THE MECHANICAL PROPERTIES AND FRACTAL CHARACTERISTICS OF THE COAL UNDER TEMPERATURE-GAS-CONFINING PRESSURE

by

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Deep mining is the most important way to obtain the resource in China now. Thus, rock is the main objective that the deep mining will encounter. Meanwhile, the frequent catastrophes in deep mining such as rock burst, coal and gas bursts, roof caving, water bursts, is the most serious problem. To have a better understanding of the mechanisms of fracture and the laws of damage evolution of rock and coal under deep environment, in this paper, the micro- and meso-scale method is employed to study the behavior of coal under different temperature, confining pressure and gas pressure. Then, the significance of the effect of temperature, confining pressure, and gas pressure on mechanical parameters is analyzed by using the ANOVA method. The fractal study of coal failure pattern by employing the SEM test and fractal dimension was carried out. The fractal dimension of coal fractures was calculated by using the box-covering method. Then, the effects of all factors on the fractal dimension of coal fractures were analyzed.

Key words*: temperature, gas pressure, mechanical test, SEM test fractal dimension*

Introduction

Deep mining is the most important way to obtain the resource in China now [1]. Thus, rock is the main objective that the deep mining will encounter. Meanwhile, the frequent catastrophes in deep mining such as rock burst, coal and gas bursts, roof caving, water bursts, are the most serious problem. This indicate that the understanding and knowledge of the physical and mechanical behavior of rocks cannot yet fully meet the needs of engineering design. The mechanisms of fracture and the laws of damage evolution of rock and coal under deep environment in the micro- and meso-scale has theoretical and practical significance.

At present, a large number of studies have shown that temperature, confining pressure, gas and other factors have important influence on the Mechanical properties of coal [2]. Du [2] obtained that the elastic modulus and compressive strength of coal increased with in-

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creasing confining pressure through triaxial tests. Li *et al.* [3] obtained that the confining pressure improves the mechanical properties of coal, and the effective stress improves the mechanical properties of coal in the triaxial compression test of gas-bearing coal. Meng [4] conducted triaxial compression tests of sandstones under different temperature and pressure conditions. The results showed that the temperature had a weakening effect on the strength and stiffness of sandstone, while confining pressure had a strengthening effect. Zha [5] carried out triaxial tests of coal under different temperatures and found that there are differences in the effect of temperature on the compression characteristics of coal.

It is well known that fractures after coal failure record its fracture process, and information about the fracture mechanism is stored on the fracture. At present, the analysis of rock fractures mainly uses fractal theory. For example, Babadagli [6] studied fractal characteristics of rock fracture surfaces under tension, and found that there exists a trend between the fractal dimension and loading rate. Ren [7] carried out a sandstone fracture test and analyzed the relationship between fracture fractal dimensions and loading methods. Ai [8] the existing method for calculating the fractal dimension of rock fractures is mainly the box covering method. Ai has improved it and verified the effectiveness of the method through experiments.

However, the study on the changes of mechanical properties and fractal characteristics of coal under the different temperature, gas and confining pressure is not enough. Therefore, in this paper, the orthogonal test of coal under different temperatures, different confining pressures and different gas pressures was carried out. The changes of the mechanical parameters and the fractal characteristics of fractures of coal under the effects of temperature, confining pressure and gas are analyzed.

Table 1. Design of orthogonal table

Group No.	T [°C]	G [MPa]	C [MPa]
M20-0-0	20	0	0
M20-1-4	20	1	4
M20-3-8	20	3	8
M40-0-4	40	0	4
M40-1-8	40	1	8
M40-3-0	40	3	0
M80-0-8	80	0	8
M80-1-0	80	1	0
M80-3-4	80	3	4

T, G, and C represents temperature, gas pressure, and confining pressure, respectively

Figure 1. Location of the coal samples

Mechanical test of the coal

Test design and specimen preparatio

To carry out a comprehensive test, a lot of manpower and material resources are required, 54 samples required for two repeated tests. It is difficult to meet such conditions in the test. Therefore, efficient test methods are necessary for multi-factor and multi-level tests.

Orthogonal test [9] is an effective test method for studying multi-factor and multi-level tests. Orthogonal table, is the basic tool for orthogonal test, which is based on the combination theory. The orthogonal table designed for this study is shown as tab. 1. Two specimens are tested in each group. The group number denotes the test condition of the group, for example, M20-3-8 represents that this group of specimen will be tested at the condition of 20 °C, 3 MPa gas pressure, and 8 MPa confining pressure.

The coal samples are collected from Shoushan mine in Xuchang, Henan Province, China as shown in fig. 1. The depth of the working face is 580~705 m and the gas pressure is 1.5-2.0 MPa and the gas content is 20-22 m^3 per tonne. The composition of coal samples is analyzed by X-ray diffraction (XRD). As shown in fig. 2, the main components of coal samples are calcite, kaolinite and quartz. Cutting and polishing work of the cylindrical cores are carried out by a diamond cutter with an acute blade and a grinder, respectively. The specimens are prepared in general accordance with ISRM standard [10]. The height and diameter of the test specimens are 100 mm and 50 mm.

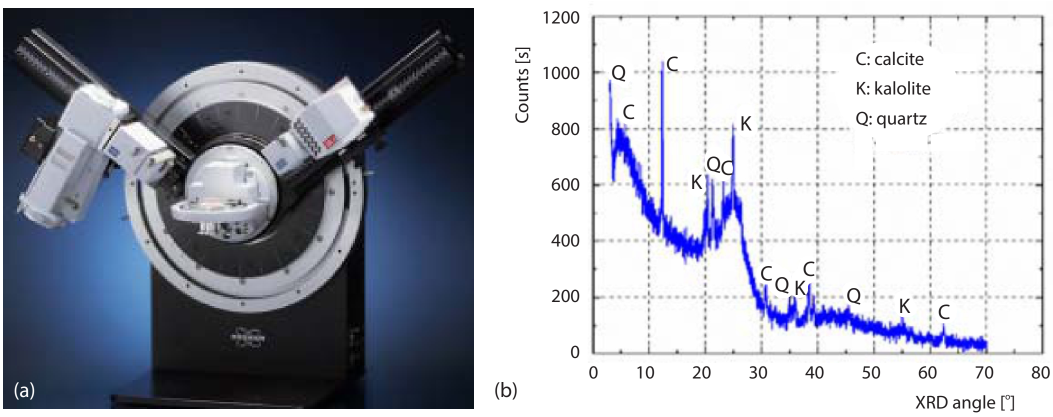

Figure 2. The XRD test on the coal; (a) X-ray equipment, (b) X-ray testing results

The test is carried on by using the TAW-2000 servo-control rock triaxial testing facility and pulse gas facility as shown in fig. 3. The experimental process is:
– to install the sensor and fix the specimen in the pressure chamber,
– to zero the readings of axial and radial sensors,
– to apply the confining pressure (for triaxial test),
– to heat up the triaxial cell (for tests at 40 °C and 80 °C),
– to apply the confining pressure (for triaxial test),
– to apply gas pressure, and
– to apply the axial load at an axial strain rate of about $3.3 \cdot 10^{-6}$/s until the specimen broken.

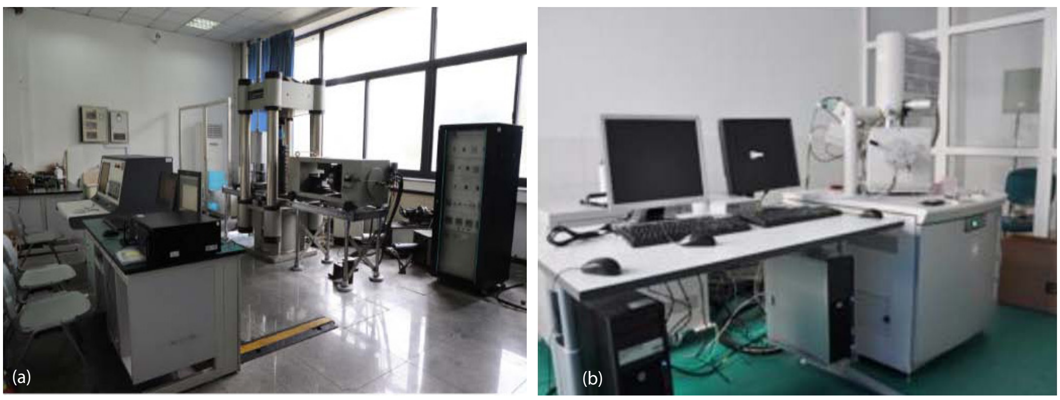

Figure 3. Experimental facility; (a) mechanical test system, (b) SEM test equipment

Test results and analysis

Mechanical parameters and analysis

According to tab. 2 and fig. 4, it's can be concluded that there are obviously different within the peak stress, denoted as σ_p elastic modulus, denoted as E and poisson's ratio, denoted as μ of coal. Therefore, analysis the effect of various factors on σ_p, E and μ of coal. by using the ANOVA.

Table 2. Summary of test data

Group No.	σ_p [MPa]	ε_1	E [GPa]	μ
M20-0-0-1	6.55	0.00898	1.48	0.19
M20-0-0-2	6.06	0.00505	1.95	0.17
M20-1-4-1	12.12	0.00623	2.76	0.37
M20-1-4-2	13.53	0.00687	3.30	0.30
M20-3-8-1	24.65	0.00708	3.64	0.27
M20-3-8-2	22.35	0.00683	3.60	0.25
M40-0-4-1	15.85	0.00884	2.11	0.18
M40-0-4-2	9.87	0.01562	1.26	0.31
M40-1-8-1	19.71	0.00848	3.83	0.26
M40-1-8-2	20.57	0.00624	4.06	0.39
M40-3-0-1	9.13	0.00530	1.70	0.36
M40-3-0-2	12.39	0.00640	2.31	0.24
M80-0-8-1	18.76	0.00958	3.48	0.26
M80-0-8-2	14.49	0.00590	3.10	0.28
M80-1-0-1	11.20	0.00515	2.79	0.29
M80-1-0-2	9.35	0.00495	3.19	0.25
M80-3-4-1	27.60	0.00895	4.19	0.41
M80-3-4-2	18.42	0.0054	4.56	0.34

σ_p, ε_1, E, and μ represents peak stress, axial strain, elastic modulus, poisson's ratio, respectively

Table 3. The ANOVA results of peak stress

Factor	Squared sum of deviation	df	Mean square	F	Significance level
G	284.739	1	284.739	24.659	**
T	175.892	1	175.892	15.233	**
C	629.517	1	629.517	54.519	**
Error	173.203	15	11.547	–	–
Total	1263.351	18	–	–	–

It can be seen from tabs. 3-5 that all factors have a significant effect on the elastic modulus, poisson's ratio, and peak stress of coal. The significant level of confining pressure and gas pressure on the σ_p, E, and μ is above 95%. The significant level of temperature on the σ_p and E is above 95%. But the significant level of poisson's ratio is 90%.

Table 4. The ANOVA results of elastic modulus

Factor	Squared sum of deviation	*df*	Mean square	*F*	Significance level
G	11.817	1	11.817	19.774	**
T	16.548	1	16.548	27.691	**
C	9.927	1	9.927	16.612	**
Error	8.964	15	0.598	–	–
Total	47.256	18	–	–	–

Table 5. The ANOVA results of poisson's ratio

Factor	Squared sum of deviation	*df*	Mean square	*F*	Significance level
G	0.041	1	0.041	3.218	*
T	0.239	1	0.239	19.312	**
C	0.075	1	0.075	6.02	**
Error	0.186	15	0.006	–	–
Total	0.541	18	–	–	–

**, * Significance level larger than 95% and 90%, respectively, the same blew

The influence of various factors on σ_p, E, and μ

The significance of each factor was studied, but the quantified relationships among them have not yet been analyzed. Table 6 summarizes the relationships of confining pressure, *C*, temperature, *T*, and gas pressure, *G*, with the mechanical parameters obtained in some previous studies. It can be observed that the relationship between peak stress, elastic modulus, Poisson's ratio and temperature, confining pressure and gas pressure can be approximated by linear model. The non-linear part of the non-linear model is very small compared with the linear part. In this study, linear models will be used to describe the relationship between various factors and mechanical parameters of coal.

As shown in tab. 7, the significance of each factor's linear fitting to mechanical parameters can be expressed:

$$E(T,C,G) = 0.013T + 0.131C + 0.434G + 1.346 \tag{1}$$

$$\sigma_p(T,C,G) = 0.042T + 1.372C + 2.38G + 4.524 \tag{2}$$

$$\mu(T,C,G) = 0.001T + 0.006C + 0.009G + 0.214 \tag{3}$$

where $E(T, C, G)$, $\sigma(T, C, G)$, and $\mu(T, C, G)$ are the functions related to the paremeters T, C, and G, respectively.

Table 6. Relationship between *T*, *C*, *G* and rock mechanics parameters

No.	Property	Factor	Equation form	Parameters	Test range	Ref.
1	σ_p	T	$\sigma_p = kT + b$	$k = –0.12$ $b = 23.54$	20 °C ≤ T ≤ 80 °C	Xu *et al*. [11]
2	E	T	$E = kT + b$	$k = –2.61$ $b = 557.2$		
3	μ	T	$\mu = kT + b$	$k = –0.0014$ $b = 0.277$	20 °C ≤ T ≤ 60 °C	
				$k = 0.0043$ $b = –0.07$	60 °C ≤ T ≤ 80 °C	
4	σ_p	T	$\sigma_p = k_1T^2 + k_2T + b$	$k_1 = –0.002$ $k_2 = 0.143$, $b = 149$	25 °C ≤ T ≤ 700 °C	Yin *et al*. [12]
5	E	T	$E = k_1T^2 + k_2T + b$	$k_1 = 9 \cdot 10^{-6}$ $k_2 = 0.004$, $b = 31.1$		
6	σ_p	C	$\sigma_p = kC + b$	k =3 .477 $b = 45.217$	0 MPa ≤ C ≤ 24 MPa	Yang *et al*. [13]
7	E	C	$E = k_1C^2 + k_2C + b$	$k_1 = –4.68$ k_2 =2 17.09 $b = 4793$		
8	E	C	$E = kC + b$	$k = 0.2$ $b = 0.73$	6 MPa ≤ C ≤ 7.5 MPa	Li [14]
9	μ	C	$\mu = kC + b$	$k = –0.0176$ $b = 0.323$		
10	E	G	$E = kG + b$	$k = –0.546$ $b = 3.913$	2.5 MPa ≤ G ≤ 4 MPa	
11	μ	G	$\mu = kG + b$	$k = –0.026$ $b = 0.12$		
12	σ_p	G	σ_p = kG + b	$k = –2.64$ $b = 8.72$	0.25 MPa ≤ G ≤ 2 MPa	Li *et al*. [3]
13	E	G	$E = a\ln G + b$	$a = –0.41$ b=1.01		

Table 7. Linear fitting results of peak stress

Factor	Dependent variable	Significance level
T	σ_p	*
G	E	**
C	μ	**

**,* Significance level is larger than 95 and 90 %, O below 90%, respectively

From the equations, we can found that all factors are positively correlated with the σ_p, E, and μ. And the influence weight of gas pressure is the highest, the confining pressure is the second, and the temperature is the least.

Analysis of fractal characteristics of fracture surface of coal

Scanning electron microscope test of coal fracture

The quanta 250 SEM is used in the test. Cutting 1 cm^2 size slices at the fracture surface of the specimen and wipe the surface clean with alcohol. Then fix it on the SEM test bench with a conductive adhesive. Electron beams generate charge accumulation on the surface of rock minerals, affecting the observations. Therefore, the surface of the specimen should be sprayed with gold before observation. The result can be seen from fig. 4.

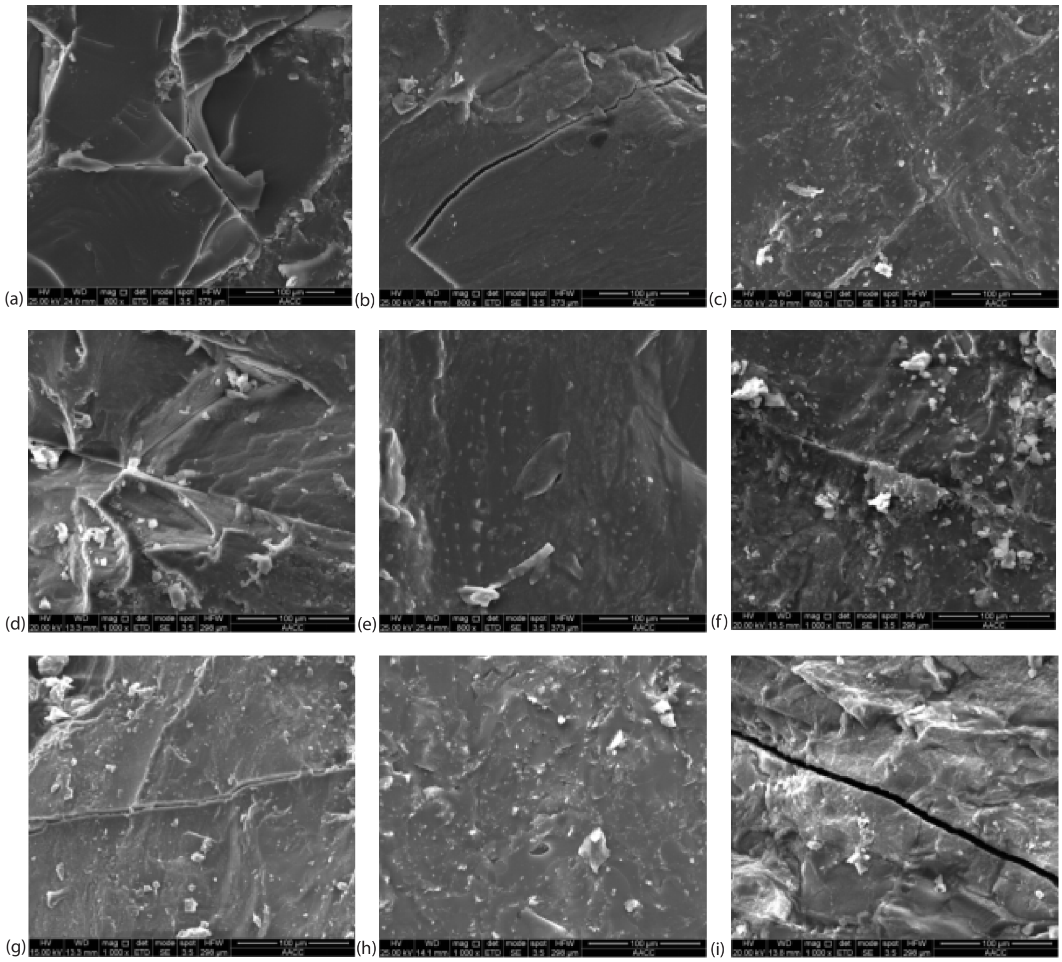

Figure 4. The SEM results of coal specimens fracture, (a) M20-0-0-2, (b) M20-1-4-3, (c) M20-3-8-3, (d) M40-0-4-2, (e) M40-1-8-2, (f) M40-3-0-1, (g) M80-0-8-2, (h) M80-1-0-3, (i) M40-3-4-1

Fractal theory and calculation method of fractal dimension

Mandelbrot proposed a fractal theory based on self-similarity and scale invariance of the measurement object's body shape. It's can be used to characterize certain irregular geometric shapes. Fractal has become a powerful tool for natural structures modelling such as fracture surfaces, cracks and fault traces [15-20]. Both micro- and macro-structure have fractal property and can be characterized by the fractal dimension. The information of the fracture process is recorded on the rock fracture and has statistical self-similar characteristics. Therefore, fractal geometry theory was used to calculate the fracture fractal dimension, and then quantitatively describe the complexity of fracture morphology.

First, the images of SEM test were binarized. Then, use box counting method to calculate fractal dimensions of fracture microscopic images. Overlay the image with squares of size r, and then change the size of r to get the number of grids N with different r values covering the fracture defects. Double-logarithm processing for r and N. The slope is the fractal dimension D. The result is shown in tab. 8. Finally, by ANOVA, the significance of the influence of various factors on the fractal dimension of coal fracture surface.

$$D = 0.000236T + 0.001C - 0.000159G + 1.965$$

According to the statistical analysis results, tab. 9, the temperature and confining pressure have a significant effect on the fractal dimension of coal fracture surface, and the significant level is above 95%. From tab. 10, it can be seen that the significant level of the fracture surface with a linear relationship between confining pressure and temperature is above 90%, and the temperature and confining pressure are positively correlated with the fractal dimension of the coal fracture surface, and the gas pressure is negatively correlated.

Table 8. The result of *D*

20-0-0-2	20-1-4-3	20-3-8-3	40-0-4-2	40-1-8-2	40-3-0-1	80-0-8-2	80-1-0-3	80-3-4-1
1.967648	1.969054	1.9736	1.982327	1.988142	1.979653	1.990819	1.98129	1.985741

Table 9. The ANOVA results of *D* of coal failure surface

Factor	Squared sum of deviation	*df*	Mean square	*F*	Significance level
T	0	2	0	139.7	**
G	9.8E-7	2	4.9E-7	0.3	O
C	9.8E-5	2	4.9E-5	31.7	**
Error	4.95	2	1.6E-6	–	–
Total	4.95	8	–	–	–

Table 10. Linear fitting results of *D* of coal failure surface

Factor	Coefficient	Error	Significance level
constant	1.965	433.4	**
T	0.000236	3.5	**
G	–0.000159	–0.1	O
C	0.001	1.9	*

**,* Significance level larger than 95 and 90 %, O below 90%, respectively, the same blew

Conclusions

- The significance of the effects of T, C, G on the σ_p, E, μ, and D of coal was analyzed by using ANOVA. It can be seen from tabs. 3-5 that all factors have a significant effect on the σ_p, E,

μ. of coal. The significant level of C, G on the σ_p , E, and μ is above 95%. The significant level of T on the σp and E is above 95%. But the significant level of μ is 90%. Temperature and confining pressure have a significant effect on the D of coal fracture surface, and the significant level is above 95%.

- The linear model is used to describe the variation law of the peak stress, poisson's ratio, elastic modulus of the coal under the confining pressure, the temperature and the gas pressure. Temperature and confining pressure are positively correlated with the D of the coal fracture surface, and the gas pressure is negatively correlated.

Nomenclature

C – confining pressure, [Nm^{-2}]
df – degree of freedom, [–]
F – F value of the ANOVA, [–]
G – gas pressure, [Nm^{-2}]
E – elastic modulus of the specimen, [GPa]
T – temperature, [K]

Greek symbols

ε_1 – axial strain of the specimen, [–]
μ – Poisson's ratio of the specimen, [–]
σ_p – peak stress of the specimen, [MPa]

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References

[1] Xie, H., Research and Consideratio on Coal Deep Mining and Ultimate Mining Depth (in Chinese), *Journal of Coal Science*, *36* (2012), 4, pp. 535-542
[2] Du, Y., Experimental Study on Triaxial Compression of Coal Containing Methane under Different Confining Pressure (in Chinese), *Safety in Coal Mines*, *45* (2014), 10, pp. 10-13
[3] Li, X., *et al*., Experimental Study of Mechanical Properties of Outburst Coal Containing Gas under Triaxial Compression (in Chinese), *Chinese Journal of Rock Mechanics and Engineering*, *29* (2010), May, pp. 3350-3358
[4] Meng, Z., Temperature and Pressure under Deep Conditions and Their Influences On Mechanical Properties of Sandstone (in Chinese), *Chinese Journal of Rock Mechanics and Engineering*, *25* (2006), 6, pp. 1177-1181
[5] Zha, W., Effect of Temperature Changes on the Mechanical Properties of Coal-Serial Sandy Mudstone Under Triaxial Compression, *Journal of Safety and Environment*, *14* (2014), 6, pp. 47-51
[6] Babadagli, T., Fractal Characteristics of Rocks Fractured under Tension, *Theoretical and Applied Fracture Mechanics, 39* (2003), 1, pp. 73-88
[7] Ren, L., Mixed-Mode Fracture Behavior and Related Surface Topography Feature of a Typical Sandstone, *Rock Mechanics and Rock Engineering*, *49* (2016), 8, pp. 1-17
[8] Ai, T., Box-Counting Methods to Directly Estimate the Fractal Dimension of a Rock Surface, *Applied Surface Science*, 314 (2014), 10, pp. 610-621
[9] Shi, Y., *Applied Mathematical Statistics*, Xi'an Jiao Tong University Press, Xi'an, China, 2005
[10] ***, ISRM, Suggested Methods for Determining the Strength of Rock Materials in Triaxial Compression, Revised Version, 1983
[11] Xu, J., *et al*., Experimental Research on Influence of Temperature on Mechanical Properties of Coal Containing Methane (in Chinese), *Chinese Journal of Rock Mechanics and Engineering*, *30* (2010), S1, pp. 2730-2735
[12] Yin, G., *et al*., Experimental Investigation on Mechanical Properties of Coarse Sandstone after High Temperature under Conventional Triaxial Compression (in Chinese), *Chinese Journal of Rock Mechanics and Engineering*, *28* (2009), 3, pp. 598-604
[13] Yang, Y., *et al*., Test Study of Coal's Strength and Deformation Characteristics under Triaxial Compression (in Chinese), *Journal of China Coal Society*, *31* (2006), 2, pp. 150-153

[14] Li, W., Research on Mechanical Characteristics and Gas Migratio Law of Coal and Rock Under Mining Influence, Chongqing University, Chongqing, China, 2014
[15] Xie, H., Fractal Geometry and Fracture of Rock, *Acta Mechanica Sinica*, 4 (1988), 3, pp. 255-264
[16] Matsushita M, Fractal View Point of Fracture and Accretion, *Journal of the Physical Society of Japan*, *54* (1985), 3, pp. 857-865
[17] Brown, S. R., A Note on the Description of Surface Roughness Using Fractal Dimension, *Geophysical Research Letters*, *14* (1987), 11, pp. 1095-1098
[18] Turcotte, D. L., Fractal and Fragmentation, Journal of Geophysical Research, *91*, (1986), B2, pp. 1921-1926
[19] Power, W. L., Euclidean and Fractal Models for the Description of Rock Surface Roughness, *Journal of Geophysical Research*, *96* (1991), B1, pp. 415-424
[20] Huang, S., Application of Fractal Characterization and Modelling to Rock Joint Profiles, *International Journal of Rock Mechanics and Mining and Science and GeoMechancis Abstracts*, *29* (1992), 2, pp. 89-98

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