Research Article

Experimental Study on the Influence of Moisture Content on the Mechanical Properties of Coal

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Water injection in coal seams will lead to the increase of moisture content in coal, which plays an essential role in the physical and mechanical properties of coal. In order to study the influence of moisture content on the mechanical properties of soft media, the forming pressure (20 MPa) and particle size ratio (0-1 mm (50%), 1-2 mm (25%), and 2-3 mm (25%)) during briquette preparation were firstly determined in this paper. Briquettes with different moisture contents (3%, 6%, 9%, 12%, and 15%) were prepared by using self-developed briquettes. Uniaxial and triaxial compression tests were carried out using the RMT-150C rock mechanics test system. The results show that the uniaxial compressive strength and elastic modulus of briquette samples increase first and then decrease with the increase of briquette water, while Poisson’s ratio decreases first and then increases with the increase of briquette water. When the moisture content is around 9%, the maximum uniaxial compressive strength is 0.866 MPa, the maximum elastic modulus is 1.385 GPa, and Poisson’s ratio is at the minimum of 0.259. The compressive strength of briquettes increases with the increase of confining pressure. With the increase of moisture content, the cohesion and internal friction angle of briquettes first increased and then decreased.

1. Introduction

Coal dust, coal and gas outbursts, and roof hazards in coal mines seriously threaten the mining of underground coal seams and the lives of workers [1–4]. Coal seam water injection is a common technical means to effectively ensure the safe production of coal mines. Water injection in coal seams will increase the moisture content of coal, thus reducing the elastic modulus and uniaxial compressive strength [5–7]. Coal is a typical heterogeneous medium, resulting in its very special mechanical properties [8–11]. There are many components in coal, among which water is the intrinsic component. Consequently, it is necessary to investigate the influence of coal moisture content on the mechanical properties of coal.

Many scientists have studied the key factor of moisture content [12–15]. Yang et al. studied the influence of moisture content on gas outbursts [6]. They found that increasing the moisture content can increase the hardness coefficient of coal seams and significantly reduce the probability of gas outbursts. Wang et al. carried out gas ad/desorption experiments on coal with different moisture contents using a self-designed gas desorption apparatus [16]. The results show that the higher the water content of coal, the higher the pressure drop of coal and the slower the gas flow rate. Perera et al. investigated the influence of water on the strength of lignite at different saturation pressures [17]. Saturated water reduced the uniaxial compressive strength of lignite by 17% and Young’s modulus by 8%. Chen et al. conducted uniaxial compression acoustic emission experiments on coal and rock assemblages with different moisture contents [18]. They found that the strain softening modulus and postpeak modulus were negatively correlated with moisture content, while the peak strain was positively correlated with moisture content. Yao et al. conducted a uniaxial compression test of coal samples and discussed the influence of moisture content on the strength and deformation characteristics of coal samples [19]. They pointed out that the peak strain increased with the increase of moisture content and the tensile strength decreased with the increase of moisture content. Vishal
et al. believed that water was the main cause of the early failure of coal samples under a low overburden load [20]. They pointed out that water causes greater strain at the same stress value. Chen et al. conducted triaxial compression and sound emission experiments on gas coal [21]. The results show that moisture content has a significant inhibitory effect on the acoustic emission of gas coal and can reduce the strength of gas coal. Most of the above scholars adopted hard coal to explore the effect of water on the mechanical properties of coal. However, there are few research studies on the effect of moisture content on the mechanical properties of coal.

Taking briquette coal as the research object, the forming pressure and particle size ratio of briquettes were determined by theoretical analyses and experiments. Then, the briquettes with different moisture contents were prepared by using the self-developed briquettes. Subsequently, uniaxial and triaxial compression experiments were conducted using the RMT-150C rock mechanics test system. The relationship between moisture content and uniaxial compressive strength, elastic modulus, Poisson’s ratio, cohesion, and internal friction angle was analyzed. The research content is hoped to provide some basis for further understanding the mechanical properties of coal.

2. Coal Sample Preparation

2.1. Coal Selection. The macroscopic mechanical properties of coal types with different moisture contents were investigated with the coal from Tian’an Coal in Pingdingshan, Henan, China. Its density is low, and the coal is easily dislodged from the coal wall. The original moisture content of coal samples selected for the mechanical tests of this research coal type ranged from 1.74 to 1.96%, with an average moisture content of 1.81%. Physical property parameters of coal samples were obtained by measuring the industrial composition of coal samples, as shown in Table 1.

2.2. Optimization of Briquette Preparation Parameters. Considering that raw coal is soft and difficult to obtain, a briquette with a similar material scheme is chosen to replace it. According to the experimental results, the porosity and strength characteristics of briquettes are consistent with raw coal to a certain extent [22–24]. In the past, similar material preparation schemes were mostly obtained according to empirical methods, without considering the characteristics of background coal samples, leading to certain errors in experimental results. In order to solve these problems, the test scheme of briquette equipment was optimized from the angle of the particle size ratio and forming pressure.

2.2.1. Forming Pressure of Briquettes. Forming pressure has a great influence on the strength of briquette samples. In order to select the appropriate forming pressure, the mechanical strength of briquettes under different forming pressures was studied. Choose the particle size of 0-1 mm pulverized coal 250 g and water 15 g. The molding pressure was, respectively, set at 5 MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa for pressing, and the pressure holding time was set at 30 min. Then, take out briquette specimens for the uniaxial strength test. Through the analysis of the test results, the rule that the forming pressure affects the briquette strength is obtained. The test results are shown in Figure 1.

According to the test results, on the whole, the uniaxial compressive strength of briquettes increases with the increase of forming pressure. When the forming pressure is less than 20 MPa, the uniaxial compressive strength of briquettes increases significantly with the increase of the forming pressure. But when the forming pressure is greater than 20 MPa, the uniaxial compressive strength of briquettes tends to be stable. Even if the forming pressure continues to increase, the improvement of briquette compressive strength will not get better results. From the test results, the optimal forming pressure is 20 MPa.

2.2.2. Ratio of Particle Size. The coal samples were crushed and screened, and briquette samples were made according to different particle size ratios. The briquette samples were dried and tested for their uniaxial compressive strength. The optimal ratio was obtained through the screening of a similar material particle size ratio scheme by observing stress-strain curve and compressive strength. The matching scheme is shown in Table 2.

Coal samples were prepared under certain forming pressures and certain forming water conditions. The compressive strength of 6 briquettes is tested, and the experimental results are shown in Figure 2. The reasonable ratio of pulverized coal was found through the analysis of compressive strength.

From C-1, C-2, and C-3, the proportion of small particle size had a significant impact on the antipressure effect. The compressive strength increases with the increase of small coal particles. In the preparation of briquettes, it was found that the coal made with coal particles of a certain particle size ratio had better quality and was closer to the mechanical properties of the original coal specimens. Among the other three combination ratios of the mixing ratio, it can be seen that the fourth group has the most obvious compressive effect and the briquette sample has the best strength and the best integrity. Therefore, C-6 is selected as the ratio to prepare briquette samples with different molding moisture contents.

2.2.3. Preparation of Briquettes. Take out the dried coal with an electronic balance of 250 g, a particle size of 20–40, a 40–80 mesh, a particle size coal sample ratio of 1:1, and the right amount of water; the first solid material in the container must be mixed evenly, and then slowly add water and make it evenly mixed, with the mixed material in Φ 50 mm similar material in the pressing mold. The mold is composed of a supporting base, a pressing bar, a Φ 50 mm cylinder, and a demolding sleeve. Then, the specimen is pressed into shape by the TAW-2000 electrohydraulic servo rock triaxial testing
machine. The forming pressure of the specimen is 20 MPa, and the pressure holding time is 30 min. Put the coal samples into the constant temperature and humidity curing box for 3 days to get briquettes with different water contents and number them. The detailed information is shown in Table 3.

3. Test and Analysis

3.1. Laboratory Equipment. The RMT-150C triaxial experimental system for high-pressure rocks and coal (as shown in Figure 3) was used to conduct uniaxial and triaxial stress-strain correlation tests. The device is mainly composed of a servo loading system, triaxial pressure chamber, and data measurement system. The specimen is a standard specimen of $\Phi 50 \text{ mm} \times 100 \text{ mm}$. The experimental device is shown in Figure 3. The system can be used to test the mechanical properties of high-pressure rock and coal under uniaxial and triaxial stress conditions in the pressure chamber of the rock triaxial instrument and can independently control the size of three-direction stress and loading and unloading (up to 70 MPa). The confining stress and axial stress can all reach 140 MPa.

3.2. Uniaxial Compression Test. The uniaxial compression tests were performed on briquette samples with different moisture contents prepared on the mechanical testing machine to analyze the variation rule of mechanical properties of briquettes with moisture content under a uniaxial load. On the host machine of the test system, set the pressure step to 0.005 mm. Then, the briquette sample is pressurized. The final macroscopic fracture damage morphology of the coal specimen is as follows: the bottom surface shedding was serious, while the top of briquette samples changed little and did not shed obviously. This is also consistent with the final rupture form of coal samples after uniaxial compression in the literature [25]. The test system automatically records the test result data. By analyzing the data, the uniaxial compressive strength, elastic modulus, and Poisson’s ratio of briquette samples with different moisture contents in molding under uniaxial compression can be obtained, as shown in Figures 4 and 5.

Figure 4 shows that when the forming moisture content of coal samples is 9%, the maximum axial stress is 0.866 MPa. The minimum axial stress of 0.503 MPa was observed when the molding moisture content was 3%. According to the trend diagram of briquette axial stress changing with molding water, with the increase of molding water, the axial stress of briquette samples increased first and then decreased. When the forming moisture content of briquettes is between 6% and 12%, the axial stress reaches the maximum. Before the molding moisture content reaches 9%, coal particles are gradually moistened by moisture with the increased moisture. At this time, the moist coal particles gradually agglomerate, improving the briquette cohesion so that the briquette compressive strength is enhanced. After the molding moisture content reaches 9%, with the increase of moisture, the coal particles are gradually overwetted by moisture. Coal particles are surrounded by water, the

![Figure 1: Trend of briquette strength with molding pressure.](image1)

![Table 2: Ratio of particle size.](image2)

| Coal number | Particle size (mm) |
|-------------|--------------------|
| C-1         | 100%               |
| C-2         | 100%               |
| C-3         | 100%               |
| C-4         | 50% 25% 25%        |
| C-5         | 25% 50% 25%        |
| C-6         | 25% 25% 50%        |

![Figure 2: Uniaxial stress-strain curves of similar material specimens with 6 composition proportions and raw coal specimens.](image3)

Table 3: Information of coal samples with different moisture contents.

| Coal sample | M-1 | M-2 | M-3 | M-4 | M-5 |
|-------------|-----|-----|-----|-----|-----|
| Moisture content (%) | 3   | 6   | 9   | 12  | 15  |
briquette begins to soften, cohesion decreases, and the briquette compressive strength gradually decreases. The uniaxial compression test shows that the uniaxial compressive strength of briquettes is closely related to moisture content, and reasonable forming moisture content is beneficial to increase axial stress of briquettes. However, excessive water will reduce the frictional resistance between particles, making the relative movement between them easier, resulting in the reduction of the coal strength phenomenon [26].

From Figure 5, it can be seen that the modulus of elasticity of coal is larger when the moisture content of molding coal is 6%-12%. When the moisture content is 9%, the elastic modulus of briquettes reaches the maximum value, which is 1.385 GPa. Considering the trend diagram of the briquette elastic modulus changing with molding moisture content, it can be seen that the briquette elastic modulus increases first and then decreases with the increased molding moisture content. When the moisture content is between 3% and 9%, Poisson’s ratio decreases gradually with the increase of forming moisture content.

It can also be seen from Figure 5 that when the forming moisture content of briquettes is 9%, Poisson’s ratio of briquettes is at the minimum value of 0.259. According to the trend chart of the briquette Poisson’s ratio changing with molding moisture content, it can be seen that the briquette Poisson’s ratio first decreases and then increases with the increase of molding moisture content. When the moisture content is between 3% and 9%, Poisson’s ratio decreases gradually with the increase of forming moisture content.
When the moisture content is more than 9%, Poisson’s ratio increases gradually with the increase of forming moisture content, and the transverse strain trend of briquettes increases. The possible reason for this phenomenon is that, in the case of low moisture content, the coal sample presents plastic failure characteristics under compression, and the longitudinal deformation is large, while the transverse deformation is reduced due to the shrinkage of extruded water. Excess water will reduce the strength of coal, resulting in increased transverse deformation. Poisson’s ratio is the ratio of transverse strain to longitudinal strain of the sample, and it is the elastic constant reflecting the transverse deformation [28].

3.3. Triaxial Compression Test. In this test, the specimen is first loaded to the predetermined confining pressure value, and then longitudinal loading is performed. After the sample is completely destroyed, the machine stops working. The confining pressures of this test are 6 groups of tests under confining pressures of 0 MPa, 0.2 MPa, 0.4 MPa, 0.6 MPa, 0.8 MPa, and 1 MPa, respectively. From the triaxial test results, Figure 6 shows the total stress-strain curve of briquettes under six groups of confining pressures under triaxial compression when the moisture content of the briquette is 9%.

The triaxial compression curves of coal with 9% water content under different circumferential pressures show that the curves basically match with the $\sigma$-$\varepsilon$ curves of typical coal rock specimens. The $\sigma$-$\varepsilon$ curve of the whole process of briquettes begins with an upper concave curve, i.e., is the compaction stage. There are a lot of fissures and pores in briquettes, which are compacted under the action of axial stress. Meanwhile, the water inside briquettes is driven deeper into the fissures and pores of briquettes, and the coal particles are in full contact with the water. Then, the curve of $\sigma$-$\varepsilon$ enters into the stage of elastic deformation. After the compaction stage, the internal structure mechanism of briquettes is compacted, and the moisture is in full contact with the coal particles. The briquette has a good pressure effect in this stage, and the axial stress in the elastic deformation stage is
not enough to make the internal fissures of the briquette expand, which leads to no failure of the briquette. When the yield strength is reached, the briquette begins to fissure and the fissures extend. Briquettes cannot resist the evolution of fissures and gradually soften and deform. However, the briquette can continue to withstand the increase of axial stress until the axial stress reaches the peak strength that the briquette can withstand. When the axial stress is greater than the briquette peak strength, the energy is released. The briquette fracture expands continuously, the briquette strength decreases, and the strain increases.

It can be seen from Figure 7 that the axial stress of briquettes first increases and then decreases with the increased moisture content of briquettes. The axial stress of briquettes increases with the confining pressure of briquette specimen loading under certain forming moisture contents. The test results show that under the condition of confining pressure, briquette samples will have a reasonable forming moisture content, and the briquette prepared by this reasonable forming moisture content has the best mechanical properties. In addition, the confining pressure during the test loading has a certain promoting effect on the mechanical properties of the water-bearing briquette.

The failure of coal is usually shear failure, so it is necessary to investigate the shear strength of coal. The shear strength of briquettes with different moisture contents was studied by the triaxial compression test combined with the basic theory of shear strength. The data of the triaxial compression test were further analyzed according to the Mohr-Coulomb criterion. The briquette with different moisture contents meets the Mohr-Coulomb criterion under triaxial compression. The cohesion ($c$) and internal friction angle ($\phi$) were calculated for different moisture contents. The fitting equations and correlation coefficients are as follows:

(a) Moisture 3%: 
$$y = 2.3836x + 1.1474$$  
$$R^2 = 0.9514$$

(b) Moisture 6%: 
$$y = 2.069x + 1.3286$$  
$$R^2 = 0.9612$$

(c) Moisture 9%: 
$$y = 2.5259x + 1.0973$$  
$$R^2 = 0.9604$$

(d) Moisture 12%: 
$$y = 2.4506x + 1.1163$$  
$$R^2 = 0.9453$$

(e) Moisture 15%: 
$$y = 2.2069x + 1.1286$$  
$$R^2 = 0.9612$$

Figure 8: Fitting curves of the maximum axial stress and confining pressure of coal briquettes with different moisture contents.
(φ) of briquettes can be approximately determined according to the Mohr envelope theory, as follows [29]:

\[
c = \frac{A}{2\sqrt{B}},
\]

\[
\phi = \tan^{-1}\left(\frac{B - 1}{2\sqrt{B}}\right).
\]  

(1)

According to the literature [30], when the relationship between \(\sigma_1\) and \(\sigma_3\) is linear, \(\sigma_1 = A + B\sigma_3\). First, the values of \(A\) and \(B\) were obtained by fitting the curves using the least-squares method based on the triaxial compressive strength data of coal \((\sigma_3, \sigma_1)\), as shown in Figure 8. Then, combined with the Mohr-Coulomb criterion theory, the values of \(c\) and \(\phi\) were solved, as shown in Figure 9.

The cohesion and internal friction angle in Figure 9 reflect the shear properties of coal. Cohesion is the result of the mutual attraction of internal molecules. The internal friction angle reflects the friction characteristics between particles. It can be seen that with the continuous increase of moisture content, cohesion shows a trend of first increasing and then gradually decreasing. When the moisture content is about 9%, the cohesion of briquette samples reaches the maximum of 1.215 MPa. As the moisture content of briquettes increases, the internal friction angle of briquettes also increases first. When it reaches its maximum value, it begins to decrease with the increased moisture content. When the moisture content is about 9%, it reaches the maximum value of 27.3°. The shear failure of briquettes is sliding along a certain section plane in the same direction as the shear, and the generated resistance to the shear surface is usually considered to be caused by the cohesive force between particles and the cohesive force of cementation or additional water film molecules. In this test, no binder was added during briquette forming, so the strength of shear failure was composed of the molecular force caused by friction and water film. When reasonable moisture is added, the water film between coal particles promotes the formation of many liquid bridges. Thus, the molecular bridge force between coal particles reaches the maximum, which improves the cohesive force of coal specimens and increases the difficulty of shear damage. Under the action of surrounding pressure, the pulverized coal particles are firstly embedded in the fine fissures under the action of reasonable water lubrication, and the extruded pulverized coal particles become dense in the molding coal. The embedding and meshing between coal particles increase the biting force and the friction characteristics. However, when too much water is present, the excessive water film will weaken the friction characteristics between the particles. Therefore, the cohesive force and internal friction angle of the coal type are enhanced only under reasonable water formation conditions, and too much or too little water content will not make it achieve the best results.

4. Conclusions

Uniaxial compression and triaxial compression of briquette samples with different moisture contents were carried out in this paper. The specific conclusions are as follows:

(1) Under uniaxial compression, the compressive strength and elastic modulus of briquettes prepared by coal first increased and then decreased with the increase of moisture content, and Poisson’s ratio first decreased and then increased with the increase of moisture content.

(2) Under triaxial compression, the compressive strength of briquettes increases with the increase of confining pressure, indicating that confining pressure is helpful for the further consolidation of granular coal under the action of moisture.

(3) With the increase of moisture content, the cohesion and internal friction angle first increase and then

![Figure 9: Trend of moisture content affecting the cohesion and angle of internal friction: (a) cohesion and (b) angle of internal friction.](image-url)
decrease, indicating that reasonable water injection is helpful to improve the shear strength of briquettes and change the mechanical properties of coal.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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