ENERGY EVOLUTION OF COAL SUBJECTED TO THERMO-GAS-MECHANICAL COUPLING

by

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In this paper, the orthogonal experiment method is employed to design mechanical test of coal under different temperature, confining pressure, and gas pressure. The results of the experiment were analyzed using statistical methods, such as elastic modulus, peak stress, Poisson's ratio. The linear model is used to describe the mechanical parameters of coal under the influence of temperature, confining pressure, and gas. The energy formula of coal sample under constant confining pressure is deduced. The evolution of input energy, elastic energy, and dissipation energy in coal deformation process are analyzed.

Key words: *temperature, gas pressure, mechanical test, energy, strength, elastic modulus, poisson's ratio*

Introduction

With the deepening of coal mining depth, the environment of coal is more complex. Temperature, confining pressure and gas pressure have great influence on the mechanical properties of coal [1-3]. Therefore, studying the Mechanical properties of deep coal is the basis for exploring the deformation and failure rules of deep coal.

Numerous studies have shown that confining pressure has an effect on the mechanical properties of rocks, such as compression strength and elastic modulus are increased with the confining pressure increases [4, 5]. Gas inside the coal can be divided into two kinds. One is adsorption of gas, and the other is free gas [6]. It is considered that the adsorption of gas reduces the strength of coal, while the free gas has an enhanced effect on the strength of coal [7]. Lam dos Santos [8] pointed out that the strength and the Young's modulus of granite were negatively correlated with temperature. Ma [9] proposed that structural thermal stress caused damage to coal specimens. However, some studies show that temperature has an enhanced effect on rock strength [10, 11]. Xu [12] states that the temperature causes the water in the rock to evaporate, increasing the friction between the particles inside the rock. Therefore, the

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compression strength of rock increases. Rock deformation and destruction process are often accompanied by the evolution of energy [13, 14]. Through the uniaxial loading and unloading tests of rock specimens under different loading rates and different loading levels, obtained the variation law of releasable strain energy and dissipated energy [15].

However, the study on the variation law of mechanical properties of coal under the different temperature, gas pressure, and confining pressure is not enough. There are few researches on the energy evolution in coal deformation under multiple factors. In this paper, orthogonal experiment method is used to design coal tests with different temperature, confining pressure and gas pressure. The influence of temperature, confining pressure and gas on the peak stress, modulus of elasticity, poisson's ratio of coal are analyzed. The energy evolution in coal deformation process is analyzed.

Experimental preparatio

As previously mentioned, the aim of this study is to investigate the influence of gas pressure, *G*, temperature, *T*, confining pressure, *C*, on the mechanical properties of coal. Therefore, a multiple factors and multiple levels test need to be carried out. However, to complete a multi-factor and multi-level of full test requires a lot of time and specimens. In fact, it is difficult to meet such conditions in experiments. It is necessary to find efficiency test method. Orthogonal test is an effective way to solve multi-factor test problems [16].

Table 1. Design of orthogonal table

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

The orthogonal table of this experiment is shown in tab. 1. Three specimens are tested in each group. The group number denotes the test condition of the group, for example, M-80-3-4 represents that this group of specimen will be tested at the condition of 80 °C, 3 MPa confining pressure, and 4 MPa confining pressure. Experimental results of orthogonal experiment using statistical analysis. For example, the Analysis of Variance (ANOVA) was used in this article. The mathematical model:

$$\left.\begin{aligned} k_1 &= \alpha + T_1 + H_1 + C_1 + \eta_1 \\ k_2 &= \alpha + T_1 + H_2 + C_2 + \eta_2 \\ k_3 &= \alpha + T_1 + H_3 + C_3 + \eta_3 \\ &\vdots \\ k_n &= \alpha + T_i + H_j + C_k + \eta_n \end{aligned}\right\} \tag{1}$$

where η_i are (i = 1, 2, 3...n, n is the number of observation) independent random variables. The T_i, G_i, C_i (i = 1, 2, 3) are effects of different temperature, gas pressure, and confining pressure values. Define S_{total} as the total sum of square of deviations. The S_{total} is decomposed into four terms S_E, S_T , S_G, and S_C. Here, S_E is the variance due to error while S_T, S_G, and S_C are the variance due to temperature, gas pressure, and confining pressure, respectively. We can obtain the equation:

$$\left.\begin{aligned}
&S_{\text{total}}=\sum_{i1=1}^{n}(k_{i1}-\bar{k})^2=\sum_{i1=1}^{n}(k_{i1})2-\delta,\quad S_T=\frac{\sum_{i2=1}^{h}(M_{Ti2})^2}{Rr}-\delta\\
&S_G=\frac{\sum_{i2=1}^{h}(M_{Gi2})^2}{Rr}-\delta,\quad S_C=\frac{\sum_{i2=1}^{h}(M_{Ci2})^2}{Rr}-\delta\\
&S_E=S_{\text{total}}-S_T-S_G-S_C\\
&\delta=\frac{\left(\sum_{ii=1}^{n}k_{ii}\right)^2}{n},\quad \bar{k}=\frac{\sum_{ii=1}^{n}k_{ii}}{n}
\end{aligned}\right\} \tag{2}$$

where h is the number of levels of each factor, R and r are the number of factors and levels, respectively, M_{Ti2} – the sum of observed quantity at $i2$ level of factor T (temperature), M_{Ci2} – the sum of observed quantity at $i2$ level of factor C (confining pressure), M_{Gi2} – the sum of observed quantity at $i2$ level of factor G (gas pressure).

The coal samples are collected from Shoushan mine in Xuchang, Henan Province, China as shown in fig. 1. The composition of coal samples are analyzed by X-ray diffraction (XRD). As shown in fig. 2, the main components of coal samples are calcite, kaolinite and quartz.

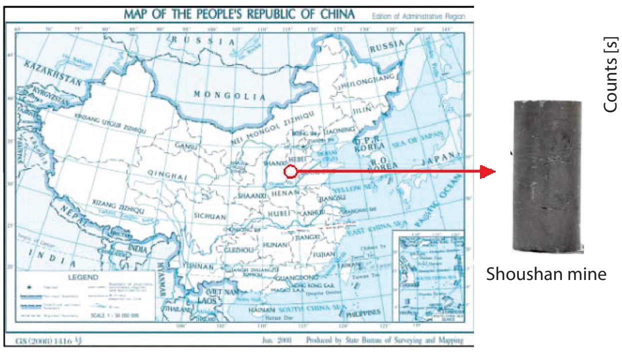


Figure 1. Location of the coal samples

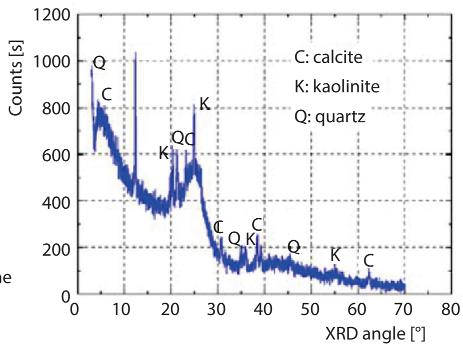


Figure 2. The XRD test on the coal

The height and diameter of the test specimens are 100 mm and 50 mm. 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 3.3×10^{-6}/s until the specimen broken.

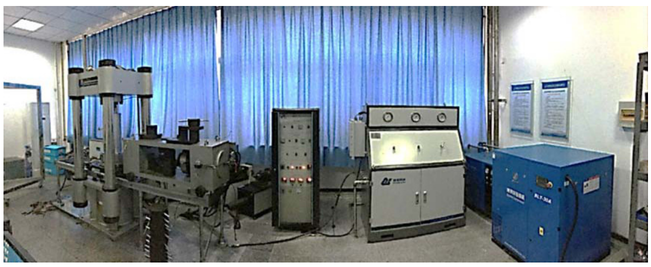


Figure 3. Experimental facility

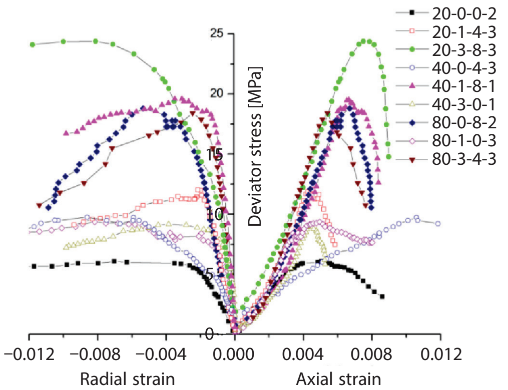


Figure 4. Stress and strain curves of some samples (*for color image see journal web site*)

Summary of experimental results

It can be seen from fig. 4 that the stress-strain curve includes the compaction phase, the elastic phase, the elastic-plastic phase, the yield failure phase. Compaction stage is not obvious at high confining pressure. It may be because of the high confining pressure have a certain degree of compaction samples. The deformation characteristics of the samples have obvious differences under different experimental conditions. It can be seen from tab. 2 that the young's modulus, E, the peak stress, σ, and poisson's ratio, μ, of specimens have obvious difference under different test conditions. As previously, it has a great influence on the mechanical properties of specimens under different experimental conditions.

Table 2. Summary of mechanical parameters

Group No.	σ_p [MPa]	Axial strain	Radial strain	Volumetric strain	E [GPa]	μ
20-0-0-1	6.55	0.00898	–0.00593	–0.00029	1.48	0.19
20-0-0-2	6.06	0.00505	–0.00703	–0.00901	1.95	0.27
20-1-4-3	12.12	0.00623	–0.01327	–0.02031	2.76	0.37
20-1-4-2	13.53	0.00687	–0.01662	–0.02636	3.30	0.30
20-3-8-3	24.65	0.00708	–0.00904	–0.01040	3.64	0.27
20-3-8-1	22.35	0.00683	–0.00532	–0.00381	3.60	0.25
40-0-4-2	15.85	0.00884	–0.00159	–0.00230	2.11	0.18
40-0-4-3	9.87	0.01562	–0.00943	–0.00325	1.26	0.31
40-1-8-1	19.71	0.00848	–0.01233	–0.01619	3.83	0.26
40-1-8-2	20.57	0.00624	–0.00302	0.01230	4.06	0.39
40-3-0-3	13.55	0.00505	–0.00866	0.01230	3.68	0.36
40-3-0-1	9.13	0.0053	–0.01118	–0.01707	1.7	0.12
80-0-8-2	18.76	0.00958	-0.00511	0.00061	3.48	0.26
80-0-8-3	14.49	0.00590	–0.00444	–0.00297	3.10	0.28
80-1-0-2	11.20	0.00515	–0.00628	0.00740	2.79	0.29
80-1-0-3	9.35	0.00495	–0.00817	–0.01140	3.19	0.25
80-3-4-2	24.12	0.00733	–0.0045	–0.00157	4.19	0.41
80-3-4-3	18.42	0.0054	–0.00246	–0.00048	4.56	0.34

Statistical analysis of test results

As previously mentioned, the test conditions are important factors that affect the deformation and mechanical characteristics of coal. Therefore, in order to further study, the influence of temperature, confining pressure, gas pressure on the mechanical properties and deformation characteristics of coal. Using statistical methods to analyze poisson's ratio, peak stress and elastic modulus of coal under different experimental conditions.

Tables 3 is the results of ANOVA of peak stress, elastic modulus and poisson's ratio under the influence of temperature, confining pressure, and gas pressure.

It can be seen from tab. 3 that the E is most affected by the gas pressure, followed by confining pressure and the temperature is the least. The influence of each factor on the E shows extremely significant, and the significance level is above 95%. The confining pressure and gas pressure have significant influence on the peak stress. The significance level is above 99%, and the effect of temperature on the σ_p is not obvious. The effect of all factors on the poisson's ratio, μ, is not obvious.

Table 3. Analysis of variance of elastic modulus, *E*, with all factors

Factor	Square sum of deviation			d*f*			Average square			*F*			Significance level		
	E	σ_p	μ	E	σ_p	μ	E	σ_p	μ	E	σ_p	μ	E	σ_p	μ
G	6.7	166.1	0.004	2			3.4	83.1	0.002	13.1	15.2	0.3	0.001	0.001	0.732
T	2.1	10.4	0.012	2			1.0	5.2	0.006	4.1	0.9	1.0	0.047	0.417	0.384
C	3.3	316.3	0.01	2			1.7	158.2	0.005	6.5	28.9	0.9	0.014	0	0.446
Error	2.8	60.2	0.065	11			0.3	5.5	0.006						
Total	184.8	4709.9	1.718	18											

Energy evolution in progressive destruction of coal

From the energy point of view, the destruction process of coal is the energy absorption, storage, dissipation, and release process. Assuming that the coal destruction process takes place in a closed thermodynamic system without heat exchange with the outside world. In the process of coal deformation, the energy conversion is in a variety of form. The main concern is the evolution of elastic energy and dissipation energy. Therefore, the energy during the deformation of coal can be simplified into input energy, elastic energy and dissipation energy [14], $U = U^e + U^d$, where U is the input energy, U^e – the elastic energy, and U^d – the dissipation energy.

The input energy can be given:

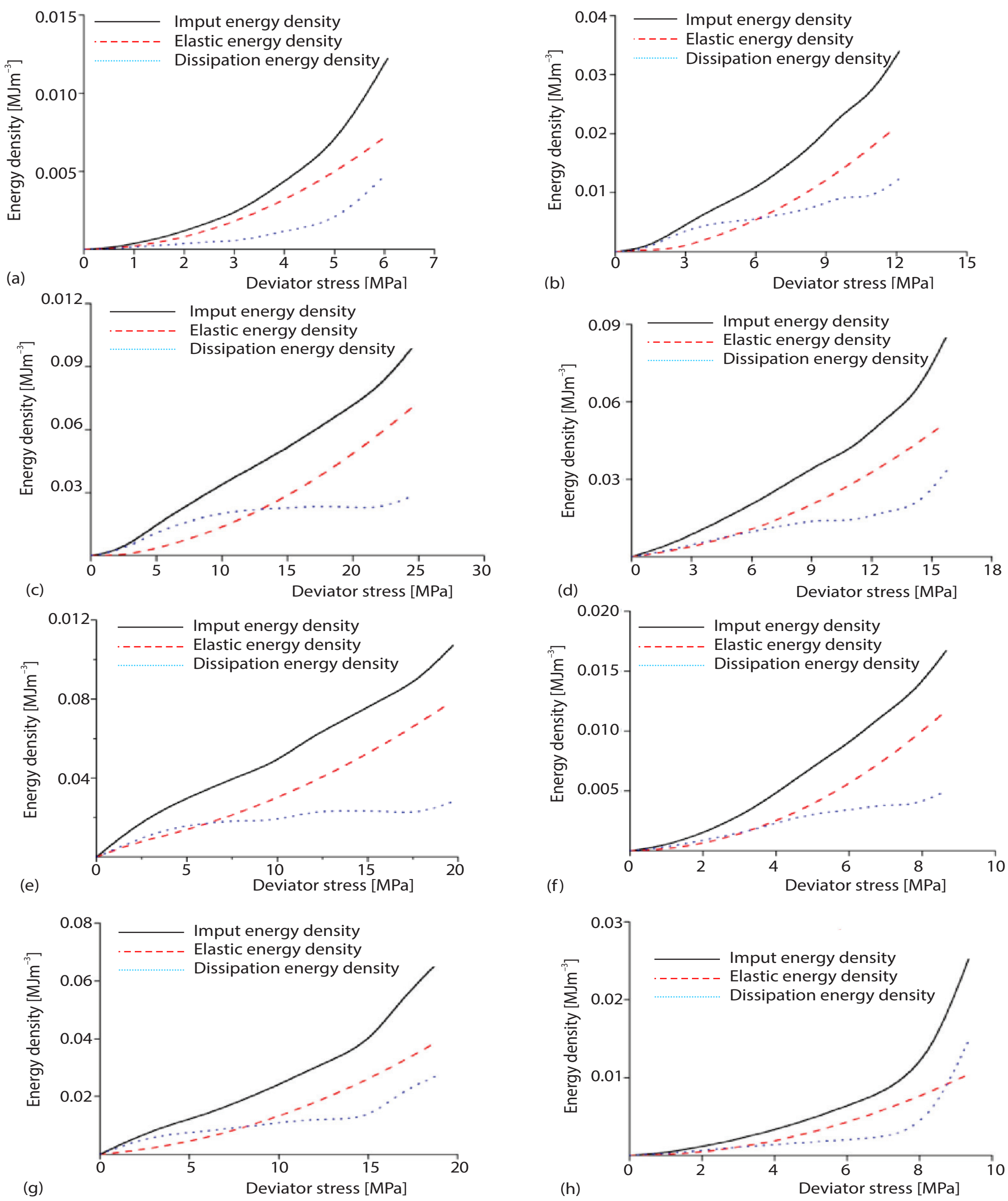
$$U = \int_0^{\varepsilon_i} \sigma_i \mathrm{d}\varepsilon_i, \quad U^e = \int_0^{\varepsilon_1^e} \sigma_1 \mathrm{d}\varepsilon_1^e + 2\sigma_3\varepsilon_3^e, \quad U^d = U - U^e \tag{3}$$

According to the generalized Hooke's law, the elastic energy can be expressed:

$$U^e = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_3\sigma_2 + \sigma_1\sigma_3)\right] = \frac{1}{2E}\sigma_1^2 - 4\nu\sigma_1\sigma_3 + \frac{1-2\nu}{E}\sigma_3^2 \tag{4}$$

Regularity of the energy storage and dissipation during specimens' deformation

It can be seen from the eq. (7) that in the process of deformation of samples, the axial deformation and radial deformation of the samples will occur with the increase of axial pressure. It can be seen from fig. 6 that the input energy density, elastic energy density and dissipated energy density increase with the increase of deviator stress. The article will discuss the energy evolution in the stage of compaction, elastic, and damage. In the compaction stage, the input energy density increases fastest, and the dissipation energy density is greater than



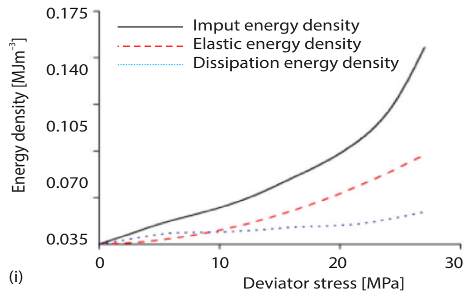


Figure 6. Energy evolution law under different experimental conditions; (a) 20-0-0-2, (b) 20-1-4-3, (c) 20-3-8-3, (d) 40-0-4-2, (e) 40-1-8-2 (f) 40-3-0-1, (g) 80-0-8-2, (h) 80-1-0-3, and (i) 80-1-4-2

the elastic energy density. This may be because the early deformation of the samples is mainly caused by the original crack closure inside the samples, which is irreversible deformation. In the elastic stage, the deformation is mainly elastic deformation. Input energy is mostly stored in the form of elastic energy. Input energy density and dissipation energy density changes linearly with deviator stress. Dissipation energy increases slowly. In the damage stage, the original cracks in the samples began to expand, and the new cracks began to sprout. The energy dissipated to cause damage to the specimen also increases. From the dissipated energy density-stress curve, it can be seen that the rate of increase of dissipation energy density increases rapidly at the damage stage.

Conclusions

The ANOVA of the peak stress, elastic modulus and poisson's ratio shows that confining pressure, temperatures, and gas pressure have significant influence on the elastic modulus. Confining pressure and gas pressure have significant influence on the peak stress. The gas pressure has the most influence on the elastic modulus E, the temperature has the least influence on the elastic modulus E. The confining pressure has the centered influence on the elastic modulus E. The energy formula of coal under triaxial compression is deduced. Input energy and elastic energy increase with the increase of deviator stress. And the evolution of dissipation energy is closely related to the expansion of internal cracks in coal.

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Nomenclature

C – confining pressure, [Nm^{-2}]
G – gas pressure, [Nm^{-2}]
R – number of factors in testing, [–]
T – temperature, [K]

Greek symbol

ε_v^c – the crack volumetric strain, [–]

Reference

[1] Wu, S., Analysis of Effective Stresses of Coal Containing Coal bed Methane, *Chinese Journal of Rock Mechanics and Engineering*, *24* (2005), 10, pp. 1674-1678
[2] Xue, Y, An Elastoplastic Model for Gas-Flow Characteristics Around Drainage Borehole Considering Post-Peak Failure and Elastic Compaction, *Environmental Earth Sciences*, *77* (2018), 19, 669
[3] Li, X., Triaxial Test of Coal and Rock and Its New Plasticity in Low and High Confining Pressure, *Rock and Soil Mechanics*, *31* (2010), 3, pp. 677-682
[4] Du, Y., Experimental Study on Triaxial Compression of Coal-Bearing Gas under Confining Pressure Conditions, *Journal of Coal Safety*, *45* (2014), 10, pp. 10-13
[5] Li, B., Research On Rock Failure Characteristics and Strength Criteria Under High Confining Pressure, Ph. D. thesis, Wuhan University of Science and Technology, Wuhan, China, 2015
[6] Li, X., Experimental Study on Mechanical Properties of Gas-Protruding Coal under Triaxial Compression, *Chinese Journal of Rock Mechanics and Engineering*, *13* (2010), 5, pp. 3350-3358
[7] Lu, P., Effective Stress and Mechanical Deformation and Failure Characteristics of Gas Containing Coal, *Journal of University of Science and Technology of China*, *31* (2001), 6, pp. 686-692
[8] Lam dos Santos, J., Temperature Effects on Mechanical Behavior of Engineered Stones, *Construction and Building Materials*, *25* (2011), 1, pp. 171-174
[9] Ma, Z., Experimental Study on the Effect of Temperature on Coal Mechanical Properties, *Journal of Mining and Safety Engineering*, *5* (2005), 3, pp. 46-48
[10] Rao, Q., Experimental Study of Mechanical Properties of Sandstone at High Temperature, *Journal of Central South University*, *14* (2007), 2, pp. 478-483

[11] Xue, Y., Evaluation of the Non-Darcy Effect of Water Inrush from Karst Collapse Columns by Means of a Non-Linear Flow Model, *Water*, *10* (2018), 9, 1234
[12] Xu, K., Experimental Study On the Effect of Temperature On the Physical and Mechanical Properties of Deep Mudstone, M. Sc. thesis, Anhui University of Science and Technology, Anhui Sheng, China, 2016
[13] Xie, P., Rock Strength and Global Failure Criterion Based on the Principle of Energy Dissipation and Release, *Chinese Journal of Rock Mechanics and Engineering*, *24* (2005), 17, pp. 3003-3010
[14] Zhang, Z., Experimental Investigations on Energy Evolution Characteristics of Coal, Sandstone and Granite During Loading Process, *Journal of China University of Mining & Technology*, *44* (2015), 3, pp. 416-422
[15] Li, L., Experimental Investigations of Releasable Energy and Dissipation Energy Within Rock, *Engineering Mechanics*, *28* (2011), 3, pp. 35-40
[16] Shi, Y., *Applied Mathematical Statistics*, Xi'an Jiao Tong University Press, Xi'an, China, 2005

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