressive strength (UCS), elastic modulus (E), peak strain (εₚ), and Poisson’s ratio (μ) of the dry, partially saturated, quasi-saturated, and fully saturated coal samples are shown in Figure 5. Here, the peak strain is the corresponding strain when the axial stress reaches its peak. It can be noticed that the inferred mechanical parameters of the different saturated samples vary significantly. With increasing water saturation, UCS, E, and εₚ decrease while μ increases. Compared to the dry samples, the UCS of the partially saturated, quasi-saturated, and fully saturated samples decreases by 4.2, 58.7, and 71.3%, respectively. E decreases by 15.2, 48.8, and 61.6%, respectively. εₚ decreases by 1.5, 25.9, and 26.8%, respectively, and μ increases by 12.5, 68.7, and 62.5%, respectively. When the coal samples have low saturation (for the partially saturated samples), the reduction of the four parameters inferred above is limited; when the coal samples are highly saturated (for the quasi- and fully saturated samples), the four parameters decrease significantly. Additionally, the sensitivity to the water saturation degree, from high to low, is UCS, μ, E, and εₚ.

Stiffness is one of the primary deformation parameters, and it can be derived from eq 2

\[ k = \frac{p}{\Delta l} \]  

(2)

where \( k \) is the stiffness, N/m; \( p \) is the axial force, N; and \( \Delta l \) is the axial displacement increment, m.

The stiffness versus axial stress curves before the peak stress of the coal samples are plotted in Figure 6. With continuing axial load, the stiffness drops sharply first in the crack closure stage, then increases gradually in the elastic deformation stage, and fluctuates in the plastic deformation stage. In the elastic and plastic deformation stages, the increasing rate of stiffness decreases gradually. Obviously, the stiffness of the wet samples, on the whole, is lower than that of the dry ones and is related to their water saturation degree. However, when the axial stress is low, the stiffness of the partially saturated samples (group 2) exceeds the dry samples slightly, which can be quantitatively proven when the average stiffness is at 2 MPa.

UCS, bursting energy index (\( K_E \)), and dynamic failure time (DT) are key parameters used in the coal burst propensity index method.\(^\text{10}\) Concerning the UCS in Figure 5a, the softening coefficients (the ratio between the UCS of the wet samples and that of the dry samples) of the wet groups are 0.96, 0.41, and 0.29, respectively. The \( K_E \) and DT values of the tested samples are illustrated in Figure 7. \( K_E \) negatively correlates with the saturation degree, although there exists obvious divergence for the \( K_E \) of the wet samples. However, DT evolves contrarily. The inferred three key parameters all indicate that the coal burst risk is reduced when the water saturation degree increases.

3.4. Energy Characteristics. During the loading process, the external force is absorbed by the coal under the condition that there is no heat exchange with the outside.\(^\text{17}\) The absorbed energy (\( U \)) is mainly divided into two parts, i.e.,

![Figure 4. (a) Stress–strain curves of different water-saturated coal samples and (b) ratio of post-peak stage.](https://doi.org/10.1021/acsomega.1c05077)
elastic energy ($U^e$) and dissipated energy ($U^d$). And they can be expressed by eq 3

$$U = U^e + U^d$$

(3)

In this study, the coal samples were uniaxially loaded; hence, the total energy $U$ and the elastic energy $U^e$ can be calculated by eqs 4 and $S_2$, and here, $E_u$ can be estimated to the loading elastic modulus.\(^{17}\)

$$U = \int_0^{\varepsilon_1} \sigma_i \, d\varepsilon_i$$

(4)

Figure 5. (a) UCS, (b) $E_i$, (c) $\varepsilon_p$, and (d) $\mu$ of different saturated samples.

Figure 6. Stiffness curves before peak stress of coal samples.

Figure 7. Bursting energy index and dynamic failure time of the tested coal samples.

$$U^e = \frac{1}{2} \sigma_i \varepsilon^i = \frac{1}{2} E_u \varepsilon_1^2 = \frac{1}{2} E_0 \varepsilon_1^2$$

(5)

where $\sigma_i$ is the axial stress, MPa; $E_u$ is the unloading elastic modulus; and $E_0$ is the loading elastic modulus.

Figure 8 shows the energy characteristics of the samples during the saturation process at peak stress. With the increase in water saturation, the energy density of the coal decreases on the whole, especially for the quasi-saturated samples. When the coal is fully water saturated, the three energy parameters ($U$, $U^e$, and $U^d$) all converge gradually. Before peak stress, the total energy is mainly transformed to elastic energy stored in the
coal, and only a small portion is converted into dissipative energy which is irreversible. The elastic energy accounts for 70.7–87.2%, and the dissipative energy is 12.8–29.3%. Particularly, when the coal is partially saturated, the elastic energy increases slightly instead of falling unexpectedly. This indicates that the capacity for storing elastic energy can be enhanced slightly when the coal has low water saturation and weakened significantly when it is highly saturated.

3.5. AE Activity. It has been shown that AE counts can be used to identify crack initiation and propagation in coal and rocks.32 In this study, the AE activity of the coal samples was examined and the results showed that the AE count evolves in a similar manner to the AE energy. Here, only the AE energy change of some typical samples is given in Figure 9.

It can be seen that AE activity is closely related to the axial loading and that its evolution can reflect the structural changes in coal samples.33 The AE activity of the different saturated samples can be divided into four stages by the three critical stresses that occur at points A, B, and C; these are the silence stage, the linear increase stage, the nonlinear increase stage, and the decline stage. The critical stresses at points A, B, and C represent the onset of stable crack development, unstable crack development, and macro fracture development, respectively. For the dry samples, in the initial loading stage, there are a few AE activities and only several AE events occur at about 200 s, which can be due to the friction between the compressed raw cracks and the fractures leading to a slight release of the accumulated energy. When the axial stress reaches about 3.7 MPa (point A), the accumulative AE energy–time curve begins to increase linearly with a small amplitude, which represents the initiation of cracks within the samples and the steady release of the cumulative energy. Afterward, when the axial stress increases to about 8.5 MPa (point B), the AE energy–time curve begins to grow rapidly and nonlinearly, which shows that unstable cracks are beginning to be developed leading to an accelerated release of the accumulated energy. Meanwhile, some slight stress drops occur on the stress–time curve. When the axial stress is about 16.0 MPa (point C), AE activity increases sharply and reaches its peak, indicating that the cracks in the samples have developed further and interconnected to form minor fractures, leading to the release of a substantial amount of elastic strain energy. After the peak stress, the accumulative AE energy–time increases and the stress–time curve decreases in a step-like manner. This may be caused by the periodic extension and activation of the fractures. Eventually, a main and macro fracture is formed, leading to the thorough failure of the coal samples.

The critical stresses at points A, B, and C are 3.8, 9.6, and 14.6 MPa for the partially saturated sample 2-3; 4.1, 5.7, and

![Figure 8. Energy distribution at the peak stress of the coal in the saturation process.](image)

![Figure 9. AE activities of (a) dry sample 1-3, (b) partially saturated sample 2-3, (c) quasi-saturated sample 3-3, and (d) fully saturated sample 4-3.](image)
4.3 MPa for the quasi-saturated sample 3-3; and 3.7, 3.8, and 3.8 MPa for the fully saturated sample 4-3, respectively. It can be seen that the critical stresses at points A and B both first increase slightly with the increasing water saturation degree and then decrease when the coal samples are quasi-saturated or fully water-saturated. In contrast, the critical stresses at point C decrease monotonically. It should be noted that for the dry and partially saturated samples, the three critical stresses all occur before the peak stress; however, for the quasi-saturated samples, the critical stress at point C is behind the peak stress, and for the fully saturated samples, the critical stresses at points B and C are both behind the peak stress. At point C, the AE energies of samples 1-3, 2-3, 3-3, and 4-3 are $7.8 \times 10^7$, $6.4 \times 10^6$, $2.5 \times 10^5$, and $1.9 \times 10^5$ aJ, respectively, and the accumulated AE energy is $4.9 \times 10^6$, $4.3 \times 10^5$, $4.7 \times 10^5$, and $6.7 \times 10^5$ aJ, respectively. It is obvious that the AE energy and the accumulated energy both decrease with the increase in the water saturation on the whole and that the AE activities of the loaded wet coal samples are depressed effectively.

**3.6. Failure Mode.** Under uniaxial loading, the failure modes of coal and rocks can be classified into three kinds in terms of the macro fracture morphology, i.e., tensile, shear, and mixed tensile-shear failure. In the tensile failure type, the macro fractures are almost parallel to the axial stress; in the shear

![Figure 10. Failure morphologies and some typical RA-AF scatter: (a) dry samples, (b) partially saturated samples, (c) quasi-saturated samples, and (d) fully saturated samples.](https://doi.org/10.1021/acsomega.1c05077)
failure type, the angle between the macro fractures and the axial stress is less than 45° or the failure plane is along a structural weakness; the mixed tensile-shear failure type is a combination of the two failure modes presented above, and the macro fracture morphology is always of an X-shape.34 The failure modes of coal and rocks are closely related to the water content, joint inclination angle, initial cracks, and so on.35 The failure modes of the four groups of coal samples analyzed in this study are presented in Figure 10, and they show significant differences.

In the loading process of the dry samples, as shown in Figure 10a, a dynamic phenomenon occurs with the fierce and continuous ejection of coal slabs, and a strong sound is also heard. The maximum size of the coal slabs reach 4 cm long, 2 cm wide, and 1 cm thick. After the uniaxial loading tests, the original cylindrical shapes of the dry samples are poorly maintained or even completely collapsed, especially sample C1-2. In addition, X-shape macro fractures are observed on the failed samples. There is also a macro fracture almost parallel to the longitudinal axis (axial stress direction) on sample C1-3. The macro fracture distribution implies that the dry coal samples exhibit mixed tensile-shear failure. During the loading of the partially saturated samples, fierce and continuous ejection of coal slabs also occurred, but the ejections were small in size. The remainder of the samples were also very seriously damaged due to macro fractures. It can be seen that most of the macro fractures in the partially saturated samples are parallel to the longitudinal axis, and notably, there is also a main X-shape macro fracture on sample C2-3, which means that the partially saturated samples underwent tensile or mixed tensile-shear failure. During the loading of the quasi-saturated samples, the process was quite calm, and only a few macro fractures almost parallel to the longitudinal axis appeared on the surface. After the uniaxial loading testing, only some local damage near the sample ends of samples C3-1 and 3-3 occurred, but sample C3-2 collapsed along the main penetrating fracture that was parallel to the longitudinal axis. It can be concluded that the quasi-saturated samples mainly underwent tensile failure. In the loading process of the fully saturated samples, only some coal spalling occurred and a dull sound was heard. The failed samples were all intact and a few macro fractures almost parallel to the longitudinal axis on samples C4-1 and C4-3 appeared. However, an obvious X-shape macro fracture was observed on sample C4-2. This indicates that the fully saturated samples C4-1 and C4-3 underwent tensile failure and that sample C4-2 underwent mixed tensile-shear failure. Given the inhomogeneity and anisotropy of coal samples, the dominant failure mode generally changes from mixed tensile-shear failure to tensile failure with increasing water saturation. Moreover, high water saturation weakens the failure severity and the coal burst tendency of the coal samples significantly.

AE signals are characterized by a series of physical parameters, as shown in Figure 11a. It has been demonstrated that tensile cracks always lead to AE waveforms with a short rise time and a high frequency and that shear cracks usually result in AE waveforms with lower frequencies and longer rise times. That is, tensile cracks give rise to high AF (count/duration time) and low RA (rise time/amplitude), while shear cracks give rise to low AF and high RA.36 The ratio of AF and RA (the transition line) is regarded as a criterion to classify crack types (Figure 11b), and this ratio can be obtained by tensile and direct shear tests.36

The typical AF and RA of the coal samples obtained during the saturation process in this test are illustrated in Figure 10. It can be seen that the AF and RA of the coal samples in the saturation process are 0−500 kHz and 0−50 ms/V, respectively. Although the ratio of AF and RA is not given here, the changes in the AF and RA distribution can also depict the influence of water content on crack development and failure modes.37 With increasing water saturation, the maximum RA of the AE events decreases significantly, especially for the fully saturated samples. It implies that the high water saturation changes the main crack type from a tensile-shear type to the tensile type, which is identical to the macro fracture distribution shown in Figure 10.

4. DISCUSSION

4.1. Effect of Water Content on the Mechanical Behavior of Coal. The water absorption rate of the coal samples in Figure 3 indicates that the coal has strong hydrophilicity. The distinct crack closure stage in the stress−strain curves in Figure 4 indicates that there are substantial inherent cracks and pores in the coal samples through which the water seeps into the coal, gets in contact with the coal particles, and fills the initial gaps and cracks. The water content in the coal samples has four effects on the coal, i.e., the liquid bridge force, the water softening effect, the water wedge effect, and the lubrication effect.38,39

Under uniaxial loading, the liquid bridge (F) in the water-treated coal samples consists of static and dynamic liquid bridge forces.39 The static liquid bridge force includes the capillary force, surface tension, and viscous forces; the dynamic liquid bridge force is mainly related to the relative velocity between two adjacent coal particles. A theoretical model39 has been built to reveal the influence of the liquid bridge volume (V) and the distance (S) between coal particles on F, as shown in Figure 12 and eq 6.
the sensitivity of then decreases during the water saturation process. However, cyclically, the mechanical strength of the samples to form macro fractures. As a result, plastic stage, where micro cracks develop and further intersect however, with continued loading, the coal sample enters the degree) has a big in particles is small and the water content (water saturation fact that, in the initial loading stage, the of the coal sample; and of the partially saturated samples can be caused by the changes heterogeneity of the samples.

According to the X-ray dirogram in Figure 13, the main components in coal include quartz (SiO₂), kaolinite (Al₄(OH)₈SiO₂₆), calcite (CaCO₃), and pyrite (FeS₂) with contents of 14.4, 60.8, 8.6, and 16.2%, respectively. When immersed in water, the mineral substances in the coal swell and

\[
F = \frac{4R_1R_2}{R_1 + R_2} \pi \sigma \cos \theta \left[ 1 - \frac{1}{\sqrt{1 + \frac{(R_1 + R_2)V}{\pi R_1R_2}}} \right] + \frac{6\pi \eta}{S}
\]

\[
\left[ \frac{R_1R_2}{R_1 + R_2} \right]^2 \left[ 1 - \frac{S}{V(R_1 + R_2) + S^2} \right]^2 \nu
\]

where \( F \) is the liquid bridge force of two adjacent coal particles; \( m_1, m_2 \) and \( R_1, R_2 \) are the quality and radii of the two adjacent coal particles, respectively; \( S \) is the distance between the two coal particles; \( \sigma \) is the surface tension of the liquid; \( \theta \) is the contact angle; \( V \) is the liquid bridge volume; \( \eta \) is the porosity of the coal sample; and \( \nu \) is the relative velocity between the two adjacent coal particles when subjected to uniaxial loading.

\( V \) is positively correlated to the water saturation degree of the coal samples. It has been demonstrated that under the same conditions of loading, \( F \) first increases with increasing water content and then decreases gradually when the water content exceeds a certain value of \( V \), that is, there exists an optimal value of \( V \) at which the \( F \) is maximum. Macroscopically, the mechanical strength of the samples first increases and then decreases during the water saturation process. However, the sensitivity of \( F \) to \( S \) is greater than its sensitivity to \( V \), and when \( S \) increases, \( F \) decreases rapidly. This is manifested by the fact that, in the initial loading stage, the \( S \) of the adjacent particles is small and the water content (water saturation degree) has a big influence on the strength of the coal; however, with continued loading, the coal sample enters the plastic stage, where micro cracks develop and further intersect to form macro fractures. As a result, \( S \) increases substantially and \( F \) declines significantly and can even be ignored. The abnormal stiffness in Figure 6 and the elastic energy in Figure 8 of the partially saturated samples can be caused by the changes of \( F \) with \( V \) and \( S \); however, they can also be due to the heterogeneity of the samples.

The energy spectrum analysis of the coal samples used in the compression test shows that the proportion of carbon is about 84% and the other components, including oxygen, calcium, sulfur, silicon, and aluminum, account for about 16%. According to the X-ray diffraction analysis in Figure 13, the main components in coal include quartz (SiO₂), kaolinite (Al₄(OH)₈SiO₂₆), calcite (CaCO₃), and pyrite (FeS₂) with contents of 14.4, 60.8, 8.6, and 16.2%, respectively. When immersed in water, the mineral substances in the coal swell and

then exert extra stress on the initial cracks, which promotes crack development. When a coal sample is treated with water for a long time, these clay minerals will dissolve. Figure 14 shows the SEM results of the dry and fully saturated samples under 500 and 2000 magnification, respectively. It should be noted that the coal specimens used for the SEM tests were derived from the external parts of the failed samples and that their average diameter is less than 1 cm. It can be seen that in the dry samples, the coal structures are intact and densely cemented. Additionally, the plane of the fracture is quite smooth, except for some fragments, and the micropores are mutually independent, as shown in Figure 14a,d. However, in the wet samples, due to the swelling and dissolution of some mineral substances, the cohesion between adjacent coal particles is decreased significantly and more unconstrained coal flakes and particles are exposed and then swept away by the free water in the samples, as shown in Figure 14b,e. Consequently, the pores enlarge, large drainage channels develop, and coal microstructures loosen or break, as shown in Figure 14c,f. During the water saturation process, the pore and microstructural changes soften the coal and its macroscopic mechanical strength declines significantly.

As shown in Figure 15, when the wet samples are loaded, the inherent pores and cracks condense, and consequently, water pressure (\( p_w \)) arises and leads to the expansion of the stress concentration at the tips of the cracks. Moreover, the water softening effect on the mineral particles and the micro-
structural damage both cause the critical crack initiation stress ($p_{tc}$) to decrease. The higher $p_{tw}$ and lower $p_{tc}$ both act on the tips of the inherent cracks and promote the development of tensile cracks, as shown in Figure 14c. Under continued loading, the shear stress ($p_{sw}$) along the crack plane increases, and when it exceeds the critical shear stress ($p_{sc}$), macro cracks form, then slipping occurs, and the sample can even collapse. It should be noted that as a result of the water lubrication effect, as well as the water softening effect, $p_{sw}$ will decrease and consequently, the macro cracks will slip and collapse at a low $p_{sw}$.

As a result of the liquid bridge force ($F$), the water softening effect, the water wedge effect, and the lubrication effect of the water content presented above, the mechanical parameters and failure patterns of the coal samples in the saturation process differ significantly. In the initial loading stage, when the water saturation degree is low, the water softening effect is weak and the $F$ between the water and the coal particles is high and cannot be ignored, which leads to higher stress–strain curves and larger stiffness of the less saturated samples compared to the dry ones, such as C2-3 and C3-3, shown in Figures 4a and 6. However, when the water saturation degree is high, the water softening effect gradually comes into play and some clay cementing substances gradually swell and dissolve in the water. Meanwhile, $S$ increases obviously and $F$ decreases rapidly and can even be ignored. This results in lower stress–strain curves and smaller stiffness of the highly saturated samples compared to the dry ones, such as C4-3 in Figures 4a and 6. During the elastic stage, the water softening effect dominates and is positively correlated with the water treatment time and the saturation degree. This leads to a high compressibility and large deformation of the highly saturated samples, which can explain the decreasing elastic modulus ($E$) and the increasing Poisson’s ratio ($\mu$) in Figure 5 as well as the decreasing stiffness in Figure 6 with increasing water saturation degree. When the axial loading exceeds the elastic limit, micro cracks begin to develop and gradually intersect to form macro fractures. Due to the water wedge effect and the lubrication effect, micro cracks develop and intersect to form macro cracks or fractures at lower stress levels, and the capacity of the coal structures to bear stress and accumulate elastic energy is weakened, which depresses the mechanical parameters of the coal samples in Figure 5a, the coal burst propensity in Figure 7, the elastic energy in Figure 8, the AE activity in Figure 9, and the coal burst intensity in Figure 10 significantly. In most coal and rocks, the tensile strength is always far less than the shear strength.
strength. With increasing water saturation and the softening of the coal structure, the effective stress it can bear decreases and the accumulated elastic energy before failure occurs is reduced significantly. This promotes the development of tensile cracks at a lower stress, weakens the severity of failure, and changes the failure pattern from a tensile-shear type to a tensile one, as illustrated in Figure 11. On the whole, for the samples treated with water for 3 h (partial-saturation samples in group 2), the liquid bridge force ($F$) dominates and the mechanical strength is only limitedly reduced. However, for the samples treated with water for 12 and 50 h that are highly saturated (quasi-saturation samples in group 3 and full-saturation samples in group 4), the water softening effect, the water wedge effect, and the lubrication effect are gradually strengthened and dominate the mechanical behavior of the coal samples, which leads to the significant decline of the mechanical strength of the highly water-saturated samples.

4.2. References for Field Engineering in Underground Coal Mines. Coal burst is induced by the abrupt release of a large amount of elastic energy when the stress exceeds the ultimate strength of coal mass. The coal burst risk is positively related to the accumulated elastic energy in coal. Water injection in coal has been a widely used method to reduce the coal burst risk, which can be attributed to the water content in the coal and rock mass around the roadway, as shown in Figure 17b. The water logging area in the advanced gates can be about 100 m from the LW, and the maximum water logging depth can reach 0.4 m. The high humid environment has a great influence on the properties of the coal and rock, as well as the support structures, and then further changes the stress field. On the one hand, the high humid environment increases the water content in the coal and rock mass around the roadway, as well as decreases the strength of the coal and reduces the coal/rock burst risks significantly. On the other hand, it leads to the severe erosion of the support materials (anchor bolt, anchor plate, steel band, and steel mesh) and the large deformation of the roadway, as shown in Figure 17b, which weakens the strength of the support and aggravates the
instability of the roadway. In the advanced gates in the Gaojiapu coal mine that are under severe humid conditions, the maximum heave of the floor and the deformation of the sidewalls can reach 1.0 and 0.5 m, respectively. The broken coal in the floor and sidewalls is composed of small-size briquettes and even powder due to the effect of water on the coal.

Therefore, in Gaojiapu coal mine, the high saturation degree of the coal seam and the inrushing of water in the LW and the advanced gates are beneficial for the prevention of coal bursts. However, it can lead to large deformation and the progressive failure of the roadways under the sustained stress. The solutions to reducing the influence of the inrushing water on the stability of the roadways can be: first, implement grouting water plugging to increase the strength and decrease the porosity and permeability of the aquifers, which will decrease the number of channels conducting water; second, lower the coal extraction height to restrict the water-conducting fractured zone; third, take pressure-relief measures to decrease the stress concentration around the roadway; and finally, inspect the support quality regularly and reinforce the anchor bolting support strength promptly when required.

5. CONCLUSIONS

Uniaxial compression tests were conducted on coal samples subjected to different degrees of water saturation. The samples were dry, partially saturated, quasi-saturated, and fully saturated. The test results and main conclusions are as follows:

1. The water saturation process of the coal samples shows a rapidly rising stage, a slowly rising stage, and a stable stage, and the water content of the samples is a logarithmic function of intrusion time. With increasing water saturation, the uniaxial compressive strength, elastic modulus, peak strain, stiffness, and bursting energy index decrease while Poisson's ratio increases.

2. The AE activities and burst severity of the coal samples negatively correlate with the water saturation degree. With increasing saturation degree, the main macro fracture and peak AE occurrence are delayed from the peak stress to the post-peak stage and the coal failure pattern changes from a dynamic type to a quasi-static one and from a compressive-shear type to a tensile one.

3. The effect of water on the coal mechanical properties includes a liquid bridge force, a water softening effect, a water wedge effect, and a lubrication effect. When the coal is low saturated, the effect of water is weak and the strength reduction is limited. With increasing saturation degree, the effect of the water increases gradually and then predominates the failure of the coal, and the coal strength is weakened significantly.

4. When mining-induced fractures reach overlying aquifers, water enters the mining area and the coal is under different natural water saturation conditions. This is conducive to decreasing the coal strength and reducing the risk of coal/rock bursts; however, it also leads to severe erosion of the support materials and large deformation of the roadways. For safe mining, further measures should be taken, such as implementing grouting water plugging, lowering the coal extraction height, taking pressure-relief measures, and reinforcing the anchor bolting support.

It should be noted that the conclusions are based on the test on four groups of coal samples taken from a single coal seam. Due to the different deposition environment as well as heterogeneity and anisotropy, more uniaxial and triaxial tests on samples from different coal seams should be conducted to further reveal the mechanical behavior of coal in the water saturation process.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was financially supported by National Natural Science Foundation of China (51934007, 51874292) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX21_2341).

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