Failure mechanics and infrared radiation characteristics of soft coal at various moisture contents

Yiju Tang\textsuperscript{a,b}, Jing Liu\textsuperscript{b}, Tianxuan Hao\textsuperscript{a,c}, Fan Li\textsuperscript{a} and Lizhen Zhao\textsuperscript{a}

\textsuperscript{a}College of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo, China; \textsuperscript{b}Department of Resources & Environment, Henan College of Industry & Information Technology, Jiaozuo, China; \textsuperscript{c}State Collaborative Innovation Center of Coal Work Safety and Clean-efficiency Utilization, Henan Polytechnic University, Jiaozuo, China

\textbf{ABSTRACT}

Soft coal is characterized by low strength and weak bonds, which play a key role in the occurrence and development of dynamic disasters. A more thorough understanding of the failure mechanics and infrared radiation characteristics of soft coal at various moisture contents is needed. In this study, infrared radiation experiments were conducted for soft coal at various moisture contents. The results indicate that moisture content affects compressive strength and elastic modulus of soft coal with compressive strength and elastic modulus being highest at moderate. Moisture has a substantial influence on the infrared radiation of compressed coal samples. Soft coals with high moisture contents show a smaller fluctuation of the average infrared radiation temperature curve and a stronger direct relationship of temperature and stress in the linear elastic stage. The coal samples with various moisture contents show a warming trend during loading. The increased amplitude of infrared radiation temperature per unit stress shows a linear relationship with moisture content. A large number of high temperature red spots appear along the diagonal line of coal samples with 0% moisture content before fracture, while changes in the infrared thermal image of the coal sample with 4% moisture content were negligible during loading.

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1. Introduction

Soft coal refers to the coal with the competent coefficient of rock less than 1, which is the product of geological structure and is also known as tectonic coal. Lower strength of soft coal is prone to dynamic disasters such as rock burst or outburst (Cao et al. 1996; Ju et al. 2004; Zhang et al. 2007). Previous research has revealed much about the occurrence mechanism of coal and rock dynamic disasters; among the findings is that the energy theory in the comprehensive mechanism of action is one of the consensus theories accepted by most scholars. It is believed that gas
outburst is a complex thermal dynamic process in which temperature changes occur from beginning to end (Li et al. 1990; Jiang et al. 1996; Guo et al. 2000; Liu et al. 2003; Xiong et al. 2015; Wu et al. 2017). ‘Coal and gas outburst prevention rules’ proposes some auxiliary prediction indexes (such as drilling cuttings temperature and coal temperature) that should be added to make the prediction of the working face more reliable (China Coal Industry Press 2019; State Administration of Coal Mine Safety 2019). Therefore, it is of great engineering significance to explore the temperature variation law before a coal rock failure disaster. The temperature variation law is used to accurately identify the dynamic disaster warning information.

As a non-destructive monitoring method, infrared technology can continuously monitor the radiation temperature changes on the rock surface in real time. By processing, analysing, and studying the infrared radiation information, it can identify internal damage development (Cui 1996; Zhi et al. 1996; Wu et al. 2004). In recent years, researchers have conducted in-depth research on the infrared radiation law during the rock loading process and obtained abundant results. Deng et al. (1997) studied the change rule of temperature during rock failure through uniaxial compression experiments. Dong (2001) concluded through experiments that micro fracture of rock would be accompanied by infrared radiation. Liu et al. (2002) obtained a quantitative relationship between stress and infrared radiation temperature using uniaxial compression tests on multi-dark mineral rocks. Zhang and Liu (2011) analysed the spatiotemporal evolution characteristics of thermal radiation in the process of rock failure under stress with circular holes. Through an experimental study, Gao et al. (2015) found that infrared abnormal precursors appeared in siltstone on the verge of rupture. Yang et al. (2019) studied the evolution law of surface infrared radiation temperature during uniaxial compression of sandstone.

Many factors affect the infrared radiation of rock during loading, among which moisture is an important factor (Zang et al. 1996; Wu et al. 2002; Zhao and Jiang 2010; Salami et al. 2017; Sun et al. 2017). Some research examined the influence of water on the infrared radiation of rock, and generally shows that the presence of water affects the occurrence of infrared radiation. Deng et al. (1997) studied the role of water in rock infrared radiation. Liu et al. (2010) studied the infrared radiation characteristics of wet rocks. Wu et al. (2015) conducted uniaxial compression experiments on saturated siltstone and found that there was an abnormal abrupt change of infrared temperature in the process of fracture. Zhang et al. (2016) concluded through experiments that water affected the infrared radiation sensitivity of siltstone fracture. Yang et al. (2017) concluded through an experimental study that the infrared radiation temperature in the process of fracture of saturated silt has fractal characteristics. Zhou et al. (2018) studied the infrared radiation characteristics of sandstone at various moisture contents.

Most of these studies were based on rocks with high strength, such as granite and sandstone, and few studies were conducted on soft coal with low strength. Coal seams normally contain some water, but the influence of moisture content on the infrared radiation characteristics of soft coal was rarely reported. Therefore, the authors took soft coal as the research object, conducted the synchronous test experiments of stress-strain and infrared radiation temperature during the loading and fracture process of coal under different moisture contents, analysed the influence of moisture on the
failure mechanics and infrared radiation characteristics of soft coal, and discussed the relationship between moisture content and infrared radiation temperature of coal.

2. Test system and method

2.1. Sample preparation

The coal samples used for testing were selected from the working face 3105 of the Hebi Coal Mine, Henan, China, which is a coal and gas outburst mine. The moisture content of the original coal seam was 1.19%, the ash content was 9.6%, the volatile content was 13.75%, the porosity was 7.61%, and the competent coefficient of rock was 0.32.

The strength of soft coal is lower, so it is generally difficult to make raw coal samples of a standard size that can meet the requirements of mechanical and infrared radiation tests. Other studies have shown that a coal briquette can replace raw coal for mechanical tests (Jasinge et al. 2012; Zhang et al. 2021). Compared with raw coal, coal briquette is homogeneous, which avoids the influence caused by structural differences that cannot be eliminated by using raw coal.

After crushing the coal samples, coal samples with three particle sizes of \(-0.5\) mm, \(0.5–1\) mm, and \(1–3\) mm were screened and proportioned according to the ratio of 2:1:1 of the three kinds of coal particles to obtain the same graded coal particle samples (Li 2017). After the coal sample is put into the 105 °C electric oven for baking for 24 hours, it is considered that the moisture content at this time is 0%. According to the plan calculated in advance for the moisture content, the corresponding quality of clean water is added and fully stirred and wetted to make the briquette with the water mass fraction of 0%, 2%, 4%, and 6% with \(\varphi 50 \times 100\) mm (±0.5 mm). The coal briquette had water overflow in the process of pressing when the moisture content reached 7%. For each coal sample with water content, four samples were made for uniaxial compression fracture test. The prepared coal sample was immediately wrapped in plastic wrap and placed into the fresh-keeping box to maintain the moisture content of the sample. Moisture content was calculated as follows:

\[
\omega = \frac{m_2 - m_1}{m_1} \times 100\%
\]

where: \(\omega\) is the test moisture content, %; \(m_1\) is the mass of test drying, g; \(m_2\) is the mass in water, g.

2.2. Test system

The RMT-150B servo control testing machine of Wuhan Rock and Soil Mechanics Test Institute was used to conduct uniform displacement controlled uniaxial compression tests on coal samples with various moisture contents, and the loading rate was constant at 0.01 mm/s. The test system could automatically collect and process the test data and compare and verify the stress-strain curves. The infrared resolution is \(320 \times 240\) pixels, the temperature sensitivity is 0.03 °C, the response spectral band range is 8–12 μm, the thermal sensitivity is < 0.05 °C@30 °C, and the acquisition
frequency is set as 30 Hz frame frequency. The experimental system was shown in Figure 1. During the experiment, the infrared thermal imager and the static load pressure controller were simultaneously turned on to ensure the synchronous collection and recording of infrared radiation and stress-strain information.

2.3. Test procedure

The test system was constructed as shown in Figure 1. The experimental steps were shown. (1) Before the experiment, place the coal sample on the loading machine, and place the infrared thermal imaging camera directly in front of the sample about 0.5 m away from the sample, while adjusting the parameters such as emissivity, temperature, and humidity of the infrared metre to make its picture clear. (2) Calibrate the display time of the computer and infrared metre so that they can collect relevant experimental data synchronously. Adjust the data acquisition rate, infrared thermal image acquisition rate of 1 frame per second, the acquisition rate of ballast data is 5 times per second. (3) Before the start of each specimen experiment, the infrared observation of the specimen should be carried out, and the experiment can be started only after the display of its surface infrared radiation temperature on the thermal imaging camera is stable. (4) The loading machine was loaded in a displacement-controlled manner, with preloading first to ensure that the loading surface was in complete contact with the specimen, followed by loading at a uniform rate of 0.002 mm/s until the specimen breaks.

Measures were taken to minimize the influence of ambient temperature change on the radiation of coal samples, including the test coal samples were placed in the laboratory at room temperature 24 hours before the experiment began; during the experiment, all indoor doors and windows were closed, the curtains were pulled, and there was no foot traffic in the laboratory, decreasing the effects of ambient air radiation; leather gloves were worn when exchanging coal samples.
3. Test results and analysis

3.1. Mechanical parameters of coal samples at various water contents

In this study, the RMT-150B rock mechanics testing machine was used to conduct uniaxial compression experiments on coal samples at four moisture contents. The ballast mechanical parameters were read as shown in Table 1, and the load-displacement curves of coal samples under different water content were shown in Figure 2.

It can be seen from Figure 2 that the load-displacement curves are generally similar during loading for coal samples at various moisture contents. At higher moisture contents, the load-displacement curve of the whole uniaxial compression process is also high. After the initial compaction stage, the linear elastic stage is quickly conducted, but at this time, there are obvious differences: the slope and length of the linear elastic stage was highest at a moderate moisture content.

Figure 3 shows the variation rule of peak stress and elastic modulus with at various water contents. In Figure 3, the peak stress and elastic modulus of the sample varied over the range of moisture contents tested but was highest when moisture content was 4%. When the moisture content of the coal sample increases by 4%, the peak stress and elastic modulus increase, the peak stress increases from 0.388 MPa to 1.041 MPa, and the elastic modulus increases from 0.061 GPa to 0.088 GPa. When the moisture content increases from 4% to 6%, the peak stress and elastic modulus decrease, the peak stress decreases from 1.041 MPa to 0.709 MPa, and the elastic modulus decreases from 0.088 GPa to 0.071 GPa. When the moisture content is less than 4%, coal particles are gradually wetted by water, and the wetted coal particles are gradually bonded to improve the cohesion of the briquette and enhance the compressive strength of the briquette. After the moisture content was 4%, the coal particles were gradually over wetted by moisture, and the coal particles were surrounded by moisture. The briquette began to soften, the cohesion was reduced, and the compressive strength of the briquette was lower. The test shows that moisture content affects the compressive strength of soft coal. Moderate water injection can improve the consolidation strength of soft coal.

| Sample ID | Sample size (mm) | Experimental quality (g) | Moisture content (%) | Peak stress (MPa) | Average peak stress (MPa) | Elastic modulus (GPa) | Average elastic modulus (GPa) |
|-----------|-----------------|--------------------------|----------------------|------------------|--------------------------|----------------------|-----------------------------|
| HB0-1     | 49.34 x 110.04  | 265.1                    | 0                    | 0.361            | 0.388                    | 0.061                | 0.061                       |
| HB0-2     | 49.33 x 111.68  | 264.62                   | 0.384                | 0.062            |                          |                      |                             |
| HB0-3     | 49.62 x 108.39  | 264.71                   | 0.403                | 0.061            |                          |                      |                             |
| HB0-4     | 49.57 x 104.06  | 258.19                   | 0.407                | 0.06             |                          |                      |                             |
| HB1-1     | 49.41 x 109.2   | 267.4                    | 2%                   | 0.468            | 0.445                    | 0.063                | 0.06                        |
| HB1-2     | 49.36 x 108.1   | 268.34                   | 0.44                 | 0.06             |                          |                      |                             |
| HB1-3     | 49.4 x 108.3    | 268.56                   | 0.427                | 0.058            |                          |                      |                             |
| HB2-1     | 49.45 x 103.79  | 278.03                   | 4%                   | 1.076            | 1.041                    | 0.087                | 0.088                       |
| HB2-2     | 49.49 x 102.96  | 277.22                   | 1.166                | 0.085            |                          |                      |                             |
| HB2-3     | 49.42 x 104.72  | 279.32                   | 0.981                | 0.088            |                          |                      |                             |
| HB2-4     | 49.91 x 106.74  | 277.38                   | 0.788                | 0.074            |                          |                      |                             |
| HB3-1     | 49.47 x 104.55  | 283.79                   | 6%                   | 0.664            | 0.709                    | 0.071                |                             |
| HB3-2     | 49.86 x 106.82  | 283.24                   | 0.66                 | 0.068            |                          |                      |                             |
| HB3-3     | 49.95 x 106.92  | 282.94                   | 0.72                 | 0.072            |                          |                      |                             |
| HB3-4     | 49.36 x 107.29  | 282.63                   | 0.666                | 0.071            |                          |                      |                             |
3.2. Infrared thermographic characteristics of coal samples at various moisture contents

The distribution and spatiotemporal evolution of an infrared thermal field on the surface of coal samples can be observed using an infrared thermal image during fracturing and instability under loading. The temperature range in the thermal image is set at 22.00–25.00°C, so that the infrared thermal image at various moisture contents is comparable. Thermal images with moisture content of 0% and 4% were compared and analysed as shown in Figure 4. During the loading process, the infrared radiation

![Figure 2. Load-displacement curve of coal sample at various moisture contents.](image)

![Figure 3. Variation rules of peak stress and elastic modulus at various moisture contents.](image)

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The temperature field of the sample with 0% moisture content showed non-uniform changes. The green low-temperature region gradually decreased with the increase of load, and the blue high-temperature region increased accordingly. Especially, the high-temperature red spots caused by the friction effect or stress concentration appeared at $0.75\sigma_{\text{max}}$. These spots were distributed on both sides of the diagonal of the thermal image, and the red high-temperature spots suddenly increased before the fracture. The sample with 4% moisture content had no infrared anomalies, and the thermal image was similar during loading. The high temperature region appeared at the upper passive loading end of the sample with 0% moisture content, and the temperature rise amplitudes at the upper and lower loading ends of the sample with 4% moisture content were higher than the middle position, showing a temperature increase.

Figure 4. Comparison of thermal image evolution of coal samples with different water content at typical moments during loading process. Where, (a) shows the samples with 0% moisture content; (c) shows the samples with 4% moisture content.
gradient effect. The reason may be that when the coal sample was loaded, there was an end effect, and heat was generated by friction between the indenter and base and the contact surface of the sample.

### 3.3. Variation characteristics of infrared radiation temperature during loading

The average infrared radiation temperature (AIRT) of the coal sample surface is the reflection of the change of surface radiation energy during the whole process of loading to fracture. It is a common and important index to analyse the change of infrared radiation characteristics of coal samples during loading. To reduce the influence of the surrounding environment on the radiation of coal samples, $\Delta t(t_t-t_0)$ is selected when analysing the infrared data. $\Delta t_{AIR}$ is the temperature difference mode, which is the temperature value calculated by subtracting the temperature of all pixels of the initial base frame from all pixels of the current frame. The statistical results of the increment of $\Delta t_{AIR}$ before the peak stress and the increment of unit stress AIRT ($\Delta t/\sigma$) in different water-cut states are shown in Table 2.

The variation curves of average infrared radiation temperature and load with time of coal samples at four moisture contents are shown in Figure 5. Figure 5 reveals, when the moisture content is low (Figure 5(a,b)), the AIRT curve of the sample fluctuates relatively large during the change process, and the temperature rise is small. When the moisture content is high (Figure 5(c,d)), the AIRT curve fluctuates slightly during the change process. When the moisture content is high, the AIRT curve of the specimen increases with an increased load, and the changes are synchronized. However, the load-time and temperature-time curves of the specimens with low moisture contents are not synchronized. When the moisture content was 0%, the temperature drastically varied during the process. The AIRT curve of the sample showed a step-like decrease at the initial loading stage. The temperature minimum appeared at the initial 44 s of the online elastic stage and then gradually increased. The temperature maximum appeared after the peak load at 14 s, and the temperature rapidly decreased after the peak load. When the moisture content was 2%, the AIRT

| Moisture content (%) | Sample ID | AIRT increase amplification before peak stress (°C) | Average increase amplification of AIRT before peak stress (°C) | AIRT increase amplification in unit stress (°C/MPa) | AIRT increase amplification in unit stress (°C/MPa) |
|----------------------|-----------|----------------------------------------------------|----------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 0%                   | HB0-1     | 0.2812                                             | 0.2868                                                   | 0.7789                                          | 0.7394                                          |
|                      | HB0-2     | 0.2932                                             |                                                          | 0.7635                                          |                                                  |
|                      | HB0-3     | 0.3036                                             |                                                          | 0.7533                                          |                                                  |
|                      | HB0-4     | 0.2694                                             |                                                          | 0.6619                                          |                                                  |
| 2%                   | HB1-1     | 0.3636                                             | 0.3872                                                   | 0.7769                                          | 0.8717                                          |
|                      | HB1-2     | 0.4432                                             |                                                          | 1.0073                                          |                                                  |
|                      | HB1-3     | 0.3548                                             |                                                          | 0.8309                                          |                                                  |
| 4%                   | HB2-1     | 1.3582                                             | 1.3567                                                   | 1.2623                                          | 1.31                                            |
|                      | HB2-2     | 1.3124                                             |                                                          | 1.3903                                          |                                                  |
|                      | HB2-3     | 1.3724                                             |                                                          | 1.1770                                          |                                                  |
|                      | HB2-4     | 1.3838                                             |                                                          | 1.406                                           |                                                  |
| 6%                   | HB3-1     | 1.3236                                             | 1.2805                                                   | 1.6797                                          | 1.8108                                          |
|                      | HB3-2     | 1.3192                                             |                                                          | 1.9867                                          |                                                  |
|                      | HB3-3     | 1.2936                                             |                                                          | 1.7967                                          |                                                  |
|                      | HB3-4     | 1.1856                                             |                                                          | 1.7802                                          |                                                  |
The curve of the sample rapidly decreased at the initial loading stage and then increased after oscillation. After entering the mid-linear elastic stage, the temperature increased with the increase of load, and the changes of the two synchronized. The maximum temperature point appeared 20 s before the peak load, and the stress at the time of the peak point was $0.85 \sigma_{\text{max}}$. For the samples with moisture content of 4% and 6%, the two showed were synchronized in the online elastic stage, and the maximum temperature appeared 30 s after the peak load. The temperature extremes of the coal body appeared to be delayed to different degrees, and the greater the water content, the longer the delay. The reason may be that when the water content of the specimen increased further, the pore fracture water content increased, and the pore water and water film stabilization links provided a certain degree of stiffness, which delayed the occurrence of frictional heat generation to a certain extent.

Figure 5 shows the AIRT increase and stress curve of different moisture content before peak load. With the increase of moisture content, the linear relationship between stress and temperature was getting better and better. The coefficient of determination, $R^2$, was 0.41 when the moisture content was 0%, and the $R^2$ was 0.95 when the moisture content was 4%. The coal samples showed warming, but the warming amplitude, that is, the slope $k$ of the curve, was substantially different. With the increase of moisture content, the warming amplitude increased first and then decreased. When the moisture content was 4%, the warming amplitude was the

![Figure 5](image-url)

**Figure 5.** Curve of increase of average infrared radiation temperature and load of coal samples at various moisture contents over time. moisture content: (a) 0%, (b) 2%, (c) 4%, (d) 6%.
largest, which was seven times that of dry coal samples, indicating that moisture enhanced the intensity of infrared radiation, which was consistent with the research results of Deng et al. (1997) and Liu et al. (2010).

From Figures 7 and 8 and Table 2, it reveals that with the increase of moisture content, AIRT first increases and then decreases and the overall shape is an open downward parabola. The average increase range of AIRT before the peak load of the sample with 0% moisture content was 0.2868 °C. When the moisture content of the sample was 4%, the average increase range of AIRT was 1.3567 °C, which was about 4.7 times of the dry sample. When the moisture content of the sample was 6%, the average increase range of AIRT was 1.2805 °C, which was about 4.4 times of the dry sample. The increase range of unit stress AIRT was linearly and positively correlated with moisture content. The average increase range of unit stress AIRT of the sample with 0% moisture content was 0.7394 °C/MPa, and the average increase AIRT of the sample with 4% moisture content was 1.31 °C/MPa, about 1.8 times that of the dry sample.

4. Discussion

4.1. Evolution mechanism of the relationship between infrared radiation temperature and stress

As a complex porous medium, coal has a large number of cracks and pores. According to its connectivity, it can be divided into open pores and closed pores. At the initial stage of loading, the open hole cracks are closed under pressure, the volume compression becomes smaller, and the gas contained expands to carry away part of the heat, resulting in a rapid decrease in temperature. With the increase of moisture content, the gas in the pore and fissure of a coal body is displaced by water particles. Therefore, the phenomenon that gas expands under pressure and absorbs heat and cools at the initial compaction stage is weakened. As shown in Figure 4, the coal samples with 0% and 2% moisture content cool during the initial loading stage,
whereas the coal samples with 4% and 6% moisture content do not cool. The displace-ment effect of water particles is the cause of temperature variation trend of coal samples with different moisture contents at the beginning of loading.

Moisture content of coal makes the compressive strength and elastic modulus of the coal increase, and the elastoplasticity increase. At the same time, the water particles leaching free gas in the coal sample hole and crack under the pressure drive. Both reasons affect the development and expansion of micro cracks in the process of compression. Arnozang conducted uniaxial compression tests on dry and wet sandstone and found that the crack density and crack length generated during the loading process of wet sandstone were less than those of dry samples. Zhang et al. (2016) experimentally verified that water affected the development of pore and fissure in the sample compression process, and there were fewer pores and fissures generated in the water-bearing sandstone.

Differences between the infrared radiation temperature and the stress curve of coal samples with different moisture contents can be described as follows. For coal samples with 0% and 2% moisture contents, the moisture content is low, and the internal pores and fissures of coal samples are fully developed and expanded in the compression process. The friction thermal effect caused by the mutual extrusion friction between the collapse pores and fissures is the main reason for the large fluctuation of the average infrared radiation temperature curve on the surface of coal samples. The thermal effects generated by the fracture development differ and depend on the coal properties. The shear fissures and tensile fissures can cause the increase and decrease of the thermal temperature, respectively. As shown in Figure 4(a,b), the micro-fracture of the specimen is fully developed in the loading compaction stage and the early linear stage, which may be the cause of temperature oscillation. In coal samples with moisture content of 4% and 6%, water immersion affects the development of pores and cracks in the sample, and the influence of friction heat effect on radiation energy is reduced. Influence of stress on infrared radiation gradually increases. The

![Figure 7. Relation between the temperature increment before peak load and moisture content.](image)
temperature curve and stress curve in the linear elastic stage are increasingly consistent, which further shows that the temperature and stress meet the linear relationship in the elastic range (Figure 4(c,d)).

4.2. Mechanism of infrared radiation temperature enhancement by water

Liu et al. (2003) considered that the variation of infrared radiation during rock loading and compression was controlled by two kinds of thermal effects: thermo elastic effect and friction thermal effect. The friction thermal effect only appeared in the plastic stage of rock micro-fracture development and expansion, and the thermo elastic effect ran through the whole loading process of rock. Yang et al. (2019) found that the temperature decreased at the initial stage of shale loading and pointed out that this was caused by the pressure spillover of gas in pores and fractures. Coal is a sedimentary rock that is heterogeneous, and there are a variety of pore cracks, joints, bedding, and other structures in coal. The pore crack structure contains certain free or adsorbed gas, which leads to the difference and complexity of infrared radiation between coal and rock in the loading process and other intact rocks.

In fact, the infrared radiation during the loading of the coal body is influenced by the coupling of four aspects: thermoelastic effect, frictional heat effect, gas expansion, and gas desorption. Among them, the thermoelastic effect and friction effect causes the temperature of the coal body to increase, and gas expansion and gas desorption cause the temperature to decrease. With the increase of moisture content, the free or adsorbed gas contained in the pores and fissures of a coal body decreases, and the cooling effect of gas compression expansion work and desorption heat absorption is weakened. At higher moisture contents, the development and expansion of the primary pores and fissures are insufficient, and fewer tensile fissures are generated, so less heat is absorbed. More friction work of water particles in the process of sliding
with coal fissures and particles results in a stronger frictional heating effect. According to the thermo elastic effect, the temperature rises when the coal sample is compressed. According to the test results, under the same load condition, higher moisture content results in greater strain and more external load, so the heating effect is greater for the coal sample. With the increase of moisture content, the infrared radiation temperature range of unit stress of coal sample increases, indicating that moisture promotes the infrared radiation of a loaded coal sample.

5. Conclusions

In this study, the damage mechanics and infrared radiation characteristics of soft coal at various moisture contents are further investigated, and the differences in temperature change patterns before peak load and infrared thermal images before rupture of coal samples are used to monitor rock engineering hazards and realize the role of prediction and early warning.

1. Moisture content affects the strength of soft coal. With the increase of moisture content of coal samples, the peak stress and elastic modulus first increase and then decrease. The peak stress and elastic modulus reached the highest observed value when the moisture content was 4%, indicating that the soft coal can be solidified when the water content is constant.

2. The infrared thermal image characteristics of coal samples with various moisture contents differ during the loading process. A large number of high temperature red spots appear in the diagonal of the fracture front of the coal sample with 0% moisture content, while the infrared thermal image changes of the coal sample with 4% moisture content are relatively calm during the loading process.

3. The coefficient of determination, $R^2$ is 0.41 for a coal sample with 0% moisture content, and the temperature curve $R^2$ is 0.95 for a coal sample with 4% moisture content. With the increase of moisture content, there is synchronization between the average infrared radiation temperature and the stress changes with time.

4. The loading process of coal samples at various moisture contents shows a warming trend, but the increase of the slope $k$ of the curve was substantially different. With increasing moisture content, the infrared radiation temperature increases before peak load and then decreases after peak load. The infrared radiation temperature per unit stress is linear and correlated with moisture content, and moisture content affects the infrared radiation of coal samples.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, Tianxuan HAO, upon reasonable request.

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