INFLUENCE OF WATER-SOAKING TIME ON THE ACOUSTIC EMISSION CHARACTERISTICS AND SPATIAL FRACTAL DIMENSIONS OF COAL UNDER UNIAXIAL COMPRESSION

by

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The water-soaking time affects the physical and mechanical properties of coals, and the temporal and spatial evolution of acoustic emissions reflects the fracture damage process of rock. This study conducted uniaxial compression acoustic emissions tests of coal samples with different water-soaking times to investigate the influence of water-soaking time on the acoustic emissions characteristics and spatial fractal dimensions during the deformation and failure process of coals. The results demonstrate that the acoustic emissions characteristics decrease with increases in the water-soaking time. The acoustic emissions spatial fractal dimension changes from a single dimensionality reduction model to a fluctuation dimensionality reduction model, and the stress level of the initial descending point of the fractal dimension increases. With increases in the water-soaking time, the destruction of coal transitions from continuous intense failure throughout the process to a lower release of energy concentrated near the peak strength.

Key words: *water-soaking time, acoustic emission, acoustic emissions counts, acoustic emissions energy, spatial fractal dimension*

Introduction

Pre-fracturing or softening top coal by water infusion, among other technologies, have gradually been implemented in coal mining to ensure the safety and efficiency and have played an important role in improving the efficiency of fully mechanized top-coal caving mining: eliminating outburst, lowing bursting liability, and reducing the amount of dust. Coal seams are often affected by water, and the coal will interact with the water via such processes as hydration, hydrolysis, and dissolution. The effect is not only reflected at the physical level, there are more complex chemical and mechanical effects [1]. The interaction of water and coal has become an engineering problem and has attracted the attention of many scholars. Su *et al.* [2] demonstrat-

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ed that after immersion, the mechanical properties of coal and the bursting liability decreased to different extents, with the decrease being greater in the earlier stages. Values for the water injection parameters were suggested based on the test results [2]. Liang *et al.* [3] found that the bursting liability decreased with increasing water content, whereas the dynamic failure time initially increased and then decreased [3].

The failure process of rock is closely related to the initiation and expansion of internal cracks. When rock is damaged, the acoustic emissions (AE) phenomena will change, with the space-time evolution of AE events reflecting the fracture and damage of rock to a certain extent [4]. According to the AE evolution difference caused by the interaction of water and coal, Qin *et al.* [5] found that as the water content increased, the cumulative ringing count of AE decreased, and a notable AE lag was produced. Xia *et al.* [6] studied the variations in the mechanical properties and AE properties of saturated rock with the water-soaking time and established an AE damage model of saturated rock based on the water-soaking. After coal seam water injection, the coal will be affected by the duration of water-soaking. The mining operation may experience water inrush, in which the coal in front of the mining face will be immersed in groundwater to different degrees and for different lengths of time. Different water-soaking times will affect the evolution of AE events during the process of coal failure. To explore this effect, coal mined by fully mechanized top-coal caving mining from the Datong Tashan mining, Datong, China, area was considered in this paper. The impact of water-soaking time on the AE properties and spatial fractal dimensions during the uniaxial compression of coal was studied, the full stress-strain process of the uniaxial compression of coal with different water-soaking times was monitored using the AE technique, the influence of water-soaking time on the AE properties during the deformation failure of coal was determined, the spatial distribution characteristics of AE were quantitatively represented based on fractal theory, and the effect of water-soaking time on the space-time evolution regularities of AE events was explored.

Methodology

The AE test of coal under uniaxial compression for different water-soaking times

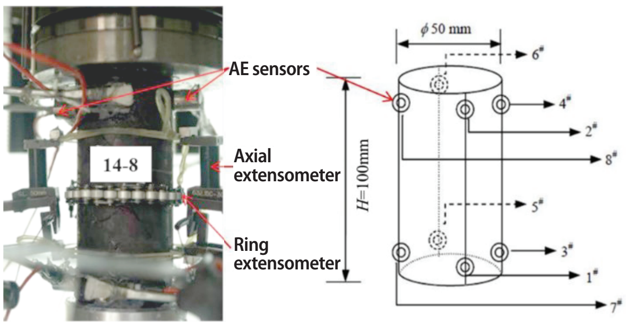

Figure 1. Uniaxial compression and AE test

Uniaxial compression AE tests of four groups of coal samples with water-soaking times of 0 hour (not soaked), 12 hour, 96 hour (4 days) and 480 hours (20 days) were conducted to investigate the influence of different water-soaking times on the physical and mechanical properties and damage evolution of coal, as shown in fig. 1. The MTS815 Flex Test rock mechanics test system at Sichuan University, Chengdu, China, was used, and an AE real-time monitoring test of the process of coal uniaxial compression was conducted using the PCI-II (PAC) AE test system.

Spatial fractal dimension calculation method of AE damage

Experiments have shown that the AE sequences of rock materials are fractal in not only the time domain but also the spatial domain [7]. The box counting method is often applied to determine the fractal dimension of AE. Liang *et al.* [8] used cubes of various sizes to cover rock samples and calculated the fractal dimensions of the AE spatial distribution during the deformation and failure process. The circle covering method and sphere covering method are also commonly used covering methods [9]. Zhang *et al.* [10] and Pei *et al.* [11] investigated the spatial distribution of AE in cylindrical specimens using the column covering method, with the centroid of a cylindrical specimen used as the base point, and the sample was covered by a cylinder with a radius of, r_i, and a height of, h_i. The relationship between the AE event number within the cylinder and radius and height is:

$$M_{(r)} \propto r_i^2 h_i \tag{1}$$

Because the height diameter ratio of a sample is constant, C_1, the eq. (1) can be expressed:

$$M_{(r)} \propto C_1 r_i^3 \tag{2}$$

Therefore, the fractal expression of the AE spatial distribution based on the column cover method is:

$$\log M_{(r)} = \log C + \log C_1 + D \log r_i \tag{3}$$

For a radius of, r_i, the corresponding, $M_{(r)}$ is obtained by eq. (3). Then, the points ($\log r_i$, $\log M_{(r)}$) in the co-ordinate system are drawn, and a linear section is fitted by the least squares method. If the fitting results of the variables are linearly correlated, the distribution of AE location points is considered to be fractal in the damage evolution process, with the slope, D, of the linear section being the fractal dimension obtained using the column covering method.

The previous three covering methods are compared and analyzed in fig. 2. The circle covering method after projection can cover all damage locations but fails to reflect the spatial distribution information of the damage. The sphere covering method can reflect the specific spatial distribution of the damage but can not cover the specimen completely. The column covering method, which uses cylinders of various sizes that are similar to the shape of the specimen, reflects all damage points and their spatial distribution information.

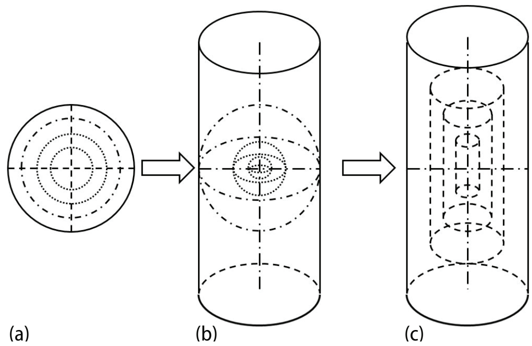

Figure 2. Circle, sphere, and column covering fractal methods of the AE spatial distribution [7]; (a) circle covering method, (b) sphere covering method, and (c) column covering method

Results and analysis

Study of the AE characteristics of coal with different water-soaking times

The results of uniaxial compression and AE tests of coal with different water-soaking times are shown in figs. 3 and 4. The evolution of the AE characteristic parameters of uniaxial compression is consistent with the stress-strain curves. The AE signals exhibit a delaying and

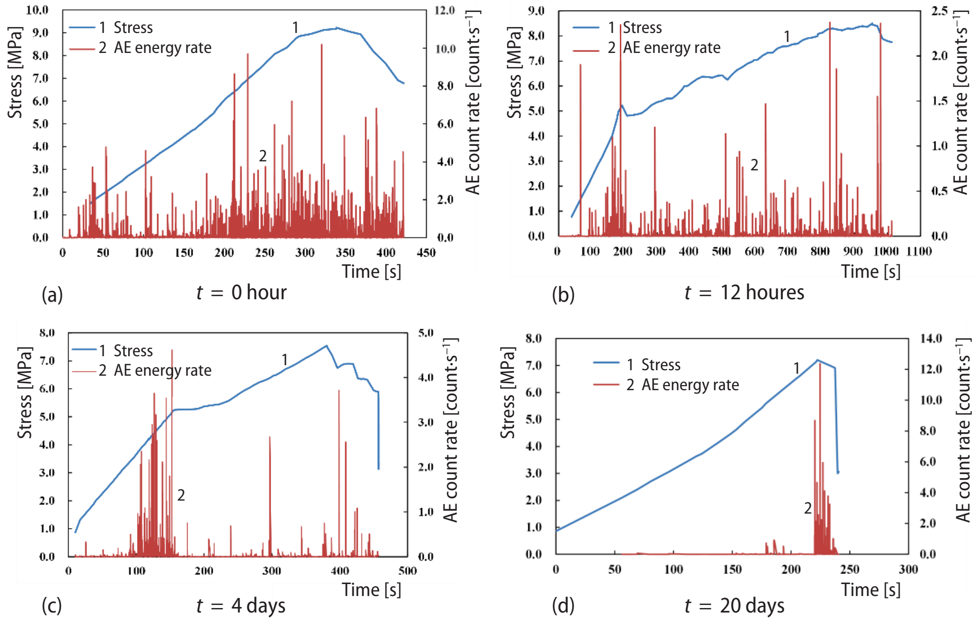

Figure 3. The AE temporal distribution parameters of count rate for different water-soaking times
(*for color image see journal web site*)

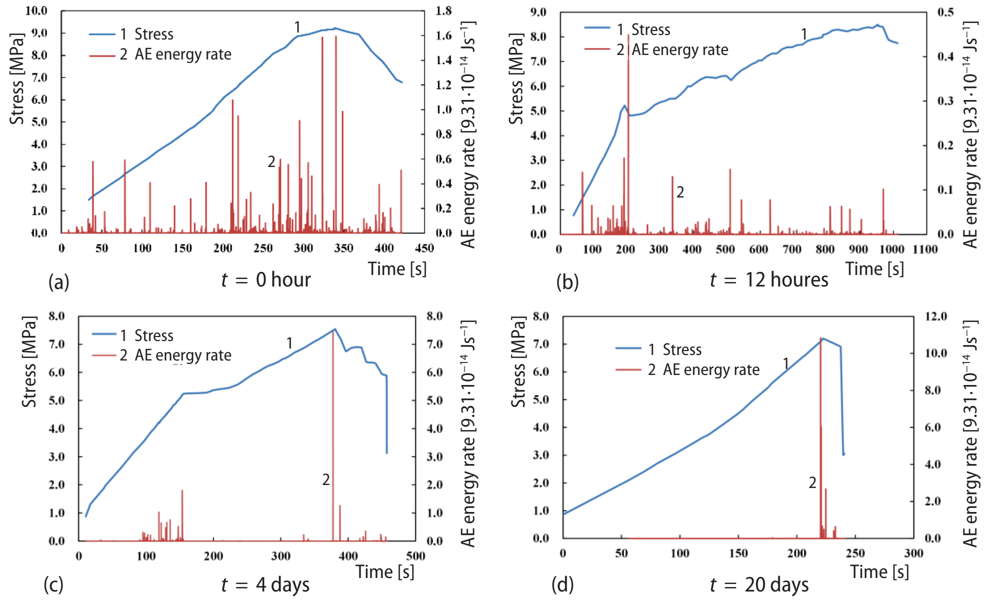

Figure 4. The AE temporal distribution parameters of energy rate for different water-soaking times
(*for color image see journal web site*)

decreasing trend with increases in the water-soaking time. The AE characteristic statistics are shown in tab. 1.

Table 1. Statistics of the characteristic AE parameters for the uniaxial compression of coal samples with different water-soaking times

Water-soaking time [h]	AE events	Cumulative ring count [10^4 times]	Cumulative energy [$9.31 \cdot 10^{-14}$J]
0	5247	16.64	4.52
12	2310	4.65	2.61
96 (4 day)	1408	3.47	1.17
480 (20 day)	523	1.96	0.19

At the initial stage of water soaking, the water bursts into the micro-fractured pores of coal, causing the moisture content to increase rapidly. Due to the brief interaction time of coal and water, the meso-structure of coal does not change considerably, and the AE parameters remain unchanged from the non-soaking state. With an increase in soaking time, the coal expands and is softened by the absorbed water. The strength of the crystal particles and the degree of cementation between particles decrease, and the strength and brittleness of the samples decrease to different extents. As a result, the AE signals are weakened during the loading process. During the soaking process, mineral particle abscission and dissolution in water occurs in the coal matrix, new cracks develop gradually, and the scale of the initial micro-pores becomes larger, causing the meso-structure to change. The initial damage to the coal is greater with a longer water-soaking time. Therefore, the intensity of the coal break is decreased, the number of AE events decreases during loading, and the cumulative energy release and ringing counts decrease. The spatial distribution of AE events follows the same trend. As shown in fig. 5, the spatial point of AE decreases with increases in the soaking time.

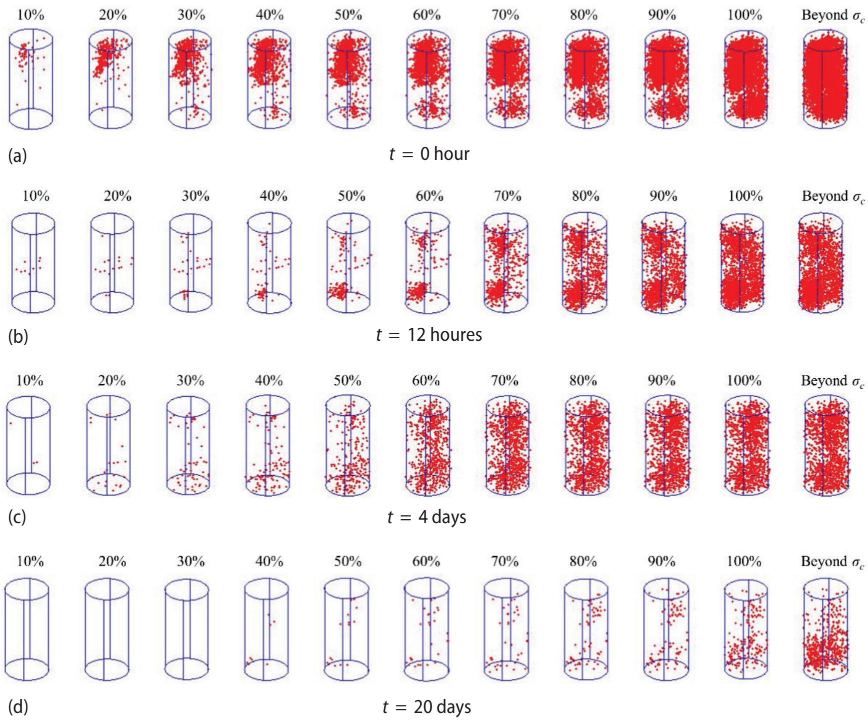

Figure 5. The AE spatial distribution for different water-soaking times

Fractal dimension of the AE spatial distribution of coal under uniaxial compression with different water-soaking times

Based on the results of the AE location in coal with different water-soaking times under uniaxial compression, the fractal dimension, D, of the AE spatial distribution was calculated using the column covering method. The results show that the logarithm of the cylindrical radius, (log$r$), is linearly correlated with the logarithm of the number of AE positioning points in the column range, (log$M_{(r)}$), within a certain range of scales, and the correlation coefficients are greater than 0.98. Therefore, the AE spatial distribution of coal under uniaxial compression has a fractal feature. Figure 6 shows the evolution of the fractal dimension with an increasing stress level of the AE spatial distribution on coal for different water-soaking times.

As shown in fig. 6, the fractal dimension of the AE spatial distribution of coal with different water-soaking times ranged between 2 and 3. The higher fractal dimension of approximately 2.8 at the beginning of loading indicates that the distribution of the AE spatial points is discrete and tends to fill the entire sample. After failure, the fractal dimension decreased to approximately 2.3 and was similar to the plane fractal dimension of 2. The AE spatial location points accumulated gradually during the failure process and eventually formed the macroscopic fracture surface. The change in the fractal dimension with stress level reveals the evolution of the microfracture from disorder to order.

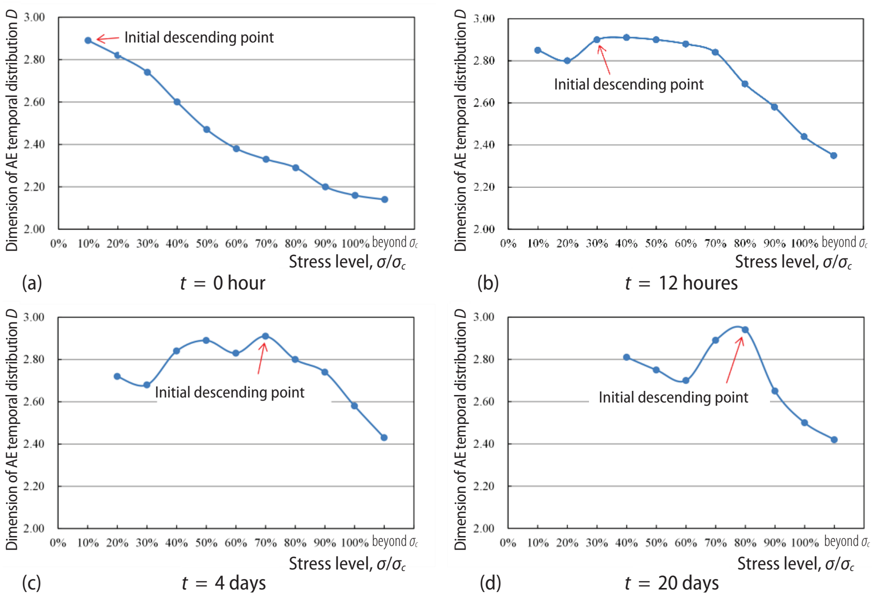

Figure 6. Evolution of the fractal dimension of the AE spatial-temporal distribution under uniaxial compression for different water-soaking times

When the water-soaking time was relatively short, the fractal dimension, D, of the AE spatial distribution exhibited a continuous downward trend during the process of loading to failure and followed a *single dimensionality reduction* model. With increases in the water-soaking time, the evolution curve of fractal dimension fluctuated while the stress level was low. The fractal dimension, D, then began to decrease and exhibited a *fluctuation dimensionality reduction* model. As shown in fig. 5, micro-fracture initially occurred in low-intensity regions under axial pressure. For coal with a longer water-soaking time, the low-intensity regions were widely distributed, and the micro-fractures exhibited a discrete distribution in these regions. The micro-fracture corresponds to the AE events, which makes the spatial location of AE more dispersed and disordered. Therefore, the AE spatial fractal dimension of coal fluctuates until a higher stress level is reached, after which it decreases. The number of AE events of the coal with no soaking or a short water-soaking time was greater than that in the coal with a long water-soaking time, but the ordering of the AE spatial distribution appeared earlier, causing the fractal dimension of the AE spatial distribution to exhibit a downward trend in the beginning of the test.

When the water-soaking time is relatively long, the initial point at which the fractal dimension descends corresponds to a higher stress level, when the water-soaking time is 20 days, the fractal dimension decreases at 80% σ_c approximately. This result indicates that the water-soaking time has a delaying effect on the ordering of the micro-crack distribution. Coals with no soaking or a short water-soaking time continue to rupture during the loading process, and the energy is released continuously. When the water-soaking time is long, the failure of coal samples is concentrated in the later stage, corresponding to the AE spatial evolution law of the coal samples. The destruction of coal transitions from continuous intense failure throughout the process to a lower release of energy concentrated near the peak strength.

The previous analysis shows that: with the increase of the water-soaking time, AE events, count rate, and energy rate in coal samples during uniaxial compression showed a delayed phenomenon, and the total amount of these showed a decreasing trend. The incident reflected in the AE spatial distribution changes from occurring continually in the whole process to concentrately before failure, and the AE spatial fractal dimension changes from a *single dimensionality reduction* model to a *fluctuation dimensionality reduction* model, and the stress level of the initial descending point of the fractal dimension increases. It can be concluded that with increases in the water-soaking time, the destruction of coal transitions from continuous intense failure throughout the process to a lower release of energy concentrated near the peak strength.

Furthermore, as shown in fig. 6, the spatial fractal dimension still exhibits a downward trend after the peak, indicating that the micro-fracturing within the coal did not stop after the peak stress. Instead, the fracture continued to expand in an orderly manner. The AE fractal dimension of coal samples with different water-soaking times decreased rapidly at approximately 70% of the peak stress. Therefore, the spatial fractal dimension, D, decreased rapidly and suddenly and can be used to indicate the unstable failure of coal.

Conclusions

The influence of water-soaking time on the AE characteristics and spatial fractal dimensions of coal under uniaxial compression was studied. The main conclusions are as follows.

- There is a significant difference in the damage evolution of coal with different water-soaking times under uniaxial compression.
- The number of AE events, cumulative ring count, and cumulative energy exhibit decreasing trends with increases in the water-soaking time.
- When the water-soaking time was relatively short, the AE spatial distribution exhibited a continuous downward trend in the process of loading to failure and followed a *single dimensionality reduction* model.
- With increases in the water-soaking time, the evolution curve of the fractal dimension is fluctuated when the stress level was low.
- The fractal dimension, D, then began to decrease and followed a *fluctuation dimensionality-reduction* model.

- If the water-soaking time is longer, the initial descending point of fractal dimension corresponds to a higher stress level.
- The destruction of coal transitions from continuous intense failure throughout the process to a lower release of energy concentrated near the peak strength with increases in the water-soaking time.

Acknowledgment

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Nomenclature

C – constant, [–]
C_1 – the height diameter ratio of sample, [–]
D – the fractal dimension, [–]
h_i – height of the cylinder in column covering method, [mm]
$M_{(r)}$ – AE event number within the cylinder with r_i and h_i, [–]
r_i – radius of the cylinder in column covering method, [mm]
σ_c – the peak press, [MPa]

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