Statistical Analysis of Acoustic Emission in Uniaxial Compression of Tectonic and Non-Tectonic Coal

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Abstract: Tectonic coal has become an important research topic for preventing coal mine disasters and for exploring and developing coal-bed methane resources. To investigate the mechanical and acoustic properties of tectonic coal, we conducted a uniaxial compression test for tectonic and non-tectonic coal, and acoustic emission (AE) signals have been simultaneous captured in the compression process. The AE energy and waiting time of events have been studied statistically. The results show that the probability density function of AE energy follows the power law distribution well, and indicates that the AE of non-tectonic coal is mainly generated from the fracture source, while the probability density function distribution of tectonic coal is the mixing result of fracture and friction effects. Only the waiting time distribution of non-tectonic coal follows the typical brittle fracture’s double power law behavior. The waiting time distribution of tectonic coal shows the single power law with a smaller exponent value, which is associated with the granular microstructure of tectonic coal. The distribution of aftershock and Båth’s law are not sensitive to microstructure, and are identical for non-tectonic and tectonic coal. At last, the correlation dimension results for the spatial distribution of AE hypocenters indicated that the rough continuous decrease in multifractal dimension might be a precursor to devastating destruction.

Keywords: acoustic emission; tectonic coal; mixing effect; multifractal analysis

1. Introduction

Tectonic coal, formed after the intact coal being subjected to long-term intense squeezing, shearing and deformation, is characterized by low strength, a high gas content, fast desorption, and low permeability [1]. The low strength characteristics of tectonic coal reduce the mechanical conditions for outburst, and the tectonic coal is easy to form a large quantity of small coal particles, which have a fast gas desorption rate. Tectonic coal has a close relationship with the preparation and occurrence of coal and gas outburst disasters [2]. Most outburst accidents occur in tectonic coal seams in China due to the difficulty of gas drainage [3,4], bringing a threat of the production of underground coal mines and the safety of miners’ lives. Thus, tectonic coal is an important research object for coal mine disaster prevention and for the exploration and use of coal-bed methane resources [5–8].

Relative to non-tectonic coal, tectonic coal has low compression strength, low permeability, and a high absorption and desorption capacity. In the process of tectonic coal generation, considerable amounts of methane are produced when the stacked aromatic rings are shed as hydrocarbon chains. The abundant specific surface area of tectonic coal makes it a good storage medium for gas. However,
extreme fragmentation of particles can block micro-fractures in the coal and cause low permeability. In addition, this interval broken structure causes a lower mechanical stability in tectonic coal relative to non-tectonic coal. The tectonic coal layer is more prone to breaking under the impact of external factors, such as crustal stress, gas pressure, and explosion. This breakage causes internal coal and gas outburst and other coal mine disasters [9,10]. The presence of tectonic coal complicates the occurrence of gas and leads to considerable deviation in traditional gas forecasting methods. The existing data indicate that essentially all coal and gas outburst seams have developed tectonic coal with a certain thickness. In addition, the majority of initial outburst points occur near tectonic coal. Many studies have focused on the genesis, evolution, physical structure, and storage properties of tectonic coal [11,12]. Due to the need for coal-bed exploration and development, the storage properties of tectonic coal are often studied. These storage properties include the porosity, permeability, absorption, and desorption properties of tectonic coal [13,14]. However, the effective disaster prediction method for tectonic coal collapse is rare. Although some geophysical seismological methods have been introduced into mine safety prevention, the related coal and gas outburst disaster still appears. The most common field monitoring method is acoustic solution, such as acoustic emission (AE). The AE technique is based on monitoring the elastic waves generated by propagating and expanding micro cracks. Due to stress and other factors, a certain point in the material will break and release the elastic wave. The surface of the material will be captured by an AE probe as the elastic wave propagates. There are some standard parameters that contain plentiful information regarding the microstructure, and the physics background of AE techniques which have been described [15].

Recently, sudden disasters have been investigated by statistical physics, especially for earthquake and avalanche [16,17]. From the perspective of statistical physics, the catastrophic events share a similar dynamic evolution and without characteristic scale, which means that statistical rules work in different scales, like earthquake and rock sample failure in the laboratory [18]. Indeed, this robust similarity has been confirmed by earthquake catalog and silica glass failure [19]. In laboratory research, AE was usually adopted to investigate the statistical physical behaviors of porous material collapse [20].

Previous results showed that the probability distribution is related to the porous material’s damage situation [21,22]. Sandstone uniaxial collapse shows that the distribution exponents change from a non-critical steady state to an all-important precursor regime, which means that the prediction of the collapse is possible in principle [23]. This agrees well with discrete element computer simulations [24,25].

The tectonic coal could be seen as one kind of mechanical and thermal-damaged coal, and the probability distribution of AE should reflect the structural difference between tectonic and non-tectonic coal. Therefore, in this study, we introduce the probability density distribution of AE, and the multifractal of AE location points to investigate the deformation and failure process of tectonic and non-tectonic coal under uniaxial compression.

The main purpose of this study is first to show if tectonic coal and non-tectonic coal have different acoustic characteristics under compression, and whether the statistical physical analysis is sensitive to the collapse of tectonic coal, and can be used as potential disaster forecast technology.

2. Experiment

2.1. Materials for the Experiment

The tectonic coal was collected from Shihao coal mine, located in Qijiang district of Chongqing (Southwest of China), and the non-tectonic coal was collected from Xieqiao coal mine, located in Huainan City of Anhui Province (East of China). The coal bearing strata in the two areas are both Permian. However, geological activity is more active in western China than that in eastern, and the tectonic coal from western China is affected by geological activity, which makes it different from the same period non-tectonic sample, such as the volatile content of tectonic coal is only 1/3 that of non-tectonic coal (see Table 1).
Table 1. Proximate analyses and elemental analyses of coal samples.

| Parameters               | Tectonic | Non-Tectonic |
|-------------------------|----------|--------------|
| Moisture contents       | M<sub>a</sub> | 2.17%        | 2.72%        |
| Ash content             | A<sub>a</sub> | 8.50%        | 9.24%        |
| Volatile matter content | V<sub>daf</sub> | 10.67%       | 31.24%       |
| Elemental C content     | C<sub>a</sub> | 79.63%       | 73.73%       |
| Elemental H content     | H<sub>a</sub> | 2.02%        | 3.85%        |
| Elemental N content     | N<sub>a</sub> | 2.62%        | 2.56%        |
| Elemental S content     | S<sub>a</sub> | 1.96%        | 1.17%        |

Table 2 shows the maceral content analysis of the samples, the vitrinite content of tectonic coal is greater than the vitrinite content of non-tectonic coal, which also indicates that the geological influence leads to the enhancement of tectonic coal coalification.

Table 2. Maceral content.

| Parameters | Tectonic | Non-Tectonic |
|------------|----------|--------------|
| Vitrinite  | 83.1%    | 58.2%        |
| Liptinite  | 5.3%     | 9.0%         |
| Inertinite | 10.4%    | 31.2%        |

Tables 3 and 4 show the pore features of the coal samples. The porosity and specific surface area were acquired using the mercury intrusion method and low-temperature liquid nitrogen absorption, respectively. The macro pores in the coal mainly hosted laminar flow and slow laminar flow. Capillary condensation and gas diffusion occur in the meso pores. The proportion of meso pores in the tectonic coal was twice the proportion in the non-tectonic coal. In addition, the pore volume of the 10 to 20,000 nm pores was 3 to 7 times greater in the tectonic coal relative to the non-tectonic coal. Furthermore, the specific surface area of the tectonic coal was three times the specific surface area of the non-tectonic coal. These results indicate that the tectonic coal is good for methane gas absorption. The structure of tectonic coal is loose, and the mechanical properties of tectonic coal are poor.

Table 3. Pore size distribution derived from the mercury intrusion analysis.

| Diameter | Tectonic | Non-Tectonic |
|----------|----------|--------------|
| 100~0.1 mm | 38.97%   | 70.34%       |
| 10~100 nm  | 61.03%   | 29.66%       |

Table 4. Pore volume and specific surface area derived from low-temperature liquid nitrogen absorption.

| Parameters   | Tectonic | Non-Tectonic |
|--------------|----------|--------------|
| 1000~2000 Å   | 0.000918 cm³/g | 0.000186 cm³/g |
| 100~1000 Å    | 0.001668 cm³/g | 0.000468 cm³/g |
| 14~100 Å      | 0.001548 cm³/g | 0.000689 cm³/g |
| BET Surface Area | 3.2650 m²/g | 1.1130 m²/g |

The pore characteristics and surface morphology of tectonic coal and non-tectonic coal were observed with secondary electron (SE) scanning electron microscopy (SEM, TESCAN VEGA 3 LMH). The tectonic coal and non-tectonic coal samples were made into about 3 × 3 × 2 mm cubes for observation. Figure 1a shows the rough surface morphology and some developed microcracks of tectonic coal. Compared with tectonic coal, non-tectonic coal (Figure 1b) has a relatively smooth surface.
For both kinds of coal samples, four-prism test pieces were used. The four sides of the test pieces are perpendicular to the bottom surface, and the top surface and bottom surface are parallel. The height of sample is 100 mm, and the width of the bottom is 50 mm. Furthermore, the four sides are sanded and polished to improve the coupling between the probe and the surface of the test pieces. During the entire manufacturing process, the test piece maintained most of its integrity. For tectonic coal, it is prone to crumbling during cutting, so we first fixed the coal sample by cement before cutting, and then carefully cut and polished it.

2.2. Experimental Facilities

The experimental system is shown in Figure 2, which consisted of loading equipment and a real-time AE detection device. Loading equipment was SHIMADZU AGI-250 high-precision electric-servo digital experiment machine, equipped with a visual operation and high-speed data acquisition system, which could track the current load, stress and displacement values. In the compression, we adopted the displacement load control method with a loading rate of 0.1 mm/min. The AE acquisition device adopted the Physical Acoustics Company DISP AE system: 132 MB/SEC of data transmission speed; 150 mflops high-performance processing capabilities; minimum noise threshold value of 18 dB; frequency range was from 10 to 2.1 MHz (±1 dB) and 20,000 hits per second high-speed processing speed. The AE sensors were arranged on the coal sample’s side surface directly, and acoustically coupled with a sample by a thin layer of Vaseline, and this experiment has been undertaken with the simultaneous use of eight AE sensors. The elastic waves, generated by sample inner failure, were captured by AE sensors and were transferred into electronic signal waves, see Figure 1. According to the recommendation of Physical Acoustics Company, for natural rock samples the Peak Definition Time (PDT) is 35 µs, the Hit Definition Time (HDT) is 150 µs, and the Hit Lockout Time (HLT) is 300 µs. A proper setting of the PDT ensures the correct identification of the signal peak for rise time and peak amplitude measurements.
Figure 2. The sketch map of experimental system. (a) loading equipment, (SHIMADZU AGI-250 high-precision electric-servo digital experiment machine, Japan), and insert shows the coal sample and acoustic emission (AE) sensor arrangements, (b) real-time AE detection device. (c) the original AE signal feature extraction diagram, A proper setting of the peak definition time (PDT) ensures correct identification of the signal peak for rise time and peak amplitude measurements. Proper setting of the hit definition time (HDT) ensures that each AE signal from the structure is reported as one and only one hit. The AE system needs hit lockout time (HLT) to get ready for the next signal detection.

3. Results

The AE original amplitude spectrum for non-tectonic coal, and tectonic coal are shown in Figure 3a,b. The most common AE parameter for statistical analysis is absolute energy $E$, which can be calculated by fast numerical integration of the squared voltage of signals $E = \frac{1}{R} \int_{t_i}^{t_f} U^2(t)dt$, where $R = 10 \, \Omega$ is inner resistance, $U$ is the voltage signal. The amplitude dB follows this relation with voltage, $dB = [20 \lg (U_{peak}/1\mu V)]$.

The compressive stress curve and AE absolute energy of coal samples during the entire test process are shown in Figure 3c,d for non-tectonic coal, and tectonic coal. The entire compression process can be roughly divided into three stages. The first stage is the microstructure compaction stage (1). In this stage, the stress curve is concave, which reflects that the micro-porous fractures in the coal underwent a compaction process. In addition, the tectonic coal was more active than the non-tectonic coal. This result occurred because the extensive pores experience damage under the external stress and emit acoustic events. In this process, AE cumulative energy rarely occurs. When there is obvious AE cumulative energy, the stress curve begins to transform to a linear and elastic straight line. Therefore, the appearance of the cumulative AE energy may be considered as the end of this stage.
multiple AE signals. This result occurred because the micro-cavities combine to form a macroscopic weak surface. However, the coal body does not completely lose the loading capacity, and the entire coal structure shares the load. At this stage, the rate of AE events for non-tectonic coal is 5 to 10 times greater than that for tectonic coal.

The third stage is the flow failure stage (3). After a relatively large stress drop, the coal sample enters into a stage where the stress oscillates in a limited range but the strain increases. At this stage, the stress curves of the two coal samples generally enter a platform. However, the tectonic coal generally increases and the non-tectonic coal generally decreases, which is accompanied by a dramatic enhancement in AE cumulative energy. The number of AE events roughly maintains the level of the previous stage. At failure, both coal samples dramatically lose the loading capacity and release the AE signal.

4. Analysis and Discussion

4.1. Probability Density Function Distribution of AE Absolute Energy

Previous studies show that the probability density function of AE absolute energy in porous material collapse exhibits critical behavior, following the power law distribution [17,26]. Figure 4a shows the probability density function of AE absolute energy for both kinds of coal sample. The AE energy follows the power law very well, especially for the distribution of non-tectonic, which spans near seven energy decades. The slope of the power law line is the exponent which controls this distribution. In order to investigate this critical exponent in more detail, we use the ML (maximum likelihood) method [27] to study the AE energy probability density function distribution. ML avoids the choice of bins and construction of histograms. If the AE energy following the power law probability density function distribution, $P(E) \sim E^{-\epsilon}$, the ML estimated probability density function distribution

![Figure 3. (a,b) are AE amplitude for non-tectonic and tectonic coal. (c,d) are AE absolute energy spectrum, cumulative energy curves, and compression stress curves for non-tectonic and tectonic coal.](image-url)
exponent $\epsilon$ is: $\epsilon(E_{\text{min}}) = 1 + n \sum_{i=1}^{n} \ln \frac{E_i}{E_{\text{min}}}^{-1}$, and the ML curve leads to a plateau for the exponent $\epsilon$. Moreover, theoretical study shows [28] that the shape of ML curves shows if the AE data correspond to a unique density function distribution, or mixing of two different sources. Figure 4b shows the maximum likelihood curves for tectonic and non-tectonic coal. The shape of maximum likelihood curve for non-tectonic coal shows that a typical one fixed the power law distribution behavior, and the estimated exponent values from the shoulder of maximum likelihood curve (about 1.38) also agrees with the mean filed theory for fracture mechanism [16]. For tectonic coal, the maximum likelihood curves show mixing fixed points behavior. The ML curve of mixing shows the horizontally arranged S shape, the maximum corresponds to a lower bound of the high exponent. The minimum of the curve approximately corresponds to an upper bound of the low exponent. For the tectonic coal’s ML curves, the lower exponent is consistent with that of non-tectonic coal, so one source of the fixed point is also the fracture mechanism. Moreover, the higher exponent value is close to 1.7. The dashed curve comes from the theoretical prediction of mixing ML curve [28], which agrees with the result of tectonic coal well. This experimental exponent value is very similar to the theoretical prediction from friction source [29]. This result agrees with the material structure difference between these two kinds of coal samples. Non-tectonic coal is more intact, and the main collapse used by the crack propagation and fracture, while the tectonic coal has a weaker structure and even granular-like structure, which introduces the friction effect in the compression process.

**Figure 4.** (a) probability density distribution of absolute energy for non-tectonic and tectonic coal, and fitting by the power law function, (b) the power law exponent estimated from maximum likelihood curve, with error bar, and dashed curve is from the mixing maximum likelihood estimation.

### 4.2. Waiting Time Analysis of AE

The Figure 5 shows the probability density distribution of waiting times. Waiting time is the difference between the two starting times of adjacent hits (see Figure 2c). The adjacent hits can be grouped as defined: $\delta_j = t_j - t_{j-1}$, with $j$ labeling only the events with energy larger than a given threshold energy. $P(\delta)$ is the waiting time distribution function and indicates the probability to observe a waiting time for a threshold energy. The waiting time distribution result showed in Figure 5 is normalized by its average $<\delta>$. After normalization, all waiting time distributions $P(\delta)<\delta>$ collapse together [23, 30]. The waiting time distribution between non-tectonic and tectonic coal show obvious difference. For non-tectonic coal, all data in a single curve show double power law behavior. The power law exponents of small and large waiting time arguments are close to 1 and 2, respectively, which agrees well with previous studies about brittle materials failure, like sandstone [23], goethite [31], and even earthquake catalog [19]. For tectonic coal, only the small exponent value has been observed. The small distribution exponent associated with small waiting time, which was linked with the granular-like structure of tectonic coal, and it is consistent with the energy analysis above.
1.2 [34,35]. The ratio or ‘relative magnitude’ is stable, and can be defined as

\[ \Delta M = \log(E_{MS}/E_{AS*}) \]

The result agrees well with Båth’s law, with no significant differences between non-tectonic and tectonic coal.

4.3. Analysis of Aftershock and Båth’s Law

Unlike the distribution of energy and waiting time, some distributions are supposed to be stable and is not sensitive with material structure. In earthquake catalog analysis, distribution of aftershock and Båth’s law holds from worldwide to local scales, and for quite different tectonic environments [32]. The number of aftershocks (AS) is described [33] as often employed for the analysis of earthquakes. This states that the number of AS decays as the power law after each mainshock (MS). We define MS as AE signals with energies \( E_{MS} \) between \( 10^k \) to \( 10^{k+1} \) aJ, with \( k = 1, 2, \) and 3. The sequence of AS is then continued until another MS is found, which terminates the AS sequence. The results of distribution of aftershock are shown in Figure 6 with different main shock energy levels. The exponent of aftershock distribution was about −1 for both tectonic and non-tectonic coal. The Båth’s law states that the average ratio of the energy magnitudes of one MS and the largest aftershock, \( AS* \), is around 1.2 [34,35]. The ratio or ‘relative magnitude’ is stable, and can be defined as \( \Delta M = \log(E_{MS}/E_{AS*}) \).

Figure 7 shows the relative magnitude as a function of mainshock energy \( E_{MS} \), and the result agrees well with Båth’s law, with no significant differences between non-tectonic and tectonic coal.

Figure 5. Probability density distribution of waiting time for (a) non-tectonic and (b) tectonic coal. The waiting time distribution of non-tectonic coal follows the typical brittle fracture’s double power law behavior, while the waiting time distribution of tectonic coal shows the single power law.

Figure 6. Rate of aftershocks per unit time, \( r \), as function of the time lapse to the main shock for different main shock energy levels. The black dashed line indicates the Omori’s behavior with slope = −1, (a) for non-tectonic and (b) tectonic coal.
Figure 7. Relative magnitude $<\Delta M>$ versus mainshock energy for non-tectonic and tectonic coal. Dashed horizontal line (1.2) indicates the prediction of Båth’s law.

4.4. Multi-Fractal Analysis of AE

The next step is the location event measurements. Investigations showed that the spatial distribution of earthquake epicenters manifests statistically self-similar properties in a wide range of scales. It can be treated as fractal or multifractal [36]. The distribution of earthquakes on the fault are due to the heterogeneity of stress or strength on the fault. Since this fractal dimension of the spatial distribution of triggered earthquakes results in part from the fractal structure of the fault system [37,38], the multifractal approach is appropriate to investigate the details of these dynamics. Considering the similarity between an earthquake and rock collapse, in this paper we applied a multifractal analysis of the events distribution dynamics during the compressive process. We also applied multifractal analysis of the seismicity distribution dynamics prior to strong earthquakes [39,40]. Dispensing with 2D analysis, we studied the 3D distribution of the AE centers.

As shown in Figure 8, the points in the cubic specimen are AE location centers, namely points of energy released in the failure experiment. Because of the heterogeneity of the specimens, AE centers are not evenly distributed; most of them are in the bedding and fissure zone, similar to seismic zones. The inset is ideally divided into cubic unit cells (side length L) for the sake of further statistical multifractal analysis. We define distribution function as follows [40–42]

$$P_j(L) = \frac{N_j(L)}{N}$$  \hspace{1cm} (1)

where $N_j(L)$ is the number of AE events occurred in the unit with $j$ and size $L$ of subperiod, $N$ is the total number of events in the whole time series.

Renyi entropy [40] of order $q$, $d(q)$ is defined as a slope of the best fit line of Renyi entropy $I_q(L)$ versus $1/L$, in a log–log plot

$$\ln(I_q(L)) = \frac{\ln(\sum_j p_j^q(L))}{1-q}, \text{ if } q \neq 1$$  \hspace{1cm} (2)

$$\ln(I_q(L)) = -\sum_j p_j(L) \ln(p_j(L)), \text{ if } q = 1$$  \hspace{1cm} (3)

$$d(q) = \lim_{L \to 0} \frac{\ln(I_q(L))}{\ln(\frac{1}{L})}$$  \hspace{1cm} (4)

where $d(2)$ is the correlation dimension of the considered AE distribution.
Here, we use the distribution function and calculate the correlation dimension $d(2)$. These results are shown in Figure 9. The correlation dimension variations for non-tectonic coal were greater than those for tectonic coal. Because only a few AE signals occurred at the microstructure compaction stage, the variation in the correlation dimension began at the second stage during the near-linear elastic stage. The stress drops of non-tectonic coal at this stage caused a clear fluctuation in the correlation dimension. However, because the degree of the stress drop was not large, the magnitude of the fluctuation in the correlation dimension was not large. At this stage, variations in the correlation dimension of tectonic coal are not pronounced. At the flow failure stage, the features exhibited by two coals are similar, and the correlation dimension fluctuates as the stress changes. In this stage, the state of change is more regular and more obvious relative to the previous stage, and generally exhibits a downward trend. This decreasing agrees with previous earthquake studies [39,40]. This result may provide an approach for predicting instability and failure.

![Figure 8](image-url)  
**Figure 8.** One typical spatial distribution of AE location hypocenter for non-tectonic, and there are 1051 hypocenters have been captured in this sample. Since grids are too dense, the large figure does not show cells. The inset shows AE centers and cubic unit cells with grids. (Unit: mm).

![Figure 9](image-url)  
**Figure 9.** Correlation dimension results of the AE hypocenters distributions, AE energy and compression stress for (a) non-tectonic and (b) tectonic coal.

The data analysis technology used in this study can be easily implemented online, and it can be used for continuous monitoring of the coal mine and other underground engineering. However,
the laboratory results should always be taken with caution, and extensive filed testing is needed to determine the true forecasting ability of this method.

5. Conclusions

The AEs of the uniaxial compression experiment for tectonic coal and non-tectonic coal have been captured and studied statistically. For both kinds of coal, the probability density function of AE energy follows the power law well, but with different power law exponent values. The AE energy distributions show the AE signals of non-tectonic coal mainly comes from the fracture source, while the probability density function distribution of tectonic coal is a combination of fracture and friction effects. Only the waiting time distribution of non-tectonic coal follows the typical brittle fracture’s double power law; the waiting time distribution of tectonic coal shows the single power law with smaller exponent value, which is associated with its granular like microstructure. The distribution of aftershock and Båth’s law are not influenced by the different microstructures between two kinds of coal. At last, the correlation dimension results for the distribution of AE hypocenters indicate that the rough continuous decrease in dimension might be a precursor to devastating destruction. This study just considers the uniaxial compression condition; the future research direction is to study more realistic underground environmental conditions, such as triaxial and multi-fields coupling, and carry field experiment. Moreover, the coal samples in this study come from Permian; further related research can consider samples from different geological periods and with different coalification degrees.

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