DIRECT TENSILE MECHANICAL PROPERTIES AND ACOUSTICE MISSION CHARACTERISTICS OF COAL AT DIFFERENT DEPTHS OF PINGDINGSHAN MINING AREA

by

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Uncertainties in the basic theory of shallow mining that continues to be used in deep mining result in frequent engineering disasters with deep characteristics. Thus, it is necessary to elucidate the mechanism of mechanical deformation and failure behavior of coal from shallow to deep depths. Coal samples from the same coal seam in the Pingdingshan mining area of Henan Province were obtained at depths of 300 m, 600 m, 700 m, 850 m, and 1050 m. Direct tensile tests were conducted on the coal samples obtained at different depths. The tensile strength exhibits as low decreasing trend with increasing depth, reaching a minimum at 1050 m. This variation trend is consistent with that of acoustic emission cumulative ring-down counts and the cumulative energy measured during tensile tests on coal samples obtained at different depths. These conclusions provide a reference for the differences between the mechanical behavior of shallow and deep coal, which has both theoretical and engineering significance.

Key words: *different depths, coal, acoustic emission, direct tensile strength*

Introduction

After several years of development, the mining depth has been gradually increasing, the characteristics of *high temperature, high geostress, and high permeability* was highlighted by Zhou *et al*. [1]. Shallow rock mechanics theory and support methods are still used in many deep mines and the difficulty of adapting these schemes to different depths in coal mines has resulted in prominent engineering disasters characterized by deep failure in [2]. In particular, tensile mechanical properties are essential rock characteristics, that significantly affect engineering safety. Therefore, the mechanism of tensile mechanical deformation and the energy evolution process of coal were elucidated from shallow to deep depths by Xie *et al*. [3].

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A dynamic tensile impact loading test to investigate the physical and mechanical properties of granite at different depths was conducted by Man *et al*. [4], and changes in the physical characteristics of deep granite under environmental action affected the dynamic tensile strength. With increasing depth, the coal structure gradually becomes denser, and the content of carbonaceous organic compounds, the ultrasonic wave velocity and the coal density gradually increase were found by Liu *et al*. [5]. With increasing basalt depth, the density, uniaxial compressive strength, uniaxial tensile strength, triaxial compressive strength, elastic modulus, cohesion and internal friction angle increase linearly, found by Zhou *et al*. [6] and Zuo *et al*. [7], whereas Poisson's ratio decreases linearly, and both the input energy and dissipation energy at failure increase. Data for the in-situ stress environment and physical characteristics of coal at different depths in Pingdingshan mining area was obtained by Zhang *et al*. [8], which were used to propose a two-factor simulation experimental method.

The acoustic emission (AE) of rock is a transient elastic wave phenomenon generated by the rapid release of energy in the internal local areas of rock materials under the influence of external stress conditions or temperature in Li *et al*. [9]. The AE technique is widely used to synchronously monitor the development and propagation of internal microcracks in rock during deformation and failure processes and to accurately locate microcracks in space. The spatiotemporal evolution of AE events reflects the fracture and damage laws of rocks under different loading conditions [10-12]. The mechanical properties and damage evolution characteristics of coal under direct tensile loading investigated by Zhang *et al*. [13] and established an AE-based damage model. A uniaxial compression AE test of coal samples soaked in water for different times was conducted by Jia *et al*. [14] and investigated the influence of the soaking time on the AE characteristics and spatial fractal dimensions during the coal deformation and failure process. Laboratory experiments to simulate mining-induced behavior conducted by Yang *et al*. [15] and utilized AE techniques to capture the variation in AE temporal and spatial parameters synchronously. The obtained typical AE characteristics of coal under deep mining provided an important basis for studying the mechanical behavior and fracture mechanisms in deep mining coal.

However, most previous studies have focused on the mechanical properties and AE activity differences of coal under different loading conditions at the same depth. Few studies have been conducted on the tensile mechanical properties of rocks at different depths, especially those obtained from direct tensile tests. As the tensile properties of rock are an important mechanical index, it is necessary to conduct direct tensile tests to investigate the tensile mechanical behavior of coal at different depths.

Methodology

Experiments were performed in which the MTS815 flex test GT rock mechanics test system of Sichuan University, fig. 1, was used to collect the loading and stress deformation data, and the PCI-II AE test system manufactured by the American Physical Acoustics Company (PAC) was used to perform AE tests. The MTS815 provides a maximum tensile load of 2300 kN, and the range of the axial extensometer is – 4 ~ +4 mm. Considering that coal generally has a low tensile strength, a force sensor with a measuring range of ±25 kN was used

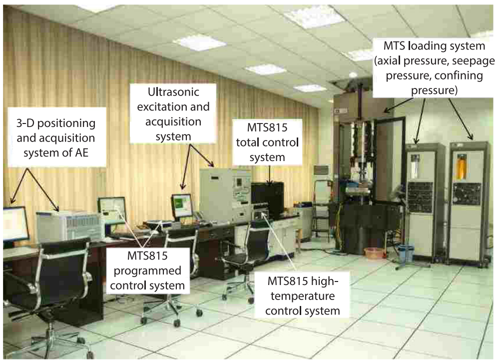


Figure 1. The MTS815 flex test GT rock mechanics test system

to ensure accurate testing. The AE test was performed using a nano-30 miniature AE sensor which has a resonant response at 300 kHz and a good frequency response over the 125~750 kHz range. The small sensor size was an ideal for the test. The preamplifier gain was 40 dB.

The Pingdingshan mining area was selected as the research base. In order to ensure the depth as the main influencing factor at depths of the experimental results, and coal samples were obtained from five mining faces of 300 m, 600 m, 700 m, 850 m, and 1050 m of the JI 15 coal seam. The coal blocks taken from the site were processed into standard coal samples (ϕ 50 mm, H = 100 mm) based on the following recommendations by ISRM. The non-parallelism of both ends of the coal samples should not be greater than 0.05 mm. Deviations in the diameter of the upper and lower ends of the coal samples should not exceed 0.3 mm. The coal sample surface should be smooth, and stress concentration induced by surface irregularities should be avoided.

The coal samples obtained at different depths (300 m, 600 m, 700 m, 850 m, and 1050 m) were prepared for tensile testing. Five coal samples were prepared corresponding to each depth *i.e.*, a total of 25 samples were tested. A high strength binder was used to bond the ends of each sample with two rigid tensile joints. The bonded samples are shown in fig. 2.

Figure 2. Bonded samples obtained at different mine depths

Test results

Direct tensile mechanical properties of coal with different depths

The direct tensile stress-strain curves for the coal samples obtained at different depths are shown in fig. 3. The tensile strength of coal can be calculated using:

$$R_t = \frac{P}{A} \tag{1}$$

where R_t is the direct tensile strength of the specimen, P – the axial maximum load of the specimen, and A – the cross-sectional area of the specimen.

The direct tensile strengths of coal samples obtained at different depths in the Pingdingshan mining area are shown in tab. 1. Some samples were damaged during the pre-test installation, or the data recorded during the test were too low to obtain an accurate tensile strength. The results in the table show that the tensile strength of coal at different depths in the Pingdingshan mining area is generally small and that the maximum tensile strength does not exceed 0.6 MPa. The tensile strain corresponding to the peak stress is also small, where the maximum does not exceed 0.3%. The tensile bearing capacity of coal is far lower than the compression bearing capacity. The minimum uniaxial compressive strength of coal at the five different depths is 4.58 MPa. The coal deformation for tensile failure is also much smaller than that corresponding to compression failure. The minimum uniaxial compressive deformation of coal at the five different depths is 0.6%. During the coal tensile test, cracks and damage began to expand from the weak surface or initial hole cracks in the coal material. The damage accumulated with the continuously increasing load, and gradually converged and connected along the primary cracks until tensile failure finally occurred.

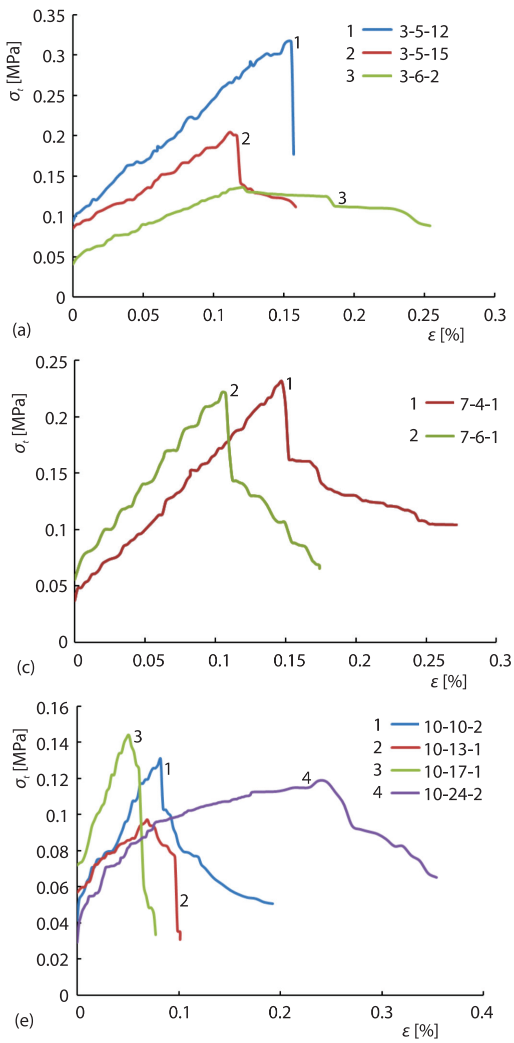


Figure 3. Direct tensile stress strain curves for coal samples obtained at different depths; (a) 300 m, (b) 600 m, (c) 700 m (d) 850 m, and (e) 1050 m

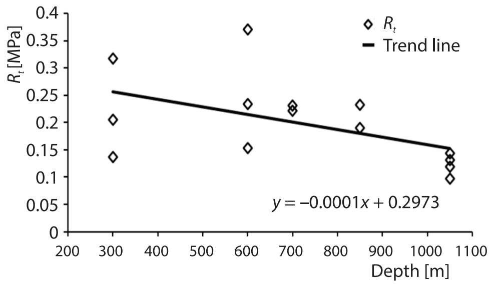


Figure 4. Variation in coal tensile strength with depth

The tensile strength and deformation of Pingdingshan coal are generally relatively low, but the coal tensile mechanical properties vary with the depth. The coal direct tensile strength *vs.* depth are shown in fig. 4. The coal tensile strength gradually decreases with increasing depth. The tensile strength reaches a minimum at a depth of 1050 m. The confining pressure of deep coal is larger than that of shallow coal, increasing the number of cracks produced during unloading, which leads to a decrease in the coal tensile strength. Thus, the tensile strength decreases with increasing depth. According to the relation curve of tensile stress and depth, the formula of tensile stress and depth is fitted:

$$R_t = KH + B \tag{2}$$

where R_t is the direct tensile strength of the specimen, H – the depth of the sample, K – the coefficient, and B – the coefficient.

Table 1. Direct tensile test results

Samples	D [mm]	H [mm]	ρ [gmm^{-3}]	R_t [MPa]	ε [%]	Depth [m]
3-5-12	49.42	100.00	1.349	0.317	0.153	300
3-5-15	49.43	99.96	1.345	0.205	0.112	
3-6-2	49.38	99.78	1.337	0.137	0.121	
6-8-6	49.27	100.71	1.407	0.234	0.114	600
6-22-2	49.37	100.33	1.402	0.153	0.098	
6-23-3	49.32	100.14	1.414	0.370	0.266	
7-4-1	49.15	100.57	1.356	0.231	0.147	700
7-6-1	49.31	100.61	1.346	0.222	0.105	
85-8-3	49.30	99.83	1.461	0.232	0.155	850
85-14-1	49.54	99.74	1.385	0.190	0.146	
10-10-2	48.50	100.23	1.334	0.131	0.082	1050
10-13-1	48.89	100.17	1.326	0.097	0.069	
10-17-1	48.63	100.18	1.314	0.144	0.051	
10-24-2	48.91	100.28	1.334	0.119	0.237	

The coal direct tensile strength decreases with increasing depth in the Pingdingshan coal mine, and the coal has a far lower ability to bear a tensile load than to bear a compressive load. Thus, mine safety accidents are more likely to occur when coal is in the tensile stress state than from stress concentration in the compression area. Therefore, the tensile stress area during the mining process should be strictly controlled, especially in deep regions.

Kachanov [16] defined the damage variable:

$$D = \frac{A_d}{A} \tag{3}$$

where D is the damage factor, A_d – the cross-sectional area of the damage, and A – the cross-sectional area of the specimen.

Lemaitre [17] proposed the hypothesis of strain equivalence. A constitutive equation for a damaged material was established based on a simple equivalent transformation of the constitutive equation of the raw material. The application of eq. (4) facilitated the rapid development of damage mechanics. The equation is derived by assuming that the strain in the damaged state of an elastic material under a stress, σ', is equal to the strain, ε, in a fictitious non-destructive state under the action of an effective stress, σ':

$$\sigma_1 = \frac{E'}{E}\sigma' = E\varepsilon(1-D)+2\mu\sigma_3 \tag{4}$$

where σ_1 is the axial stress, E – the deformation modulus of the material in the undamaged state, E' – the deformation modulus of the damaged material, σ' – the effective stress, ε – the strain, D – damage factor, μ – the Poisson's ratio, and σ_3 – the confining pressure.

Table 2 shows the damage factors after failure calculated using eq. (4). Similar damage factors are obtained after coal failure at different depths. The experimental results show that the damage factor after failure increases with the depth. The damage factor reaches a maximum at a depth of 1050 m. The deeper the coal is buried, the higher the damage factor is after the direct tensile test. These results verify that the higher the confining pressure of deeply buried coal is, the more cracks there are after unloading, resulting in a lower tensile strength.

Table 2. Calculated damage factor for different samples after failure

Samples	D after failure	Average, D
3-5-12	0.794	0.856
3-5-15	0.892	
3-6-2	0.882	
6-8-6	0.829	0.861
6-22-2	0.873	
6-23-3	0.880	
7-4-1	0.878	0.866
7-6-1	0.853	
85-8-3	0.877	0.873
85-14-1	0.868	
10-10-2	0.851	0874
10-13-1	0.853	
10-17-1	0.881	
10-24-2	0.911	

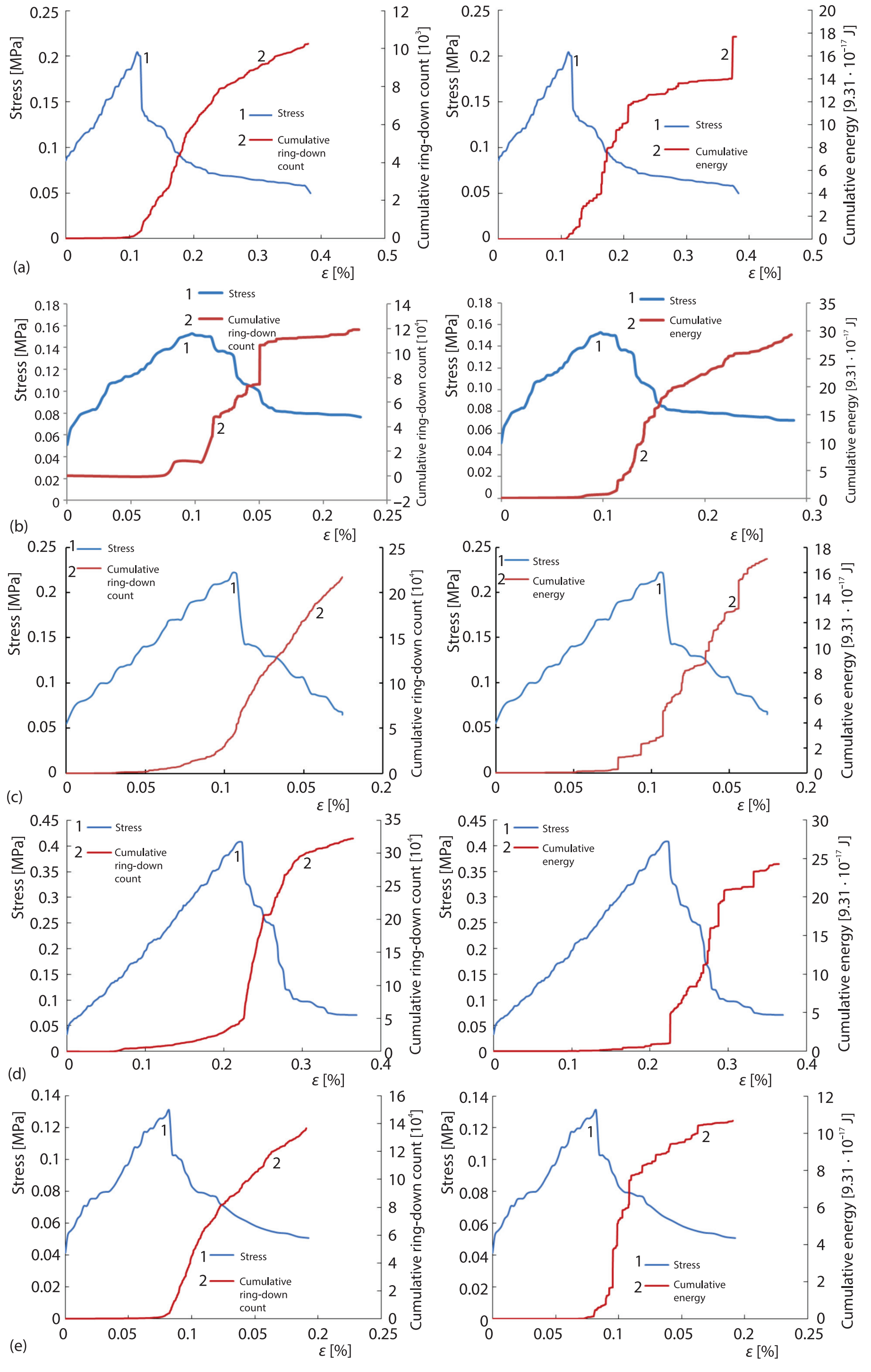
The AE characteristics of coal samples obtained different depths under a direct tensile load

Under a tensile load, the coal samples obtained at different depths not only shows the differences in mechanical properties, but also is accompanied with AE events. The AE characteristics also change with depth. The differences in the AE characteristics further explain the mechanical behaviors of coal samples obtained at different depths under a direct tensile load. Figure 5 shows the evolution law for the AE parameters for the coal samples obtained at different depths under a direct tensile load. It is concluded from fig. 5 that a small AE signal is produced in coal before the stress peak occurs during the direct tensile test, and almost no AE signal is generated as the strain increases. The AE cumulative ring-down count and the AE cumulative energy are very low in the early stage, whereas rapid AE generation begins near the peak stress and post-peak stage. The AE cumulative ring-down count and AE cumulative energy begin to increase rapidly near the peak stress, and the steep growth curve reaches a maximum at the peak stress.

Combined with eq. (3), the damage factor can be defined by the count of rings:

$$D = \frac{F_d}{F_c} \tag{5}$$

where D is the damage factor, F_d – the cumulative AE ring count, and F_c – the cumulative AE ringing count when the specimen is completely lost bearing capacity. The AE damage evolution



Figire 5. The AE evolution of coal samples obtained at different depths during direct tensile test; (a) 300 m, (b) 600 m, (c) 700 m, (d) 850 m, and (e) 1050 m

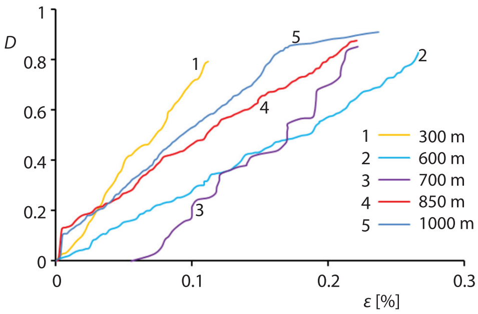


Figure 6. The AE damage evolution curve of coal with different depth

curve of coal with different depth is shown in fig. 6. It shows that the damage factor after failure increases with the depth. In the elastic stage, the trend of damage increases linearly with strain.

Combined with eq. (5), the damage constitutive equation of rock under triaxial compression condition based on AE ringing count can be deduced:

$$\sigma_1 = \frac{E'}{E}\sigma' = E\varepsilon\left(1 - \frac{F_d}{F_c}\right) + 2\mu\sigma_3 \tag{6}$$

where σ_1 is the axial stress, E – the deformation modulus of the material in the undamaged state, E' – the deformation modulus of the damaged material, σ' – the effective stress, ε – the strain, F_d – the cumulative AE ring count, F_c – the cumulative AE ringing count when the specimen is completely lost bearing capacity, μ – the Poisson's ratio, and σ_3 – the confining pressure.

Conclusion

Direct tensile tests were performed on coal samples obtained at different depths in the Pingdingshan mining area, and the results for the tensile mechanical properties and AE evolution law of coal are presented as folows.

- The coal tensile strength at different depths in the Pingdingshan mining area decreases gradually with increasing depth and reaches a minimum at 1050 m.
- The damage factor after coal failure exhibits an inverse variation law with the depth.
- The deeper the coal is buried, the higher the damage factor is after the direct tensile test.

Pingdingshan coal under a direct tensile load mainly undergoes axial extension: the main failure modes are tensile fracture near the middle of the sample, and the fracture is nearly horizontal, corresponding to the fracture characteristics of brittle materials. Few failure characteristics can be observed along the inclined plane of the samples. Low AE occurs in coal samples obtained at different depths before the 50% peak stress during the direct tensile test, and a large number of AE signals only begin to occur near the peak stress and during the post-peak stage. The AE characteristics obtained during direct tensile tests on coal samples obtained at different depths are consistent with the tensile mechanical properties of the samples.

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Nomenclature

A – cross-sectional area of the specimen, [m^2]
A_d – the cross-sectional area of the damage, [m^2]
E – deformation modulus of undamaged state, [GPa]
E' – deformation modulus after damage, [GPa]
H – height, [mm]
P – axial load of the specimen, [kN]
R_t – tensile strength, [MPa]

Greek symbols

ρ – density, [kgm^{-1}]
σ' – effective stress, [MPa]
σ_3 – confining pressure, [MPa]
σ_1 – axial stress
ϕ – diameter, [mm]

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