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Research Article

Feasibility of Water Injection on the Coal Wall of Loose Thick Coal Seam to Prevent Rib Spalling and Its Optimal Moisture Content

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Rib spalling of loose thick coal wall seriously restricts the high yield, high efficiency of coal mine, affecting the safety production of coal mine. Based on the engineering background of water injection to control rib spalling of loose thick coal seam in the Luling Coal Mine of the Huaibei Mining Group, the mineral composition and microscopic morphology of III811 loose thick coal seam in Luling Coal Mine were analyzed by X-ray diffraction and scanning electron microscope. Through uniaxial compressive strength tests of coal samples with different moisture content, the relationship between uniaxial compressive strength, peak strain and moisture content, and their failure characteristics was studied. The results showed that the natural moisture content of III811 coal seam in Luling coal mine is low, and it contains a large amount of kaolinite (75.2%) belonging to clay mineral which is easy to absorb water and then expand, fully bond loose coal body and fill cracks to improve the integrity of coal body. These two factors provide feasibility for injecting water in workface to prevent rib spalling. The compressive strength of coal samples decreased slowly with the raise of moisture content, while the peak strain increased first and then decreased. The peak strain was the largest when the water content was 6.0%. The failure degree of coal samples intensifies with the increase of water content, and the failure form changes from tensile failure at low water content to shear failure at high water content. Considering the relationship between compressive strength, peak strain, and moisture content of coal samples, the optimal moisture content of III811 workface in loose thick coal seam is determined to be 4.5% ~6%.

1. Introduction

In recent ten years, in all coal mine accidents in China, the casualties due to roof accidents caused by rib spalling and roof caving account for 43% of all underground accidents. The rib spalling and roof caving pose a great threat to the production of workface and seriously affect advance speed and output of workface [1–4]. In the process of loose thick coal seam mining, because of the loose coal body and a higher workface mining height, the coal body fissure in front of the workface develops, and the rib spalling and roof caving are more serious [5, 6].

The stability of the coal wall can be enhanced by optimizing the advance speed of the workface, controlling the reasonable height of the workface and ensuring the reasonable support strength of the support, or changing the physical and mechanical parameters of the coal body by physical and chemical methods [7–10]. Due to the characteristics of loose coal seam, its compressive strength is low, and its bearing capacity is weak. It is particularly important to take physical and chemical methods to improve the mechanical properties and structure of coal body for the prevention of rib spalling [11, 12]. A large number of engineering practices showed that reasonable water injection in coal wall for soft coal seam with large mud content can effectively improve the cohesiveness, reduce the rib spalling and roof caving accidents. Cheng et al. [13] studied the stability of the surrounding rock of the workface after water injection. It shows that after water injection, the peak value of abetment pressure in front of the coal wall shifts to the deep, the pressure relief zone and plastic zone increase, the compression deformation of the coal body increases, and the water injection is beneficial to improve the stress state and enhance the stability of the coal wall. Wang et al. [14] analyzed the limit condition of coal wall failure and adopted $FLAC^{3D}$ simulation to analyze the effect law of different water injection pressure on vertical stress distribution and compression of coal wall and coal body in front of workface. The results showed that water injection can increase the compression of coal wall and reduce the elastic energy of coal body. Yang et al. [15] used intermittent water injection technology to increase the moisture content of the coal seam from 4% to 5% ~6% and reduce the range of rib spalling from 50% ~70% to 10% ~30%. The problem of rib spalling is effectively solved by water injection. Yao et al. [16] conducted variable-angle shear test (compression-shear test) and research on the mechanism of crack propagation and strength weakening on coal samples with different moisture content in the 4-2 coal seam of the Meihuajing Coal Mine of Shenhua Ningxia Coal Industry. It showed that the main cracks of the dry coal samples exist along the shear plane, while the fracture surface of the saturated coal samples deviated from the shear plane and formed many irregular shear cracks. The shear strength, cohesion, and internal friction angle of the coal samples decreased linearly or exponentially with moisture content. Zhang et al. [17] conducted direct shear test on coal samples with different moisture content in Yiluo coal seam and used the X ray diffraction (XRD) to analyze the influence of different moisture content and clay minerals (kaolinite, montmorillonite, illite) to the bond strength of coal, and it showed that when the moisture content increased from 6.6% to 17.6%, bond strength increased and then decreased with increasing moisture content, determined that of 17.6% is the best moisture content to improve the stability of Yiluo coal seam. Zhou et al. [18] used extremely soft coal to make coal samples and conducted direct shear experiments under different moisture content and normal stress. The results showed that the cohesive of the coal samples increases first with the raise of the moisture content and reaches the optimum moisture content (about 17.64%), and the cohesive decreases with the raise of the moisture content; the moisture content has no obvious effect on the internal friction angle of the coal samples. Zhen et al. [19] used ultra-high speed digital image to analyze the influence of moisture content on the deformation trend and failure characteristics of extremely soft coal samples. It is shown that the dynamic stress-strain curve of coal samples consist of four stages. With the raise of moisture content, the brittleness of coal samples decreased and the plasticity increased. Wang et al. [20] carried out the uniaxial compression tests on coal samples with different moisture content. The results showed that with the raise of moisture content, the range of the stress-strain curve of coal samples increased in the compaction stage, decreased in the elastic stage, and became more significant in the yield stage. There was a negative linear relationship between compressive strength and moisture content, a positive linear relationship between peak strain and moisture content, and a negative exponential relationship between elastic modulus and moisture content.

The above researches are not accurate enough to influence factors of coal seam water injection, such as the feasibility of coal seam water injection and the optimal moisture content. In this paper, the water injection on the coal wall of loose thick coal seam to prevent rib spalling in the Luling Coal Mine of the Huaibei Mining Group was used as the engineering background, and the mineral composition and microscopic morphology of III811 loose thick coal seam in the Luling Coal Mine were analyzed by X-ray diffraction and scanning electron microscope. Through uniaxial compressive strength and shear strength tests, the relationship between uniaxial compressive strength, peak strain and moisture content of coal samples with different moisture contents, and their failure characteristics was studied. The research results are conducive to reveal the feasibility of water injection to prevent rib spalling and the optimum moisture content of coal seam in III811 workface of the Luling Coal Mine.

2. Feasibility of Water Injection on Loose Thick Coal Wall to Prevent Rib Spalling

2.1. Project Background. III811 workface in the Luling Coal Mine of the Huaibei Mining Group is located in one mining area in the east of the third level of the mine, mainly mining 8# and 9# coal seams. The thickness of 8# coal seam is 3.33~14.75 m with an average of 8.25 m, which belongs to stable coal seam. The thickness of 9# coal seam is 0 ~ 4.25 m, with an average of 1.21 m, which belongs to extremely unstable coal seam. III811 workface is mostly combined area of 8# and 9# coal seam, and inclination is 15° ~28° with an average of 20°, for gently inclined thick coal seam. The hardness coefficient of coal seam is 0.16~0.53, the whole coal seam is loose and extremely soft, and the joints are developed. The direct roof of III811 workface is mudstone with an average compressive strength of 14.92 MPa and tensile strength of 0.68 MPa. The direct floor is sandy mudstone with an average compressive strength of 15.07 MPa and with an average tensile strength of 1.04 MPa. The coal seam of III811 workface is a typical loose, extremely soft, thick coal seam, and the strength of the roof and floor strata is low.

In addition, in order to improve the recovery rate of coal resources, the III811 loose thick coal seam workface using a full high fully mechanized caving mining technology caused that the rib spalling of coal wall is serious in mining process, seriously affecting the safety of coal mine production and mining progress. Therefore, it is necessary to carry out the research of feasibility of water injection on the coal wall of loose thick coal seam to prevent rib spalling and its optimal moisture content, in order to achieve III811 loose thick coal seam workface of Luling Coal Mine safety, efficient mining.

2.2. Mineral Composition of Coal Seam

2.2.1. Test Coal Sample. Figure 1 shows the coal sample and test instrument for the mineral composition of coal seam. The test coal sample was taken from III811 workface of the Luling Coal Mine of the Huaibei Mining Group. The coal at III811 workface was ground into powder, and the coal

(a) Coal sample (b) X-ray diffractometer

Figure 1: Coal seam mineral component testing.

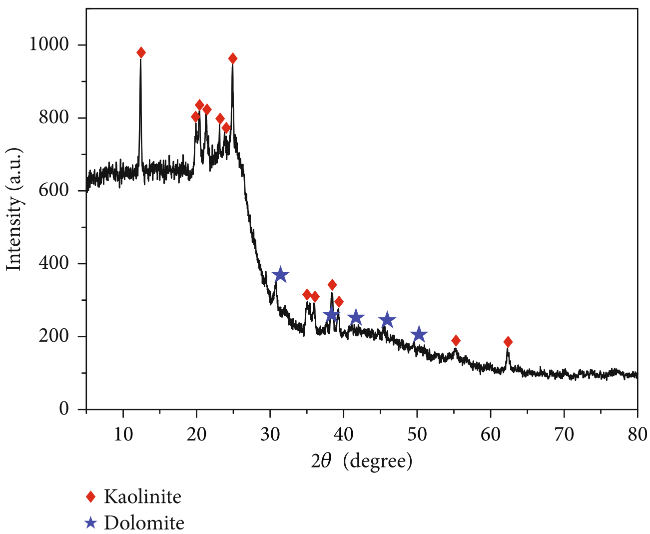


Figure 2: X-ray diffraction pattern of mineral components in coal sample.

sample (above 50 mg) was identified and analyzed by X-ray diffractometer. The principle is to compare the lattice plane spacing and diffraction intensity measured on the material with the diffraction data of the standard phase; so, the mineral composition of the coal seam at III811 workface can be determined.

2.2.2. Test Results. Figure 2 shows the X-ray diffraction pattern of mineral components in the test coal sample. It can be seen that the mineral composition of the coal seam at III811 workface of the Luling Coal Mine is mainly dolomite and clay mineral kaolinite. Kaolinite has a content of up to 75.2% in the test coal sample. It is characterized by soft quality, strong water absorption, and easy expansion in water absorption. It is easy to disperse and suspend in water and has good plasticity and high adhesion. The existence of large amounts of clay mineral kaolinite in the coal seam of the III811 workface provides the feasibility for preventing the rib spalling of coal wall by water injection in the Luling Coal Mine.

2.3. Microscopic Morphology of Coal Samples

2.3.1. Test Equipment. Figure 3 shows the microscopic morphology coal samples for testing and test equipment (scanning electron microscope). The test coal sample was taken from III811 workface of the Luling Coal Mine of the Huaibei Mining Group. The lump size of the test coal sample is 1 cm^3. FlexSEM 1,000 scanning electron microscope was used to observe the pore and crack structures and their distribution characteristics of the coal samples for testing. The principle is to scan the surface of the coal sample through the electron beam emitted and focused by the electron gun and stimulate the coal sample to produce various types of physical signals. After signal detection, video amplification, and signal processing, the scanning image that can reflect the surface characteristics of the coal sample can be read out on the fluorescent screen.

2.3.2. Test Results. Figure 4 shows the microcracks of the coal sample for testing at different magnification ratios. When the coal sample was magnified to 500 times, it can be seen that the coal sample is seriously damaged and attached with many crushed particles, as shown in Figure 4(a). When the coal sample was magnified to 5,000 times, a fine crack could be seen in the coal sample and the crack fracture was smooth, indicating that the coal sample was a brittle fracture, as shown in Figure 4(b).

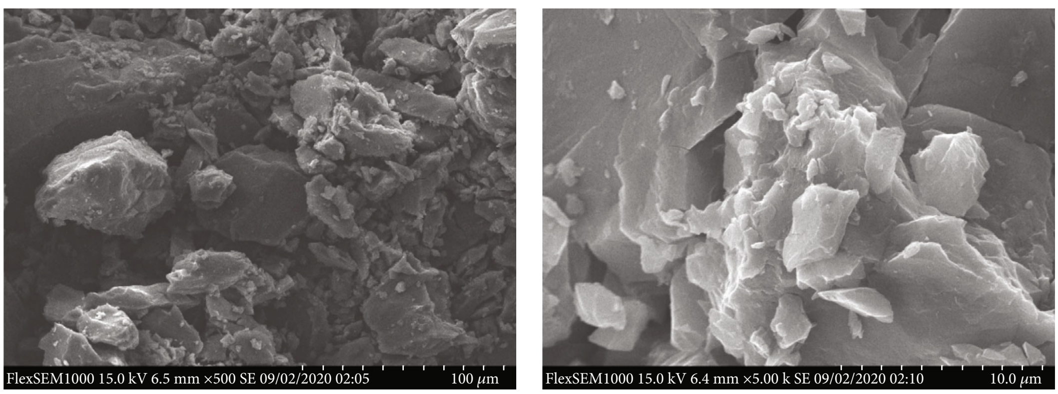
Figure 5 shows the adhesion of coal sample particles under different magnifications. When the coal sample is magnified to 500 times, it can be seen that the integrity of the coal sample is poor, and a large number of tiny particles are attached, indicating that the coal sample is loose, as shown in Figure 5(a). When the coal sample is magnified to 5,000 times, it can be seen that the particle surface of the coal sample is smooth, indicating that the coal sample is prone to brittle fracture and has a low moisture content, as shown in Figure 5(b).

3. Optimum Moisture Content of Water Injection on Loose Thick Coal Wall to Prevent Rib Spalling

After injecting water into coal seam, the water molecules bound to the surface of coal will pull the particles closer and pick up it tighter in the loose coal seam through its connection effect which has a more obvious influence on the mechanical properties of the coal in the loose coal seam. However, if inject too much water, too high moisture content in this test which leads to the connecting force weakened, and friction reduced between loose coal particles because water plays a role of lubrication. The most hydrophilic rocks are clay minerals, and the rocks with more clay minerals are also most affected by water. Therefore, it is necessary to accurately control the moisture content and improve its ability of preventing rib spalling.

3.1. Preparation of Coal Samples with Different Moisture Contents. The coal samples were selected from III811 workface of the Luling Coal Mine. After being crushed by the

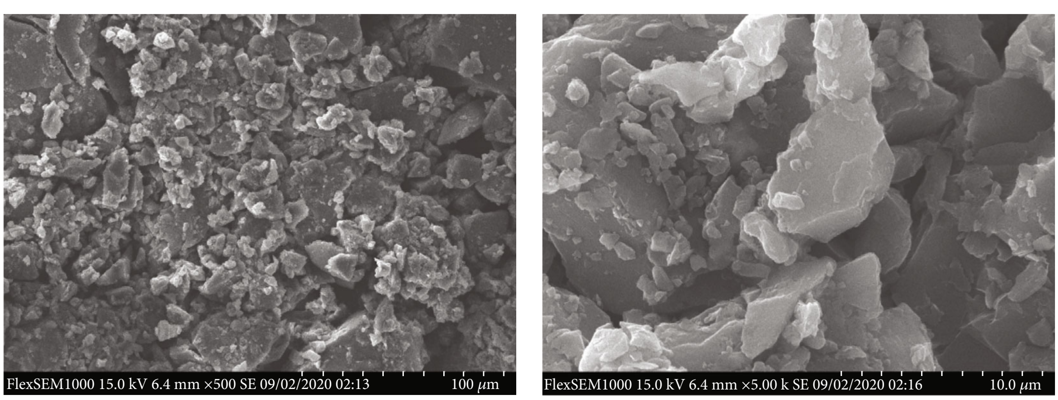
Figure 3: Test coal sample and scanning electron microscope.



(a) 500 times

(b) 5,000 times

Figure 4: Microcracks in coal sample at different magnification ratios.



(a) 500 times

(b) 5,000 times

Figure 5: Particle attachment of coal sample under different magnification.

mill, pulverized coal particles of more than 0.25 mm and less than 1 mm were screened by classification and placed in a 105°C constant temperature drying box for drying. Mixed the water with the pulverized coal particles dried in a certain proportion and stir evenly and weighed mixture of a certain quality by using an electronic balance and put into the briquette pressing mold. Through a universal experimental machine (pressure 50 kN and maintain constant pressure 10 min), the mixture is pressed into $\Phi 50 \times 100$ mm, used for compressive strength test.

Figure 6 shows the variation curve of the moisture content of the coal sample with drying time. It can be seen that drying under the condition of constant temperature at 105°C, the moisture content of the coal sample decreased

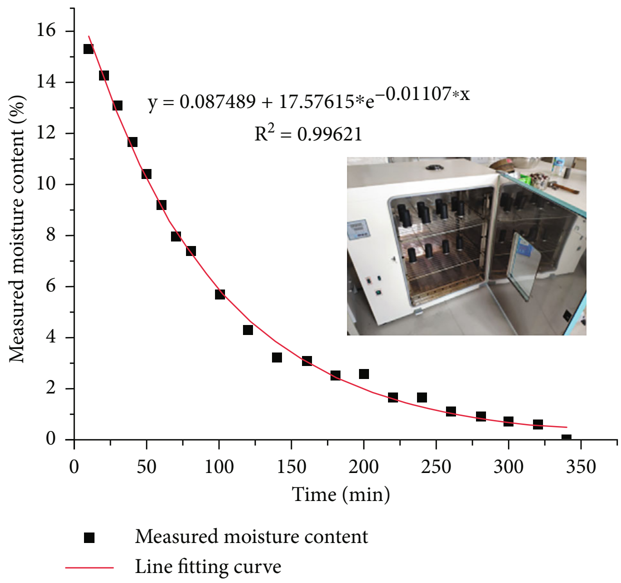


FIGURE 6: Variation curve of moisture content of coal sample with drying time.

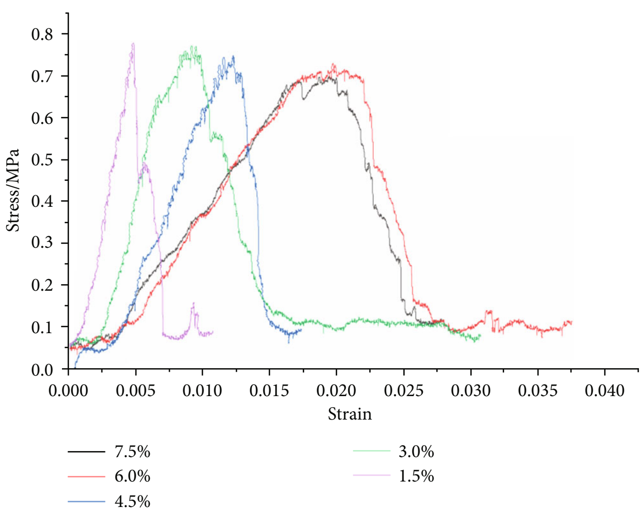


FIGURE 7: Total stress-strain process curves of coal samples with different moisture contents.

exponentially with the increase of drying time, especially in the early stage, and the moisture content decreased rapidly. In addition, it can be seen that the variation curve of the moisture content of the coal sample with drying time has a high fitting degree ($R^2 = 0.99621$). Therefore, coal samples with different moisture contents can provide reliable data support for compressive strength test and shear strength test. As can be seen from Figure 6, when drying for 345 minutes, the coal sample had the same weight twice as before and after; so, its moisture content can be considered to be 0. When the moisture content is 15%, the coal sample is considered to be in the state of saturation. According to the variation curve of moisture content with drying time (Figure 6), briquette with different moisture contents (1.5%, 3.0%, 4.5%, 6.0%, and 7.5%) can be obtained by drying the prepared briquette for different drying time, which can be used for compressive strength test.

3.2. Stress-Strain Curves of Coal Samples with Different Moisture Contents under Uniaxial Compression. Figure 7 shows the complete stress-strain process curves of coal samples with different moisture contents. It can be seen that in the process of uniaxial compression, coal samples with different moisture contents all go through four stages, including pore fracture compaction stage, elastic stage, yield stage, and postfracture stage. At the initial loading stage of coal samples with different moisture contents, there is a compaction stage, pulverized coal particles and tiny pores in the coal samples gradually close with the increase of load, and the stress of coal samples increases slowly with the increase of strain. After the compaction stage, the original microcracks of the coal samples had basically closed and began to enter the elastic stage. At this stage, the new cracks in the coal sample had not yet appeared, the overall structure was relatively stable, and the relationship between stress and strain shows a "linear growth." With the raise of axial stress, small cracks began to appear inside the coal samples. The development of cracks destroyed the stable state of the coal samples, and the coal samples entered the yield stage, in which the relationship between stress and strain presents a "nonlinear growth," and the increased rate of stress slows down. When the coal samples reach the peak strength, the internal structural failure occurred. After the coal samples passed the yield stage, the internal cracks developed rapidly, and many cracks appeared on its surface. After continuous loading, the coal samples did not fail and become unstable immediately, indicating that the loose coal still has a certain residual bearing strength after the peak strength. The water-bearing coal samples did not show obvious brittle failure after the peak strength but show certain ductility and plastic deformation in the complete stress-strain curve, that is the post-fracture stage.

By comparing the complete stress-strain curves of coal samples with different moisture contents, it is found that with the raise of moisture content, the compaction stage of coal samples gradually becomes longer and the elastic stage becomes longer, and the slope of stress-strain curve in the elastic stage also decreases; that is, the elastic modulus of coal samples decreases with the increase of moisture content. With the increase of moisture content, the yield stage of coal samples is gradually obvious, the peak strength decreases, and the peak strain increases gradually. Especially when the moisture content increases from 4.5% to 6.0%, the strain increases significantly and then decreases slightly (7.5%). After the peak strength, the deformation and failure characteristics of coal samples with different moisture content were similar, none of which showed obvious brittle failure, but obvious plastic failure, and there was a certain residual deformation. It should be noted that the coal samples with higher moisture content have strong compressive deformation resistance during the compression process and can withstand pressure for a long time to realize the overall expansion of the coal samples. The postpeak displacement is also large, which indicates that the maximum axial strain

Table 1: Mechanical parameters of coal samples with different moisture contents under uniaxial compression.

Moisture content/%	Coal samples	Compressive strength/MPa	Average/MPa	Elastic modulus/GPa	Average/GPa	Peak strain	Average
	1-1	0.77962		0.18690		0.00469	
1.5	1-2	0.77465	0.77656	0.18346	0.185	0.00478	0.00472
	1-3	0.77541		0.18464		0.00468	
	2-1	0.76758		0.13323		0.00908	
3.0	2-2	0.77082	0.77003	0.12809	0.132	0.00906	0.00907
	2-3	0.77169		0.13468		0.00907	
	3-1	0.74722		0.08045		0.01209	
4.5	3-2	0.74359	0.74599	0.07817	0.08	0.01214	0.01212
	3-3	0.74716		0.08138		0.01213	
	4-1	0.72881		0.04609		0.01966	
6.0	4-2	0.72347	0.72737	0.04546	0.046	0.01932	0.01956
	4-3	0.72983		0.04645		0.0197	
	5-1	0.69487		0.04503		0.01923	
7.5	5-2	0.69761	0.69707	0.04413	0.045	0.01934	0.01928
	5-3	0.69873		0.04584		0.01926	

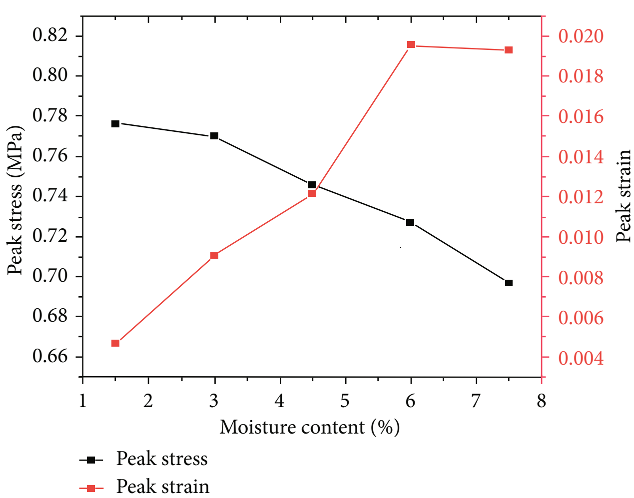


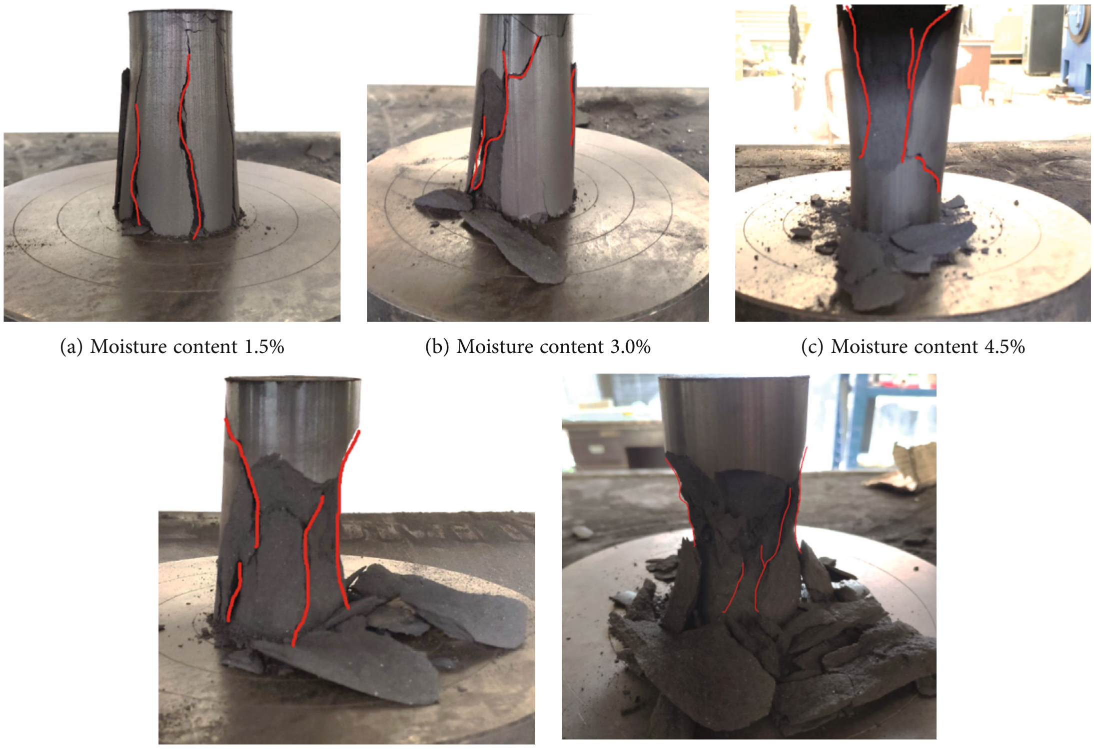
Figure 8: Relationship between compressive strength and peak strain of coal samples with different moisture contents.

of coal samples can increase with the raise of moisture content. Macroscopically, the plastic deformation of coal wall can increase with the raise of moisture content.

3.3. Uniaxial Compressive Strength of Coal Samples with Different Moisture Contents. Uniaxial compressive strength tests were carried out on 5 groups of coal samples with different moisture contents (1.5%, 3.0%, 4.5%, 6.0%, and 7.5%), with 3 test samples in each group and a total of 15 coal samples. During the uniaxial compression test, the universal testing machine adopts displacement control, and the loading rate is 3 mm/min. During the loading process, the failure characteristics of test coal samples are observed and obtain mechanical parameters (compressive strength, elastic modulus, and peak strain) of coal samples with different moisture contents under uniaxial compression load, as shown in Table 1.

As can be seen from Table 1, with the increase of moisture content, the uniaxial compressive strength of coal samples shows a slight downward trend, and the peak strain first increases and then decreases. When the moisture content is 6.0%, the peak strain is the largest. The elastic modulus decreases gradually with the increase of moisture content, and the rate of descent is the fastest when the moisture content is 6.0%, which is about 42.5% less than when the moisture content is 4.5%. When the moisture content is 7.5%, the rate of descent of elastic modulus becomes slow and only decreases by 2% compared with 6.0% moisture content. The elastic modulus refers to secant modulus. The elastic deformation before samples' failure increases gradually due to the binding effect of water on mineral particles, and the peak stress decreases slowly because the softening effect of water on samples is little. When the moisture content is exorbitant, the peak stress decreases further, and the elastic deformation before failure decreases gradually because the lubrication of water on mineral particles plays a dominant role.

Figure 8 shows the relationship between compressive strength, peak strain, and moisture content of coal samples with different moisture contents. It can be seen that the compressive strength of coal samples decreases slowly with the increase of water content, while the peak strain increases first and then decreases with the increases of moisture content. When the moisture content is 1.5%, the compressive strength of the coal sample is 0.77656 MPa, and the peak strain is 0.00472. When the moisture content is 4.5%, the compressive strength of the coal sample is 0.74599 MPa, and the peak strain is 0.01212. Compared with the moisture content of 1.5%, the compressive strength of the coal sample decreases by 3.93%, and the peak strain increases by 176.19%. The increase of moisture content greatly improves the plastic deformation of the coal samples. When the moisture content increases to 6.0%, the compressive strength of



(a) Moisture content 1.5% (b) Moisture content 3.0% (c) Moisture content 4.5%

(d) Moisture content 6.0% (e) Moisture content 7.5%

Figure 9: Failure characteristics of coal samples with different moisture contents.

the coal sample decreases slightly to 0.72737 MPa, while the peak strain increases to 0.01956, which is 60% higher than when the moisture content is 4.5%, and the peak strain reaches the maximum at this time. Therefore, considering the compressive strength and peak strain of coal samples, the optimal range of moisture content of coal seam is 4.5% ~6.0%, which can ensure that the coal wall of Luling Coal III811 workface has a certain compressive strength, and also provide maximum plastic deformation without damage.

3.4. Failure Characteristics of Coal Samples with Different Moisture Contents under Uniaxial Compression. Figure 9 shows the failure forms of coal samples with different moisture contents (1.5%, 3.0%, 4.5%, 6.0%, and 7.5%) under uniaxial compression. It can be seen that the failure degree of coal samples increases with the increasing of moisture content, and its failure form also changes. When the moisture content is 1.5% and 3.0%, the coal samples are mainly tensile failure, and there are two obvious tensile failure cracks. With the increase of water content (4.5%, 6.0%), the coal samples show x-shaped conjugate inclined plane shear failure, and the degree of breakage also increases. When the moisture content increases further (7.5%), the coal samples gradually become the main shear failure, and the degree of breakage is further intensified.

4. Conclusions

(1) The mineral composition and microscopic morphology of III811 loose thick coal seam in the Luling Coal Mine were analyzed by X-ray diffraction and scanning electron microscope. There is a large amount of clay mineral kaolinite (75.2%) in the coal seam of III811 workface. It has the characteristics of soft quality, strong water absorption, and easy expansion of water absorption. It has good plasticity and high adhesion. In addition, there are more small cracks in the coal seam and more pulverized coal particles, and the natural moisture content is low, which provides the feasibility for III811 loose thick coal seam workface through water injection to prevent and control the rib spalling of coal wall

(2) Through uniaxial compressive strength test of coal samples, the relationship between uniaxial compressive strength, peak strain, and moisture content of III811 loose thick coal seam in the Luling Coal Mine was studied. With the raise of moisture content, the compressive strength of coal samples decreases slowly, while the peak strain increases first and then decreases. When the moisture content is 4.5%, the compressive strength is 0.74599 MPa, and the peak strain is 0.01212. When the moisture content increases to 6.0%, the compressive strength decreases slightly to 0.72737 MPa, while the peak strain increases to 0.01956. At this time, the peak strain reaches the maximum, indicating that increasing the moisture content can increase the plastic deformation of the coal wall

(3) As the moisture content increases, the degree of coal samples' failure intensifies, and its failure form

changes accordingly. When the moisture content is 1.5% and 3.0%, the coal samples are mainly tensile failure. With the increase of water content (4.5%, 6.0%), the coal samples show x-shaped conjugate inclined plane shear failure, and the degree of breakage also increases. When the water content is further increased (7.5%), the coal sample gradually becomes the main shear failure, and the degree of breakage is further intensified

(4) Considering the compressive strength, peak strain, and moisture content of coal samples, the optimal range of water content of coal seam is determined to be 4.5% ~6.0%, which can guarantee the coal wall of Luling coal III811 loose thick coal seam workface with certain compressive strength and large plastic deformation

Data Availability

Without any supplementary materials for this study, all the data, table, and picture have been presented in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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