Influence of water content and maceral composition on the properties of outburst-prone coal: laboratory experiment

Shuang Gong\textsuperscript{1,2,3,}\textsuperscript{*}, Zhen Wang\textsuperscript{1,3}, Guoqiang Zhang\textsuperscript{4}, Lei Zhou\textsuperscript{1,3}, Wen Wang\textsuperscript{1,3}, Yixin Zhao\textsuperscript{5}

\textsuperscript{1} School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China
\textsuperscript{2} Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources, Jiaozuo 454000, China
\textsuperscript{3} Collaborative Innovation Center of Coal Work Safety, Jiaozuo 454000, Henan Province, China
\textsuperscript{4} Department of Energy Engineering, Gansu Vocational College of Energy and Chemical Industry, Lanzhou 730000, China
\textsuperscript{5} School of Energy and Mining Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

Corresponding author: Shuang Gong (gongcumtb@126.com)

\textbf{Abstract.} We conducted laboratory experiments to investigate the influence of water content and maceral composition on the properties of outburst-prone coal using X-ray diffraction and optical electron microscope. For comparison, two groups of experiments were completed on contrasting coals, namely, outburst-prone and outburst-resistant coals. The complete stress–strain behavior, uniaxial compressive strength, Young’s modulus, and acoustic compressional velocity were measured and correlated with water content. Test results showed that the microhardness and microembrittlement of the outburst-prone coal were higher than those of the outburst-resistant coal. When the water content increased to 4%, the uniaxial compressive strengths of the outburst-prone and outburst-resistant coals decreased by 82.4% and 85.1%, respectively; and their elastic moduli decreased by 90.3\% and 86.6\%, respectively. The difference between the maximum reflectance and the minimum reflectance of vitrinite was smaller for the outburst-resistant coal than for the outburst-prone coal. The distribution of maceral composition in the outburst-resistant coal was simple, and the primary damage was minimal.

\textbf{Keywords:} Water content; Maceral composition; Outburst-prone; Laboratory experiment

1. Introduction

Coal bump is a process involving the sudden release of strain energy gathered in coal seams. It often causes the sudden instability of coal bodies near working faces or coal pillars, coal inrush into roadways, and even one-time impact damage on panel roadways covering hundreds of meters. Coal bump clearly poses a threat to mining safety. This threat increases with increasing mining depth \cite{1,2}. Over the years, researchers have been focusing on the mechanism, prediction, and prevention of coal bump. A large number of effective studies have been carried out. One of the most widely used theories is the theory of impact propensity proposed by Polish and former Soviet Union scholars. According to this theory, impact propensity is the inherent capability or attribute of a coal body to produce impact damage. A test method is used to judge the susceptibility of coal to outburst on the basis of three indexes:
dynamic failure time, elastic energy index, and impact energy index. However, most existing theoretical and experimental studies mainly focused on the macroscopic mechanical properties of outburst-prone coal. Hence, an in-depth analysis of the microstructural characteristics affecting outburst-prone coal is lacking.

Coal itself is composed of minerals with different chemical compositions and crystal lattices with different structures. The physical and mechanical properties of coal are closely related to its internal microstructure and microdefects. As coal bump is a process involving the slow accumulation and sudden release of strain energy of coal and surrounding rocks, the characteristics of energy accumulation and release in coal should be related to two aspects: the structural characteristics of the coal body, such as the layered structure and fold structure; and the inherent microstructure and composition of coal. For the structure of outburst-prone coal, scholars have conducted preliminary studies by using the method of structural physics; their results reveal that the structure of this coal type is abnormal and that its macromolecules form a “manifold-like spherical structure” [3]. The relationship between the composition, structure, and outburst proneness of coal-bearing rocks shows that with an increase in the content of elastic particles, the possibility of strain coal bump increases. As the particle size of elastic particles decreases, the number of fine-grained flaky minerals increases, and outburst proneness decreases [4]. However, due to the complexity of coal itself and the limitations of research methods, the previous research on the microstructure characteristics and macerals of outburst-prone coal remains unsystematic.

Taking Zhagoezhung coal seams 7, 9, and 12 and Xinzhouya coal seam 11 of the Datong mining area as examples, this study investigates the influence of mineral components, organic macerals, microcracks, and other factors on coal’s outburst proneness by means of X-ray diffraction (XRD), scanning electron microscopy, and optical microscopy. The micromorphology characteristics of the coal surface with different levels of outburst proneness are analyzed as well. The influence of different levels of water content on the strength of outburst-prone coal is studied to provide a new way to understand the mechanism of coal bump and determine the outburst proneness of coal.

2. Experimental results and discussion

2.1 X-ray diffraction analysis of outburst-prone coal

XRD is an important method for determining crystal structures. In recent decades, XRD has been widely used to study the physical structure of amorphous materials. A number of researchers at home and abroad have made important progress in the study of coal structure based on XRD [5,6]. In the current work, coal seams 7, 9, and 12 of the Zhaogezhuang mine in the Kailuan mining area are selected. The location and property of each coal mining point are described in Table 1. The D/Max-2500 X-ray diffractometer produced by RIGAKU company is used in the experiment. The voltage is 40 kV, the current is 100 mA, the scanning speed is 6 (°)/min, and the scanning angle range is 0°–60°. The experiment results show obvious differences in the clay mineral and amorphous contents of coal under different geological structure conditions. Even for the coal seams in the same mining area, the clay mineral and amorphous contents of coal also vary due to the different coal forming periods. The clay mineral content in the coal seams with strong and moderate outburst proneness is relatively low, whereas that in the coal seams with weak outburst proneness is high; the amorphous content in these coal seams is obviously low.

According to the research methods used in coal petrology and coal chemistry, the changes in the physical and mechanical properties of coal and the influence of impact energy release on coal properties can be investigated by using the parameter microcrystalline parameter of coal. Generally, the distance $d_{002}$ (002 mesh spacing) between single aromatic layers, the average stacking thickness $L_C$ of microcrystalline layers, and the diameter $L_a$ of aromatic layers are used as the microcrystalline parameters of coal; they are given as

$$d_{002} = \frac{\lambda}{2 \sin \theta_{002}}$$

(1)
\[ L_c = 0.94 \lambda / \beta_{002} \times \cos \theta_{002} \]  
\[ L_a = 1.84 \lambda / \beta_{100} \cos \theta_{100} \]

where \( \lambda \) is the X-ray wavelength; \( \theta_{002} \) and \( \theta_{100} \) are the peaks of (002) and (100), respectively; and \( \beta_{002} \) and \( \beta_{100} \) are the integral half height widths of the two peaks respectively. The results of the comparison of the XRD structural parameters of the coal samples are shown in Table 2.

### Table 1. Results of analysis of coal samples by XRD

| Serial number | Coal source | Depth (m) | Properties      | Mineral type and content (%) |
|---------------|-------------|-----------|-----------------|------------------------------|
|               |             |           |                 | Clay mineral content (%)     |
| Z-7           | No. 7 coal seam of Zhaogezhuang mine | -110 | Resistant | 1.0 | 91.2 | 7.8 |
| Z-9           | No. 9 coal seam of Zhaogezhuang mine | -110 | Weak outburst propensity | 9.3 | 10.8 | 0.4 | 71.2 | 8.3 |
| Z-12          | No. 12 coal seam of Zhaogezhuang mine | -110 | Strong outburst propensity | 1.3 | 1.4 | 91.6 | 5.7 |
| X-11          | No. 11 coal seam of Xinzhouyao mine | -300 | Moderate outburst propensity | 0.6 | 1.9 | 3.2 | 1.2 | 90.8 | 2.3 |

The test shows that the greater the \( \Delta L = (L_a - L_c) / L_c \) or \( L_a / L_c \) value of coal is, the greater the risk of coal bump will be. The corresponding \( \Delta L \) values of Z-7, Z-9, Z-12, and X-11 are 0.154, 0.135, 0.162, and 0.930, respectively. In the same stress field under the same geological conditions, coal seam 11 of the Xinzhouyao mine is more prone to coal bump than coal seams 7, 9, and 12 of the Zhaogezhuang mine. This result explains the occurrence of coal bump at ~300 m in the Xinzhouyao mine and at ~876 m in the Zhaogezhuang mine. This outcome is consistent with the field situation and outburst proneness of the Zhaogezhuang mine.

### Table 2. Comparison of XRD structural parameters of coal samples

| Serial number | \( 2\theta_{002}/(°) \) | \( \beta_{002}/\text{rad} \) | \( 2\theta_{100}/(°) \) | \( \beta_{100}/\text{rad} \) | \( d_{002}/\text{nm} \) | \( L_c/\text{nm} \) | \( L_a/\text{nm} \) | \( L_a/L_c \) | \( (L_a-L_c)/L_c \) |
|---------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Z-7           | 23.7                   | 0.166                  | 45.2                   | 0.298                  | 0.375                  | 0.892                  | 1.029                  | 1.154                  | 0.154                  |
| Z-9           | 23.7                   | 0.155                  | 44.2                   | 0.274                  | 0.375                  | 0.904                  | 1.012                  | 1.135                  | 0.135                  |
| Z-12          | 23.9                   | 0.172                  | 42.7                   | 0.305                  | 0.372                  | 0.857                  | 0.996                  | 1.162                  | 0.162                  |
| X-11          | 22.1                   | 0.241                  | 43.4                   | 0.258                  | 0.402                  | 0.613                  | 1.183                  | 1.930                  | 0.930                  |

#### 2.2 Influence of macerals of coal on outburst proneness

The content, distribution, and vitrinite reflectance of macerals in coal with different levels of outburst proneness are observed using the optical microscope MPV-3 microscope photometer.
produced by Leitz company of Germany. The relationship between macerals and the outburst proneness of coal is discussed, and the influence of different macerals on coal outburst proneness and the correlation between maceral distribution, structural characteristics, and coal outburst proneness are analyzed. The samples in the test are the same as those used in the XRD test to understand the relationship between macerals and the outburst proneness of coal. The test results are shown in Table 3 and Table 4.

2.2.1 Relationship between outburst proneness and microcomponent content

The results of the analysis of Table 3 are described as follows. (1) The influence of the exinite and mineral composition on the outburst proneness of coal is minimal. (2) A high correlation is observed between the outburst proneness of coal and the content of vitrinite and inertinite; that is, the lower the content of vitrinite is, the higher the content of inertinite is, and the lower the outburst proneness is. (3) The contents of vitrinite, filar, and inertinite show an obvious correlation with the outburst proneness of coal; that is, the higher the content of vitrinite, filar, or inertinite is, the lower the outburst proneness is. (4) For the Zhaogezhuang mine, a certain correlation is noted between clay mineral content and the outburst proneness of the coal seam; that is, the higher the clay mineral content is, the smaller the outburst proneness is. The conclusion is consistent with the results of the XRD analysis.

The mechanical properties of organic macerals in the same lump of coal are different. They are mainly determined by the mechanical properties of the organic macerals themselves. The different contents of organic macerals exert a great influence on the microhardness, microbrittleness, and toughness of coal. The current test results show that coal with high microhardness and microbrittleness is likely to be prone to outburst.

With the application of optical microscope manufacturing technology and advanced equipment in the last decade, scholars at home and abroad have studied the degree of coal metamorphism and the structural evolution characteristics of different metamorphic types of coal under high temperature and high pressure conditions by using optical microscopy and other methods [8-10]. In particular, vitrinite reflectance has received increasing attention as a direct physical quantity reflecting the evolution characteristics of coal structure. The vitrinite reflectance of coal with different levels of outburst proneness is analyzed by combining the outburst proneness and vitrinite reflectance of coal. As discerned from the test results in Table 4, the vitrinite reflectance of coal with different levels of outburst proneness does not directly reflect the outburst proneness of coal while the difference between the maximum reflectance and the minimum reflectance of vitrinite has a certain correlation with the outburst proneness of coal; that is, the smaller the difference is, the smaller the outburst proneness will be [11].

### Table 3. Quantitative statistical results of macerals of coal samples

| Coal macerals | Z-9  | Z-7  | Z-12 |
|---------------|------|------|------|
| Vitrinite      |      |      |      |
| Desmocollinites| 7.6  | 10.6 | 3.0  |
| Telocollinite  | 49.3 | 4.8  | 45.3 |
| Telinite       | 15.7 | 32.2 | 20.9 |
| Corpocollinite | 4.7  | 7.4  | 2.6  |
| Vitrodetrinite | 1.2  | 0.4  |      |
| Inertinite     |      |      |      |
| Semidrisinite  | 2.9  | 10.2 | 11.5 |
| Fusinite       | 4.9  | 9.2  | 9.3  |
| Inert detritus | 2.5  | 16.6 | 4.8  |
| Macrinite      | 0.4  |      |      |
| Micronite      | 0.6  |      |      |
| Sclerotinite   | 0.6  |      |      |
| Exinite        |      |      |      |
| Sporinite      |      |      | 0.6  |
| Cutinite       |      |      |      |
| Resinite       |      |      |      |
| Mineral        |      |      |      |
| Clay mineral   | 2.4  | 5.8  | 0.2  |
| Pyrite         |      |      | 2.2  |
| Carbonate mineral | 8.8 | 0.6  | 0.2  |
Other minerals

Table 4. Analysis results of vitrinite reflectance

| Serial number | Z-9 | Z-7 | Z-12 | X-11 |
|---------------|-----|-----|------|------|
| \( R_{\text{min}} \) (%) | 1.10 | 1.11 | 1.19 | 0.76 |
| \( R_{\text{max}} \) (%) | 1.17 | 1.21 | 1.24 | 0.85 |
| \( R_{o, \text{max}} \) (%) | 1.14 | 1.16 | 1.22 | 0.81 |
| \(|R_{\text{max}}-R_{\text{min}}|\) (%) | 0.15 | 0.08 | 0.18 | 0.15 |
| Measuring points | 20 | 20 | 20 | 20 |

Note: \( R_{\text{min}} \), \( R_{\text{max}} \), \( R_{o, \text{max}} \) are the minimum reflectivity, maximum reflectivity, and average reflectivity of vitrinite, respectively.

2.2.2 Relationship between outburst proneness and microstructure of coal

The mechanical properties of coal are determined by the content of each of its organic component and are highly related to the distribution and the primary damage structure characteristics of these components. Therefore, the comprehensive analysis and identification of the outburst proneness of coal seams requires an understanding of the distribution characteristics of their components. The distribution of the macerals in the coal seam 7 of the Zhaogezhuang mine is mainly desmocollinite-cemented inert debris and is relatively uniform; primary damage is not developed, as shown in Figure 1 (a), (b). Coal seam 9 of the Zhaogezhuang coal mine shows weak outburst proneness. Its maceral is obviously different from that of coal seam 7. Its component distribution and structure are relatively complex, as reflected in the development of fractures in the vitrinite body (Figure 1 [c]). Fusinite and telinite are cemented, as shown in Figure 1 (d), (e). Coal seam 12 of Zhaogezhuang coal mine shows strong outburst proneness. Its maceral distribution is simple, but it develops surface fissures and complex primary damage, as shown in Figure 1 (f)–(h). The comparative analysis shows a certain correlation between the outburst proneness of coal and the complexity of the distribution of macerals and the distribution of primary damage in macerals. That is, when the distribution of macerals is simple and the primary damage is minimal, the outburst proneness is small, and vice versa.
Figure 1. Distribution of macerals in different coal seams of Zhaogezhuang mine (500× magnification) (a) Desmocollinite, (b) cutinite and desmocollinite-cemented inert detritus, (c) calcite filled vitreous fissure, (d) distribution of telinite, (e) filamentous plastid and vitrinite distributed in half, (f) microsomes in vitrinite, (g) cracks in telocollinite, (h) fusinite and pyrite; (a) and (b) are the results of the analysis of the coal samples of coal seam 7; (c)–(e) are the results of the analysis of the coal samples of coal seam 9; (f)–(h) are the results of the analysis of the coal samples of coal seam 12.

2.3 Influence of water content on the strength of the outburst proneness of coal

To study the influence of different water contents on the mechanical properties of coal with different levels of outburst proneness, we conduct a uniaxial compression test on the coal samples with different water contents. Figure 2 shows the stress–strain curves of the coal samples with different levels of outburst proneness under different moisture contents. The stress–strain curves of the three groups of coal samples are similar to those of typical rocks. However, the deformation characteristics of coal samples under different water cut conditions generally differ in the loading process. At the initial stage of compression and loading, the curves are concave with the increase of axial stress, but the concave amplitudes of the three curves are not the same. With the increase of water content, the concave amplitude decreases, as shown in the sharp concave on the curve of the red and green coal samples. The reason is that the water contents of the two coal samples show minimal difference, and the internal microcracks close rapidly under the action of external force. The blue curve is flat and almost straight because the cracks in the coal samples are almost filled with water and the homogeneity and compactness are satisfactory. Moreover, the liquid can transfer stress to cause the slow compression of microcracks. The stress increase is relatively low, and the initial damage shortens the
compaction stage. In the elastic deformation stage, the slopes of the red and green curves are high, the difference between them is not large, and the duration is short. By contrast, the slope of the blue curve is low, and the duration is long. The moisture content can obviously extend the elastic properties of coal samples and transform them into elastic media. This process is accompanied by the expansion of pores and fractures. The water in the saturated coal sample fills the new fractures first, reduces the damage of the coal sample, and maintains its own elastic properties. In the expansion stage, the coal sample changes from compression to expansion, and the coal sample corresponding to the red and green curves reaches the maximum bearing capacity under small deformation. At this point, the coal sample becomes prone to brittle failure, small plastic deformation, and small volume expansion. According to the blue curve, the maximum bearing capacity of the coal sample is deformed greatly, plastic failure occurs, the volume of the coal sample increases, and the release process of the elastic energy of the coal sample is slowed down. In the fracture stage, the coal sample is destroyed with a sharp sound. The red curve corresponds to the characteristics of the coal sample: the stress almost decreases in a straight line, and this process is instantaneous, that is, the coal sample is splashed during the destruction process. The green curve corresponds to the characteristics of the coal sample: the stress drops sharply, but it is slightly gentle. The blue curve corresponds to the characteristics of the coal sample: the stress drops to a certain extent, the stress does not change with the increase of strain, the sample shows certain residual strength, the damage degree is relatively gentle, almost no coal splashing occurs, and a certain degree of plasticity is retained.

In general, the stress–strain curves of the coal samples in three states, especially in the pre-peak stage, are different. With the increase of water content, the concave amplitude of the compaction stage curve becomes small, and the slope of the elastic stage curve decreases. After the peak, only the curve of the saturated coal sample has residual strength and retains certain plasticity.

The physical parameters of the uniaxial compression of the coal samples under different water content conditions are shown in Table 5. The peak strength of the coal sample in the natural state is 13.79–16.28 MPa, the dispersion is 18.06%, and the average value is 14.51 MPa. When the water absorption is about 2%, the peak strength of the coal sample is 7.72–10.19 MPa, the dispersion is 31.99%, and the average value is 8.59 MPa. The peak strength of the saturated coal sample is 1.54–3.37 MPa, the dispersion is 54.30%, and the average value is 2.44 MPa. Relative to that of natural coal, the compressive strength of the saturated coal
sample decreases by 12.07 MPa (83.18%). Relative to that of the coal sample with 2% moisture content, the strength of the saturated coal sample decreases by 6.15 MPa (71.59%). Relative to that of the natural coal sample, the compressive strength of the coal sample with 2% moisture content decreases by 5.92 MPa (40.80%). This result indicates that the saturated coal sample has a certain softening property relative to the natural coal sample. As a result of natural soaking, the coal sample can absorb water, and moisture can soften the internal components, thereby reducing the compressive strength of the coal sample. When the water content increases to 4%, the uniaxial compressive strengths of the outburst-prone coal and outburst-resistant coal decrease by 82.4% and 85.1%, respectively; and their elastic moduli decrease by 90.3% and 86.6%, respectively.

Figure 3 shows the comparison of the failure modes of the coal samples with different water contents. Figures 3 (a) and (b) present the failure images of the coal samples with water contents of 1%–2%. It With the increase of axial load, cracks start to form at the middle of the low end, extend upward in a “V” shape, and then develop laterally. Finally, on both sides, the “V”-shaped shear failure appears. The failure type of the coal sample with a moisture content of 2% is cleavage failure. An obvious crack runs through and is perpendicular to the upper and lower surfaces, and other cracks are distributed on both sides; all cracks are cleavage like. Figure 3 (d) shows shear failure and cleavage failure. The shear fracture surface starts from both sides and ends at the upper and lower ends. The cleavage surface generally exists in the middle of the coal sample. The upper part of the saturated coal sample is crushed, and the lower crack starts at the bottom and ends at the middle part of the coal sample. On the one hand, it is caused by the friction between the upper part of the coal sample and the pressure plate of the testing machine; on the other hand, the saturated coal sample has low compressive strength and high water content and thus develops internal cracks and breaks easily.

Figure 3. Comparison of failure modes of coal samples with different water contents

Table 5. Test results of coal samples with different water contents under uniaxial compression

| Serial number | Water absorption r (%) | Compressive strength (MPa) | Elastic modulus (GPa) | Deformation modulus (GPa) | Poisson’s ratio | Strain (10^-3) |
|---------------|------------------------|----------------------------|----------------------|--------------------------|----------------|----------------|
| Z-9           | 1.58                   | 13.79                      | 3.15                 | 1.089                    | 1.08           | 9.87           |
| Z-7           | 1.51                   | 16.28                      | 2.47                 | 1.35                     | 0.61           | 10.60          |
| Z-12          | 1.47                   | 14.08                      | 2.54                 | 1.37                     | 0.97           | 9.15           |
| X-11          | 1.54                   | 13.90                      | 2.45                 | 1.17                     | 0.32           | 9.77           |
| Z-9           | 2.12                   | 8.42                       | 1.44                 | 0.97                     | 1.12           | 7.42           |
| Z-7           | 2.14                   | 10.19                      | 1.90                 | 1.12                     | 3.21           | 8.68           |
| Z-12          | 2.13                   | 7.72                       | 0.68                 | 0.47                     | 3.12           | 7.73           |
3. Conclusions
In this work, the influence of water content and maceral composition on the properties of outburst-prone coal is studied using XRD and optical electron microscopy. The complete stress–strain behavior, uniaxial compressive strength, Young’s modulus, and acoustic compressional velocity of outburst-prone coal are measured and correlated with water content and microstructures. This work shows that the microstructure characteristics of coal can reflect the basic macrostructure characteristics of coal seams and the history of stress failure. The surface micromorphology and structural characteristics of the coal samples with different levels of outburst proneness are representative and can be used as an auxiliary basis to determine the outburst proneness of coal seams.

Two findings are apparent from the microscopic and macroscopic experimental results. First, the mechanical properties, content, and distribution of organic macerals determine the physical and mechanical properties of coal. The reflectance of vitrinite in coal with different impact propensities cannot directly reflect the outburst proneness grade of coal. Nevertheless, the difference between the maximum and minimum reflectance of vitrinite has a certain correlation with the outburst proneness of coal, that is, the smaller the difference is, the lower the outburst proneness is. Second, when the water content increases to 4%, the uniaxial compressive strengths of the outburst-prone and outburst-resistant coals decrease by 82.4% and 85.1%, respectively; their elastic moduli also decrease by 90.3% and 86.6%, respectively. This study deepens our understanding of the outburst proneness of coal samples affected by maceral composition and water content.

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 no conflicts of interest.

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