Research Article

Mechanical Behavior and Impact Resistance Tendency of Coal Mass with Different Water Content

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As a major hidden danger of mine safety production, the impact resistance tendency of rock seriously restricts the safety and high yield of coal mine. At the same time, as one of the puzzles of rock mechanics, it has been perplexing many domestic and foreign scholars since the recorded rock burst in South Stafford coal mine in 1738. At present, this research is relatively weak; so, it is different for economic and social benefits. The study of the impact resistance law and the antishock measures of water-bearing rocks are extremely meaningful. In order to deeply explore the impact resistance law of rock with different water content and the antishock support measures after roadway excavation, based on the previous research results of the previous research, the impact tendency of different coal samples was firstly tested by coal uniaxial compression experiment, judging and then calculating the damage characteristics of rock with different water content according to the obtained data, as one of the judgment basis of the impact law of coal mine. Secondly, according to the experimental data, the energy evolution characteristics are calculated and analyzed with the graph. Finally, the impact tendency of the rock under different moisture conditions is obtained.

1. Introduction

The property that coal accumulates deformation energy and produces impact failure is called coal impact tendency. It is the inherent property of rock burst coal, which represents the ability of coal to produce rock burst. Since the first record of rock burst in 1738 South Stafford coalfield, the world’s major coal mining countries have detected rock burst tens of thousands of times. In 1933, the occurrence of rock burst was first recorded in China. In the 60 years to 1996, it had occurred more than 4000 times, resulting in more than 400 deaths and huge economic losses. China has determined that China will insist on the energy strategy of taking coal as the principal part, electric power as the center, oil, and gas, and the development of new energy comprehensive energy strategy [1]. Therefore, the coal industry is the basic industry of China, and the healthy, stable, and sustainable development of it is a major issue related to national energy security. To satisfy China’s national economic construction, the mining volume of China’s coal resources will be larger and larger, and the mining depth will be deepened year by year [2, 3]. Mining conditions will be more complex, and mine disasters such as gas outburst, gas explosion, water permeability, coal seam spontaneous combustion, roof fall, and rock burst will always threaten the safe of coal mines [4–7].

Rock burst [8] is a complex mine dynamic phenomenon. The causes of rock burst are very complex, and there are many influencing factors. The manifestation forms of rock burst in different coal mines are also different. Therefore, there are different theories on the occurrence mechanism of rock burst, with different occurrence conditions and judgment criteria. Because the causes and characteristics of rock burst in different mines are different, find out the force
source of rock burst according to different positions of rock burst, master the occurrence law, and find out the causes of rock burst in the mining area or mine. It is very necessary to take targeted antiscour measures. At present, the mechanism of rock burst has not been fully studied. Relevant scholars have put forward a variety of theories of rock burst mechanism through field practice investigation and laboratory test research of rock burst [9, 10].

The strength theory holds that as long as the stress on the material exceeds its strength limit, the material begins to damage. According to this principle, the early strength theory holds that stress concentration occurs around the roadway and stope [11]. The stiffness theory is derived from the test theory of the rigid testing machine, which holds that if the stiffness of the testing machine is less than the later deformation stiffness of the specimen, sudden instability failure will occur [12]. Zhang et al. put forward that rock burst is an instability failure phenomenon of coal. They believe that under the influence of stress, the local stress of coal exceeds the peak strength and becomes a strain softening material. Rock burst occurs when the rock is disturbed in an unstable state, and they put forward the instability theory of rock burst [13–15]. Qi et al. carried out the experimental research on coal friction and sliding, analyzed the friction and sliding properties of coal and the stability of friction and sliding, and proposed that rock burst is one form of friction and sliding damage of coal mass structure, which is manifested as an instantaneous stick slip instability process [16]. According to the movement change characteristics of mechanical structure and mechanical condition of “surrounding rock-coal body” system in the mining process, Li studied the physical and mechanical process of “surrounding rock coal body” system from stable state to losing stability under instantaneous loading. They put forward the discrimination criterion of rock burst and achieved a relatively successful application in the field [17]. The instability theory reveals that the rock burst is caused by the instability and damage of coal mass structure in the mining space and makes an in-depth discussion in theory. However, it is difficult to establish a practical criterion for the risk of rock burst; so, the role of guiding the prevention and control of rock burst is limited. Yin et al. established the catastrophe theoretical model and analyzed the bifurcation set of spatial coal mass system instability controlled by horizontal force and vertical force and the process of coal mass state mutation caused by their changes [18]. Academician Xie initially introduced fractal geometry into the theoretical research of rock burst and used fractal theory to explain the fractal characteristics of rock burst. According to this theory, a strong rock burst or rock earthquake is equivalently a fractal cluster of fracture in rock, and the dissipation of energy required for the fractal cluster of fracture increases exponentially as the fractal dimension decrease [19]. Based on the theory of fracture mechanics, great progress has been made in the study of rock burst theory. Zhang et al. [20–23] made a preliminary study on the propagation of crack near surface and the

<table>
<thead>
<tr>
<th>Moisture content/%</th>
<th>2.4</th>
<th>3.4</th>
<th>4.4</th>
<th>5.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidification treatment time/h</td>
<td>0</td>
<td>17</td>
<td>33</td>
<td>69</td>
</tr>
</tbody>
</table>

**Table 1: Grouping of coal and rock specimens.**

**Figure 1: Axial stress-axial strain curve.**
stability of local wall rock combined with the actual situation. They discussed the formation and destruction mechanism of wall rock layer crack zone near the coal mine tunnel and established the instability failure model of the layer crack plate structure caused by the rock burst of the coal mine through theoretical analysis and experimental simulation. Huang and Gao analyzed the mechanism of impact rock pressure caused by wing-type tension crack at...
Figure 3: Elastic modulus of coal sample under different stresses.
Table 2: Mechanical parameters of coal samples under different water content.

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>Peak energy (total energy)</th>
<th>Peak stress (MPa)</th>
<th>Poisson’s ratio</th>
<th>Elastic modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>12.1839</td>
<td>29.2375</td>
<td>0.432</td>
<td>45.6894</td>
</tr>
<tr>
<td>3.4</td>
<td>3.0624</td>
<td>13.6775</td>
<td>1.3305</td>
<td>34.2916</td>
</tr>
<tr>
<td>4.4</td>
<td>2.3425</td>
<td>10.1425</td>
<td>0.285</td>
<td>28.8355</td>
</tr>
<tr>
<td>5.4</td>
<td>1.4137</td>
<td>7.105</td>
<td>0.2805</td>
<td>21.942</td>
</tr>
</tbody>
</table>

the tip of preexisting crack in coal wall of laneway, forming thin coal seam shell and bending deformation instability of thin coal seam shell. Griffith energy theory and energy criterion in fracture mechanics are adopted in the analysis process, considering the damage accumulation of materials, coupling the crack propagation process with the material damage process, determining the critical stress of rock burst, and analyzing its influencing factors [24]. By means of experimental simulation, Kang et al. reproduced the dynamic phenomenon of the whole procedure of “splitting into boards, cutting into pieces and fragment ejection” of the laminar buckling rock burst in the chamber [25]. Jiang et al. studied the mechanism of rapid nucleation, penetration, and expansion of internal microcracks in coal mass under the impact of mining and other external factors, thereby inducing the overall instability of coal [26].

Although many scholars have made great efforts in the research on the rock burst, also a lot of beneficial results, it is not possible to explain all the phenomenon of rock burst with a single theory because the comprehensive research angle cannot be guaranteed. Because of the complexity of rock burst problem, many influencing factors and extremely complex mechanism, so to accurately reveal the mechanism of rock burst, still need to do a lot of detailed and in-depth research work.

2. Experimental Research on Mechanical Behavior of Coal

2.1. Coal Sample Preparation and Pretreatment. The test coal and rock samples are taken from the same working face of the coal mine. Because there are significant differences in the internal structure of coal and rock under geological action, the mechanical properties are discrete and heterogeneous. Therefore, the samples of this test are all taken from rock strata at the same location and at the same depth. In addition, try to ensure that the sampled rock blocks are complete and uniform, large in size, and sufficient for sampling, so as to reduce the error of the experiment. The coal sample was prepared by diamond machine in the laboratory, which diameter is 50 mm, and height is more than 100 mm in the direction of vertical bedding with dense holes. According to the requirements of the experimental project and the testing machine, the standard cylinder specimens were made by the stone saw and grinding machine. A total of 8 standard specimens were obtained.

One of the difficulties in this test is water content control. Trials first weigh each specimen quality, quality of each specimen under the appropriate water content, and then to humidify coal samples to the quality of the reservation. At the same time, record the specimen to the expected when the water content of the time required, the last place the specimen in the airtight container maintenance after 24 h testing, and the water content in the same group specimens of two number. Moisture content of coal is \( A \omega \), and the mass of sample can be calculated according to Equation (1) [27].

\[
m_i = (1 + \omega)m_{i0},
\]

where \( m_i \) is the mass of sample \( i \) when the water content is \( \omega \), and \( m_{i0} \) is the mass of sample \( i \) when dried.

In the test, original moisture content for the specimens is 2.4%, and the saturated water content is 5.7%. The gradient of water content increase was set as 1%, and there were four groups (2.4%, 3.4%, 4.4%, and 5.4%). See Table 1 for specific groups and numbers.

2.2. Detection Equipment and Methods. During the loading process, the system can simultaneously collect data such as load and displacement. The load and the longitudinal and transverse deformation of coal samples stress sensor were measure by displacement sensor and static strain gauge. The strain collection instrument has 20 channels, each measuring point is automatically balanced, and the measurement results can be modified according to the sensitivity coefficient of the strain gauge, wire resistance, bridge way, and the sensitivity of various bridge sensors. In this experiment, half bridge connection is used for measurement.

2.3. Experimental Results and Analysis

2.3.1. Stress-Strain Curve. Figure 1 was obtained by processing the data obtained from uniaxial compression experiment with Origin software. The following conclusions can be drawn from the stress-strain relationship under different water content.

According to the above test results, the uniaxial compressive strength is 18.835 MPa and 39.64 MPa, 11.8 MPa and 15.555 MPa, 9.495 MPa and 10.79 MPa, and 5.885 MPa and 8.67 MPa, respectively. When the stress first increases, because of the closure of the original cracks of coal sample, the phenomenon of small increases in stress, and large strain will occur. Due to the small number of original cracks, the curve of this section is shorter. When the stress is removed, the sample will return to its original state, which means that the sample is in the stage of elastic deformation, and the stress-strain curve rises linearly. When near the peak as a result of the stress continues to increase, coal sample will regenerate the small crack and peak stress, and then the relationship between stress and strain is no longer linear. The sample will exhibits uniform plastic deformation after the stress overtop the peak value. If the strain of the sample is to be increased, it must be achieved by increasing the stress value. When the water content is 2.4%, the peak stress is 18.835 MPa and 39.64 MPa. When the water content is
Figure 4: Damage variables based on elastic modulus.
Figure 5: Continued.
3.4%, the peak stress is 11.8 MPa and 15.555 MPa. When the water content is 4.4%, the peak stress is 9.495 MPa and 10.79 MPa. When the water content is 5.4%, the peak stress is 5.885 MPa and 8.67 MPa. It is observed that the peak stress intensity decreases with the increase of moisture content, indicating that the stiffness decreases with the increase of moisture content.

2.3.2. Poisson’s Ratio. The coal is compressed along the axial direction, while the expansion deformation will occur perpendicular to the axial direction. The negative ratio of strain ε1 in the vertical direction to strain ε in the load direction is called Poisson’s ratio of the coal sample. If γ represents Poisson’s ratio, then [28]

\[ \gamma = -\frac{\varepsilon_1}{\varepsilon}. \]  

After calculating the Poisson’s ratio in the uniaxial compression experiment and processing the data with Origin, the figure is shown in Figure 2.

Poisson’s ratio of coal samples is 0.417 and 0.447, 2.453 and 0.208, 0.146 and 0.424, and 0.471 and 0.09, respectively. When the stress increases from the beginning, the original cracks of coal sample are closed, and there will be a large axial strain and almost no transverse strain. Therefore, at the beginning of the curve, it basically starts from zero. However, due to the small number of original cracks, the curve in this section is shorter. When all the original cracks are closed, the stress is proportional to the strain. In this stage, Poisson’s ratio is stable and in a straight line parallel to the stress. Because the stress increase continuously hen near the peak, small cracks will regenerate in the coal sample. At this time, Poisson’s ratio gradually increases, but the increase amplitude is not obvious. When exceeds the peak stress, the sample will occurs uniform plastic deformation, which shows that the coal sample is destroyed with the augment of stress little by little. The transverse deformation increases sharply while the axial deformation is not obvious, which shows that Poisson’s ratio increases rapidly in the graph. When the water content is 2.4%, Poisson’s ratio is 0.417 and 0.447. When the water content is 3.4%, Poisson’s ratio is 2.453 and 0.208. When the water content is 4.4%, Poisson’s ratio is 0.146 and 0.424. When the water content is 5.4%, Poisson’s ratio is 0.471 and 0.09. It is observed that with the augment of moisture content, Poisson’s ratios firstly increases, then stabilizes, and finally continues to increase.

2.3.3. Modulus of Elasticity. In the process of uniaxial compression, its elastic modulus and its elastic modulus are statistically analyzed, and the following figure is obtained after Origin processing. The law is shown in Figure 3.

The elastic modulus under different moisture content is 36.1017 and 55.2772, 29.9468 and 38.6363, 15.8267 and 41.8443, and 18.4 and 25.4839, respectively. When the stress increases from the beginning, because the original cracks of coal sample is closed, the stress increase is small, and the strain is large. Therefore, the starting point of the curve is low at the beginning, but the curve of this section is shorter due to the small number of original cracks. When the stress is removed, the coal sample will return to its original state; so, the elastic modulus of this section is parallel to the stress. When near the peak, due to the continuous increase of stress, small cracks will be regenerated in the coal sample, and then the stress reaches the peak, at which time the elastic modulus shows a slight downward trend. When exceeds the peak stress, the sample has obvious and uniform plastic deformation, and at this stage, the elastic modulus decreases continuously and sharply. When the water content is 2.4%, the value of elastic modulus is 36.1017 and 55.2772. When the water content is 3.4%, the elastic modulus is 29.9468 and 38.6363. When the water content is 4.4%, the elastic modulus is 15.8267 and 41.8443. When the water content is 5.4%, the elastic modulus is 18.4 and 25.4839. Obviously, that the elastic modulus decreases when the moisture content increase.

The calculated parameters are summarized in Table 2. The mechanical parameters of coal and rock with different moisture content are shown in the table below. It can be seen from Table 2 that with the increase of water content, the peak energy, peak stress, Poisson’s ratio, and elastic modulus of coal samples show a downward trend. This further shows that water softens coal and rock with the increase of water.
Figure 6: Continued.
content. When water seeps into the pores or fissures of coal and rock, dissolution and hydration will occur between them, resulting in the reduction of strength of some coal and rock and softening.

3. Damage Characteristics of Coal Samples

3.1. Damage Variables Based on Elastic Modulus. Strain and damage can be expressed as

\[
\varepsilon = \frac{\sigma}{E} = \frac{\sigma'}{E} = \frac{\sigma}{(1-D)E'},
\]

\[
D = \frac{1-E'}{E} = 1 - \frac{\sigma}{E}.
\]

The value of damage variable was calculated from the above equation, and the relationship between damage variable and strain was drawn, as shown in Figure 4.

3.2. Damage Variables Based on Axial Strain. To describe the dynamic evolution process of damage in coal, the strain related damage variables are defined, which can be expressed as

\[
D = \begin{cases} 
0 & 0 < \varepsilon < \varepsilon_f, \\
\frac{\varepsilon - \varepsilon_f}{\varepsilon_u - \varepsilon_f} & \varepsilon_f < \varepsilon < \varepsilon_u, \\
1 & \varepsilon_u < \varepsilon.
\end{cases}
\]
where $\varepsilon_f$ is the threshold strain of damage evolution of rock medium under unidirectional stress, and $\varepsilon_u$ is the limit strain. The relationship between damage and strain can be obtained from the above equation, as shown in Figure 5. The relationship between damage and strain can be obtained from the above formula, as shown in Figure 5. It can be seen from the figure that the damage of the rock sample is almost zero at the initial stage of strain. At this time, it is in the compaction stage; so, the damage is very small. With the increase of strain, the rock sample begins to fracture and the damage variable begins to increase sharply.

### 3.3. Damage Variable Based on Crack Volume Strain

Under external load, cracks will go through various stages of compaction, initiation, stable growth, and rapid growth, and the development of cracks reflects the internal damage evolution of coal. Therefore, the damage evolution law of coal can be more intuitively reflected by using crack volume strain to define the damage variable.

Axial strain and transverse strain can be measured according to the uniaxial compression test of coal, but proper strain cannot be measured directly; so, it can only be obtained by approximate method [29]

$$\varepsilon_u = \varepsilon_1 + 2\varepsilon_2$$

where $\varepsilon_1$ is the axial strain, and $\varepsilon_2$ is the transverse strain.

The total volume strain $\varepsilon_v$ is mainly composed of two parts. One part is the volume change caused by the closure of the original crack in the coal sample or the opening and expansion of new cracks during the loading process; the other part is the elastic volume strain $\varepsilon_v^e$ under the same stress level,

$$\varepsilon_v^e = \frac{(1 - 2v)\sigma}{E},$$

where $E$ is the average elastic modulus, $v$ is the average Poisson's ratio, they are obtained according to the linear elastic stage, respectively, and $\sigma$ is the axial stress. By subtracting the elastic volume strain from the volume strain $\varepsilon_v$, the volume strain $\varepsilon_{vc}$, which reflects the crack closure and opening during the loading process, can be obtained [30]

$$\varepsilon_{vc} = \varepsilon_v - \varepsilon_v^e.$$  

Therefore, the damage variable $D$ is defined by crack volume strain as [31]

$$D = \frac{\varepsilon_{vc}}{\varepsilon_v},$$

where $\varepsilon_{vc}'$ is the crack volume strain when the coal can no longer carry the load. As the crack volume decreases in the initial loading process, the crack will start to expand when the load is increase; so, the damage variable calculated will have a negative value when the load is small, but the crack volume is small in the compaction stage; so, the value of the damage variable is also small. At the magnitude of $10^{-3}$, it can be considered that the initial damage variable value is 0. The relationship between damage variables and strain defined by the above equation is shown in Figure 6. By evaluating the damage of coal and rock from different angles, it
Figure 9: Continued.

(a) Sample A-1

(b) Sample A-2
Figure 9: Continued.
Figure 9: Continued.
Figure 9: Evolution of strain energy of coal under uniaxial compression.

Table 3: Energy characteristics of coal samples with different water content.

<table>
<thead>
<tr>
<th>Number</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
<th>A-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>80% before peak (MPa)</td>
<td>4.708</td>
<td>9.440</td>
<td>8.632</td>
<td>12.444</td>
<td>7.596</td>
<td>15.068</td>
<td>6.660</td>
<td>31.712</td>
</tr>
<tr>
<td>80% of total energy before peak (mJ/mm$^3$)</td>
<td>0.728</td>
<td>1.793</td>
<td>1.120</td>
<td>2.201</td>
<td>2.796</td>
<td>3.854</td>
<td>0.926</td>
<td>13.932</td>
</tr>
<tr>
<td>80% elastic energy before peak (mJ/mm$^3$)</td>
<td>0.602</td>
<td>1.488</td>
<td>0.890</td>
<td>2.004</td>
<td>1.823</td>
<td>3.145</td>
<td>0.870</td>
<td>9.096</td>
</tr>
<tr>
<td>80% dissipate energy before peak (mJ/mm$^3$)</td>
<td>0.126</td>
<td>0.305</td>
<td>0.230</td>
<td>0.197</td>
<td>0.973</td>
<td>0.710</td>
<td>0.056</td>
<td>4.836</td>
</tr>
<tr>
<td>Pre peak stored energy (mJ/mm$^3$)</td>
<td>1.325</td>
<td>2.581</td>
<td>1.768</td>
<td>3.791</td>
<td>2.863</td>
<td>4.949</td>
<td>1.520</td>
<td>19.370</td>
</tr>
<tr>
<td>Total energy (mJ/mm$^3$)</td>
<td>2.042</td>
<td>4.149</td>
<td>3.355</td>
<td>5.517</td>
<td>11.170</td>
<td>8.004</td>
<td>2.196</td>
<td>80.800</td>
</tr>
<tr>
<td>Postpeak failure energy (mJ/mm$^3$)</td>
<td>0.717</td>
<td>1.568</td>
<td>1.587</td>
<td>1.726</td>
<td>8.307</td>
<td>3.055</td>
<td>0.676</td>
<td>61.430</td>
</tr>
<tr>
<td>Impact energy index (KE)</td>
<td>1.848</td>
<td>1.646</td>
<td>1.114</td>
<td>2.197</td>
<td>0.345</td>
<td>1.620</td>
<td>2.249</td>
<td>0.315</td>
</tr>
<tr>
<td>Peak energy (total energy)</td>
<td>1.315</td>
<td>2.274</td>
<td>1.774</td>
<td>3.851</td>
<td>2.911</td>
<td>5.067</td>
<td>1.512</td>
<td>19.301</td>
</tr>
</tbody>
</table>
is revealed that the damage variable of coal body has the change trend of small to large and sudden sharp increase in the loading process, which is consistent with the experimental process.

4. Energy Evolution Characteristics of Coal Mass

Through analyze the above experimental data, the stored energy is shown in Figures 7 and 8.

The conversion of energy is the intrinsic nature of the process of physical characteristics change. From the perspective of energy, the damage to failure is the evolution of the next macroinstability phenomenon caused by energy and is the consequence of the comprehensive effect of accumulation and transformation process. Figure 9 shows the strain energy evolution curve of coal. The energy dissipation mainly induced the damage and then led to the property degradation and strength loss, and the dissipation of energy was the internal cause of the sudden destruction. Part of the energy generated in the coal sample is dissipated in the
generation of damage and the expansion of cracks, while the other part is stored in coal sample as elastic energy. The coal samples with different water content can be divided into six stages under the uniaxial compression process.

(1) Pressure dense phase: dry coal samples with full water coal sample absorption can be released increases slightly with the augment of axial strain. For low water content of coal sample, releasable elastic strain energy rises slightly bigger than the dissipation of strain energy increase rate, and high water content of coal sample is slightly less than the coal samples of low water content. This indicates that the external work on the coal sample is mainly

<table>
<thead>
<tr>
<th>Number</th>
<th>A-1</th>
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<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
<th>A-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (%)</td>
<td>5.4</td>
<td>3.4</td>
<td>4.4</td>
<td>3.4</td>
<td>4.4</td>
<td>2.4</td>
<td>5.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Residual energy index</td>
<td>4.98182</td>
<td>12.28822</td>
<td>7.34744</td>
<td>18.1614</td>
<td>1.36126</td>
<td>30.01247</td>
<td>15.452</td>
<td>5.1633</td>
</tr>
</tbody>
</table>

Figure 12: Water content-peak energy evolution diagram of coal.

Figure 13: Water content-effective impact energy index and water content-residual energy index of coal.

Table 4: Performance indexes of coal samples with different water content.
consumed in the plastic deformation. This is because the original open structural plane or microcrack of the coal sample expends some of the strain energy in the closing process at this stage.

(2) The elastic deformation and elastic stability of crack development stage: this stage is the curve of stress-strain approximate to linear, the energy absorb from the outside mainly stored in the coal sample as releasable strain energy. This is because the coal sample absorbing energy is mainly used for coal samples from external internal bearing structure elastic deformation, strain energy dissipation a slight increase in the process.

(3) The development stage of unstable rupture: when the stress level is increase, the energy input to the coal sample gradually increases, but most of the input energy is still stored as releasable strain energy. However, the dissipated energy increases significantly in this stage, which is due to the qualitative change of the development of microcracks and the continuous development of fracture.

(4) Postrupture stage: In a rapid decline in this stage releasable elastic energy and dissipated strain increase sharply, because the bearing capacity of coal sample after peak strength, its internal structure suffered severe damage, crack development, and cross and form the macroscopic fracture surface consolidation, and plastic deformation, macroscopic crack penetration, and macrofracture surface sliding need to consume a lot of strain energy.

According to the above analysis, the energy evolution mechanism, and the accumulation, release and dissipation of strain energy of coal samples under different moisture content have similar change laws. However, due to the existence of water, the real time evolution characteristics of energy with different water content in the uniaxial compresion damage and failure process are greatly different. The energy variation characteristics of coal specimen under different moisture content during damage and failure are as follows: before peak strength, the change rate of total strain energy absorbed by coal samples with low water content and releasable strain energy with axial strain is greater than that has high water content. Before the peak strength, based on the same condition of strain, the strain energy absorbed and stored by the coal sample with low water content is greater than which has high water content, indicating that water affect the energy storage characteristics of the coal sample significantly.

Comparative analysis coal samples under different water content in energy dissipation can change law in the process of evolution, the pressure in dense phase, dissipated strain energy increases slowly with the loading process, and the coal sample with low water content has slightly bigger dissipation strain. This is because the water pressure inside the microcracks of coal sample closed primary friction energy dissipation. Secondly, pore water pressure is generated in some defects due to the high water content state. The increase amplitude of dissipated strain energy of coal samples is small, and the increase amplitude of dissipated strain energy of coal samples has high water content is slightly larger than that which water content is low. This is because the further increase of stress leads to the initiation and propagation of local microcracks in coal samples which has high moisture content. Along with the load continues to increase, coal samples are in unstable fracture development stages. This stage coal samples with high moisture content will dissipate more strain energy, and near the peak strength, water content of the dissipation strain energy of coal sample increases rate faster. This is due to the continuous increasing of the axial load, and the pore water pressure inside the coal samples increases. The pore water pressure produces additional stress on the coal samples near the original defects and locally germinated microcracks. The water also has softening effect on the coal rock mass, which makes the coal samples with high water content prone to generate new cracks at this stage, and accelerates the growth of mesocracks.

5. Influence of Water Content on Bursting Liability of Coal

The data obtained from the above experiments are processed to obtain the data shown in the Table 3 below. Impact energy index KE is an important classification index to judge whether coal seam has impact tendency. The calculation formula of impact energy index KE is [32]

\[ KE = \frac{A_X}{A_X}, \]

where \( A_X \) is the deformation energy accumulated before the peak, and \( A_X \) is the deformation energy lost after the peak.

After processing the data with the Origin software, the law of water content and bursting liability index is obtained, as shown in Figure 10.

Water content has different effects on peak energy, elastic modulus, peak stress, and Poisson’s ratio. Water content at 3.4% influences the peak energy, peak stress, and elastic modulus of coal sample, and then the effect of water content on Poisson’s ratio is not obvious.

Many studies show that the strength is a key factor which affects the bursting liability of coal [33]. On the basis of test of all specimens by peak stress value, the average of each group of specimen under uniaxial compressive strength and fitting curve is obtained as shown in Figure 11. You can see in the following picture, peak stress has good correlation with water content, and peak stress of the specimen showed a trend of index is lower when the water content is increase. It follows that the uniaxial compressive strength of coal can be significantly reduced after water injection.

During uniaxial compression, the area enclosed by the stress-strain curve represents all the energy absorbed by the coal sample at this point, including the energy consumed during damage and plastic deformation inside the rock and the stored elastic energy that can be released. The average
peak energy of each group of specimens was calculated by energy statistics of each coal sample at the vertex. Origin software was used to fit the peak energy and water content, and the following fitting curve was obtained, which is shown in Figure 12. As the figure below, the peak energy has a good correlation with water content. When water content is increase, the peak energy of the specimen shows an exponential decrease trend. This shows that the uniaxial compressive strength of coal can be significantly reduced after water injection, which also reduces the possibility of rapid release of strain energy when the strain energy falls off after peak during uniaxial compression.

Figure 13 shows the variation law of effective impact energy and dump energy index of coal mass under different water content. It can be seen from Figure 13 that with the increase of water content, the effective impact energy index and residual energy index have a downward trend, indicating that the impact tendency of coal and rock decreases significantly with the increase of water content. After processing the data obtained from the experiment, the data are shown in Table 4.

6. Conclusion

(1) Through the different water content of coal samples, when the water content of uniaxial compressive strength of the specimens is increase, the peak impact energy and elastic modulus are different degrees of reduced, through data fitting, peak energy relationship with water content rendering index

(2) After the water content increases from 2.4% to 5.4%, the coal changes from strong impact type to weak impact type. The value of impact propensity index changes significantly while the water content is increase, and the larger the water content, the more evident the change; that is, the soak time coal sample is longer, and the change of impact propensity index is more obvious

(3) The stress-strain curve of coal (including the whole-course curve) and the characteristic parameters extracted from the whole-course curve change with the different water-bearing state. The greater the water content, the stronger the plasticity. Under the same load, the more moisture content, the bigger the deformation, and the smaller the slope of the curve

(4) In the stress-strain curve, the rock shows brittleness and shear failure, after the peak strength with obvious strain softening characteristics, the rock is mainly plastic failure after the peak strength with the augment of water content, and the strain softening characteristics are not obvious

(5) The elastic deformation index of coal decreases when the water content augmented. The bursting liability of rock decreases significantly while the water content increased. In the case of high moisture content, prepeak energy accumulation of coal samples are affected to different degrees. The compressive strength and elastic modulus of coal samples were significantly affected by water content after 33 hours of humidification treatment. With the increase of water content, the coal strength will gradually decrease, and the impact energy index of coal will also decrease. Therefore, the anti-impact measures such as coal seam water injection and deep hole blasting to reduce the coal strength are the prevention measures to eliminate the internal causes of rock burst, which will have a good effect on preventing the occurrence of rock burst

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.

References


