Open Access

The Model for Calculating Elastic Modulus and Poisson's Ratio of Coal Body

Ai Chi and Li Yuwei*

College of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China

Abstract: Coal body is a type of fractured rock mass in which lots of cleat fractures developed. Its mechanical properties vary with the parametric variation of coal rock block, face cleat and butt cleat. Based on the linear elastic theory and displacement equivalent principle and simplifying the face cleat and butt cleat as multi-bank penetrating and intermittent cracks, the model was established to calculate the elastic modulus and Poisson's ratio of coal body combined with cleat. By analyzing the model, it also obtained the influence of the parameter variation of coal rock block, face cleat and butt cleat on the elastic modulus and Poisson's ratio of the coal body. Study results showed that the connectivity rate of butt cleat and the distance between face cleats had a weak influence on elastic modulus of coal body. When the inclination of face cleat was 90°, the elastic modulus of coal body reached the maximal value and it equaled to the elastic modulus of coal rock block. When the inclination of face cleat was 0°, the elastic modulus of coal body was exclusively dependent on the elastic modulus of coal rock block, the normal stiffness of face cleat and the distance between them. When the distance between butt cleats or the connectivity rate of butt cleat was fixed, the Poisson's ratio of the coal body initially increased and then decreased with increasing of the face cleat inclination.

Keywords: Face cleat, butt cleat, elastic modulus, Poisson’s ratio.

1. INTRODUCTION

The recovery of coal bed methane, on one hand alleviated the gas hazard, on the other hand, as one type of unconventional clean energy, more and more attentions were paid to it [1, 2]. Most coal seams in China had poor permeability, therefore hydraulic fracturing and other technical measures were needed for effective exploitation of coalbed methane (CBM). Before carrying out related technical theory research, it was a prerequisite to completely understand the mechanical properties of coal.

Coal body has the dual pore structure, matrix pores and fractures, and face cleats and butt cleats in fracture system are the main structure planes which affect the mechanical characteristics of coal body. Previous studies on mechanical characteristics of fractured rock, experts and scholars have done a lot of work. R. W. Goodman [3] considered that there were a group of fractures with horizontal and uniform distribution in rock mass, and established the mechanical model of equivalent coherent mass. H. Fred [4] got three groups of equivalent coherent mass model of perpendicular fractures through the equivalent deformation theory. Shilin Yan [5-7] proposed solving method of joint rock mass equivalent elastic parameters through material mechanics simplified analysis model; using jointed element model to set up solving model of joint rock mass equivalent elastic parameters and applied software to solve; analyzed the equivalent elastic parameters of non-across jointed rock mass through the introduction of penetration rate. Jianxin Han [8] established multi-bank through fractured rock mass deformation calculation model to predict the deformation of rock mass through the principle of equivalent displacement. Nowadays theoretical studies on mechanical properties of cleat-fracture coal are still limited, mostly focused on the determination of deformation and strength properties through the experiment [9-11]. Jianping Zuo [12, 13] studied the mechanical properties of coal and rock under different inclination combinations. Xiangfeng Liu [14] introduced fractures set degree parameters, and established evolution theory model of compression deformation internal set degree, and it is used to analyze the fractures evolution. Pinjia Duan [15] studied the influence of the loading rate changing and the angle between the main fracture direction and loading direction on coal and rock mechanical characteristics through experiments. T.P. Medhurst and E.T. Brown [16] found that the peak intensity of the same kind of coal samples decreased with the increase of the size of coal samples, and the relationship between strength of coal samples and confining pressure was obtained through triaxial compression test. Weibing Shen [17] conducted triaxial experiments on different coal samples, and obtained the changing law of the elastic modulus and Poisson's ratio of different coal samples with the changing of confining pressure. V.L. Shkuratnik [18, 19] studied the acoustic emission change law of coal sample during the whole process of coal rock uniaxial and triaxial compression test, and got the corresponding relationship between coal sample strain and acoustic emission characteristics. Chengdong Su [20] conducted the triaxial compression test, and analyzed the strength and deformation characteristics of coal samples under different stress conditions. But it is still merely to see the mechanical parameter model that takes the influence of

*Address correspondence to this author at the College of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, Heilongjiang province, China; Tel: 0086-459-6503073; E-mail: liyuweibox@126.com

face cleats and butt cleats into consideration at the same time and be simplified into the combination of through and discontinuous fractures, so the study on the mechanical properties of face cleats and butt cleats combined coal body is of great significance.

2. SIMPLIFIED MECHANICAL MODEL OF COAL BODY

Coal body is a type of fractured rock masses in which lots of cleats, fractures and weak planes develop. Among those weak planes, face cleats and butt cleats are better developed and have a high density in total, and deliver on the space into a three dimensional meshes. Face cleats are approximately parallel to level and generally show plate extension with good continuity, the butt cleats develop only between two face cleats, and approximately vertical to level with poor general continuity [21].

In order to analyze the mechanical characteristics of coal body, suppose the face cleats and butt cleats as a group of through fractures and a group of discontinuous fractures respectively. The two groups' intersection is shown in Fig. (**1**). The inclination between face cleat and horizontal direction is α, length is a; the length of butt cleat is b, the space between two cleats along the same rectilinear direction is c, the space between two parallel butt cleats is S_1, the space between two butt cleats is S_2; the height of coal body is h, it is subjected to axial pressure σ_1 and confining pressure is σ_3. Assuming that coal body is isotropic elastic, and the stress and displacement of face cleat and butt cleat satisfy linear elastic relationship, and the interaction between face cleat and butt cleat can be ignored.

3. THE CALCULATION MODEL OF ELASTIC MODULUS AND POISSON'S RATIO

According to the mechanical model of delivery network of coal body, deducted the calculation model of elastic modulus and Poisson's ratio under the condition that face cleats and butt cleats were intersected. Assuming that the elastic modulus of the coal rock is E_s, Poisson's ratio is μ_s , under the influence of σ_1 and σ_3 the axial deformation is ε_s, so axial displacement is

$$\delta_s = \varepsilon_s \cdot h = \frac{1}{E_s}\left(\sigma_1 - 2\mu_s\sigma_3\right)h \tag{1}$$

where: E_s is the elastic modulus of the coal rock, MPa; μ_s is the Poisson's ratio of the coal rock; δ_s is the axial displacement, m.

Supposing that the normal stiffness of butt cleat is k_{n1}, shear stiffness is k_{s1}, and its normal and tangential displacement are δ_{f1n} and δ_{f1t} respectively, and the connectivity rate of face cleat is λ_L, there is

$$\delta_{f1n} = \lambda_L \frac{\sigma_{nf1}}{k_{n1}} \tag{2}$$

$$\delta_{f1t} = \lambda_L \frac{\tau_{nf1}}{k_{s1}} \tag{3}$$

where: δ_{f1n} and δ_{f1t} are the normal and tangential displacement respectively, m; σ_{nf1} is the normal stress exerted on butt cleat, MPa; τ_{nf1} is the shear stress exerted on butt cleat, MPa; k_{n1} is the normal stiffness of butt cleat, MN/m^3; k_{s1} is the shear stiffness of butt cleat, MN/m^3; λ_L is the connectivity rate of face cleat on the same line, and its physical meaning is the same as the connectivity rate of intermittent fractures in rock mechanics.

The connectivity rate of butt cleat is

$$\lambda_L = \frac{b}{c+b} \tag{4}$$

where: b is the length of single fractures of butt cleats, m; c is the space between two butt cleats on the same line, m.

For the butt cleat, the normal stress and shear stress exerted on the cleat plane can be represented as

$$\sigma_{nf1} = \sigma_1 \sin^2\alpha + \sigma_3 \cos^2\alpha \tag{5}$$

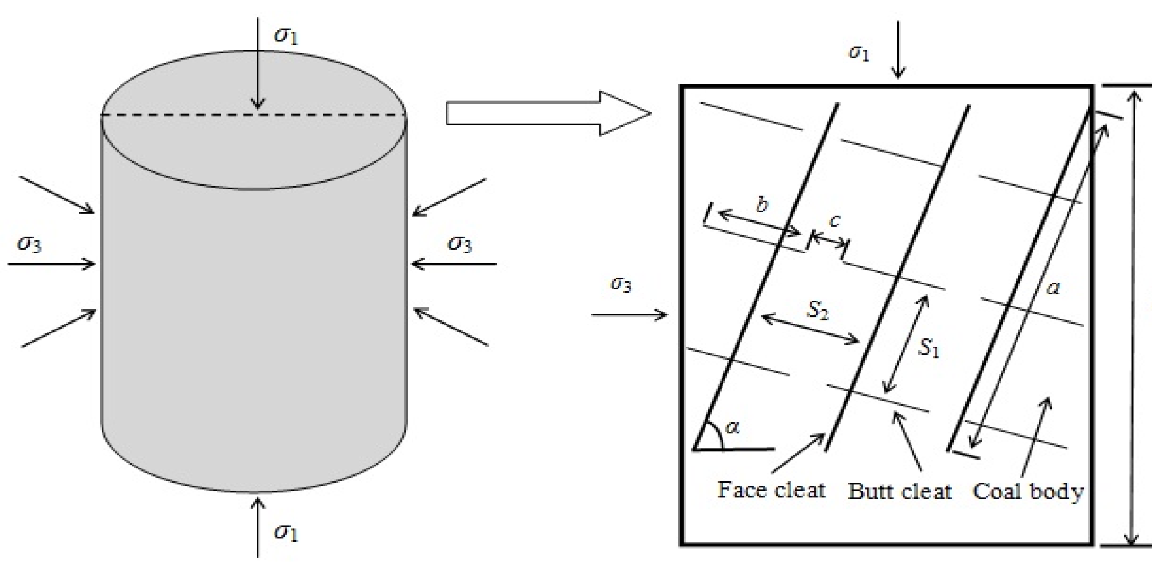

Fig. (1). Mechanical model of cleats combined coal body.

$$\tau_{nf1} = (\sigma_3 - \sigma_1)\sin\alpha\cos\alpha \tag{6}$$

where: α is the inclination between face cleat and horizontal direction, (°).

While the number of butt cleats in coal body can be represented as

$$n_1 = \frac{h\cos\alpha}{S_1} \tag{7}$$

where: n_1 is the number of butt cleats in coal body; S_1 is the space between two parallel butt cleats, m; h is the height of coal body, m.

So axial displacement generated by the butt cleat is

$$\delta_{f1} = n_1\left[\delta_{f1n}\cos\alpha + \delta_{f1t}\sin\alpha\right] = \frac{bh\cos^2\alpha}{(b+c)S_1}\cdot \left[\frac{\sigma_1\sin^2\alpha + \sigma_3\cos^2\alpha}{k_{n1}} + \frac{(\sigma_3-\sigma_1)\sin^2\alpha}{k_{s1}}\right] \tag{8}$$

where: δ_{f1} is axial displacement generated by the face cleat in coal body, m.

For the axial displacement generated by face cleat, it can be obtained through the deduction method for that of butt cleat, but the connectivity rate of cleats can be ignored, so axial displacement δ_{f2} produced by n_2 face cleats is

$$\delta_{f2} = n_2\left[\delta_{f2n}\cos\alpha + \delta_{f2t}\sin\alpha\right] = \frac{h(\sigma_1\cos^2\alpha + \sigma_3\sin^2\alpha)\cos^2\alpha}{S_2k_{n2}} + \frac{h(\sigma_1-\sigma_3)\sin^2\alpha\cos^2\alpha}{S_2k_{s2}} \tag{9}$$

where: δ_{f2} is axial displacement produced by face cleat, m; δ_{f2n} and δ_{f2t} are the normal and shear displacement of face cleat respectively, m; σ_{nf2} is the normal stress exerted on face cleat, MPa; τ_{nf2} is the shear stress exerted on face cleat, MPa; k_{n2} is the normal stiffness of face cleat, MN/m^3; k_{s2} is the shear stiffness of face cleat, MN/m^3; n_2 is the number of face cleats in coal body; S_2 is the space between paralleled cleats, m.

According to the principle of superposition of elastic mechanics, the axial displacement of cleat combined coal is the sum of axial displacement of coal rock, face cleat and butt cleat:

$$\begin{aligned}\delta &= \delta_s + \delta_{f1} + \delta_{f2} \\ &= \frac{1}{E_s}(\sigma_1 - 2\mu_s\sigma_3)h + \\ &\quad \frac{bh\cos^2\alpha}{(b+c)S_1}\left[\frac{\sigma_1\sin^2\alpha + \sigma_3\cos^2\alpha}{k_{n1}} + \frac{(\sigma_3-\sigma_1)\sin^2\alpha}{k_{s1}}\right] \\ &\quad + \frac{h(\sigma_1\cos^2\alpha + \sigma_3\sin^2\alpha)\cos^2\alpha}{S_2k_{n2}} \\ &\quad + \frac{h(\sigma_1-\sigma_3)\sin^2\alpha\cos^2\alpha}{S_2k_{s2}}\end{aligned} \tag{10}$$

where: δ is the axial displacement of coal rock, m.

According to the definition of strain, the axial strain ε of coal body can be obtained:

$$\begin{aligned}\varepsilon = \frac{\delta}{h} = \sigma_1 &\left[\begin{array}{l}\dfrac{1}{E_s} + \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{n1}} - \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{s1}} \\ + \dfrac{\cos^4\alpha}{S_2k_{n2}} + \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{s2}}\end{array}\right] \\ - \sigma_3 &\left[\begin{array}{l}\dfrac{2\mu_s}{E_s} - \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{n2}} + \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{s2}} \\ - \dfrac{b\cos^4\alpha}{(b+c)S_1k_{n1}} - \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{s1}}\end{array}\right]\end{aligned} \tag{11}$$

where: ε is the axial strain of coal body.

Supposing that the elastic modulus of the delivery cleats combined network coal body is E, the Poisson's ratio is μ, so the axial strain is

$$\varepsilon = \sigma_1\frac{1}{E} - \sigma_3\frac{2\mu}{E} \tag{12}$$

where: E is the elastic modulus of the delivery cleats combined network coal body, MPa; μ is the Poisson's ratio the delivery cleats combined network coal body.

Compare formula (11) and (12), it is easy to get the representation of E and μ

$$E = \left[\begin{array}{l}\dfrac{1}{E_s} + \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{n1}} + \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{s2}} \\ - \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{s1}} + \dfrac{\cos^4\alpha}{S_2k_{n2}}\end{array}\right]^{-1} \tag{13}$$

$$\mu = \frac{E}{2}\left[\begin{array}{l}\dfrac{2\mu_s}{E_s} - \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{n2}} + \dfrac{\sin^2\alpha\cos^2\alpha}{S_2k_{s2}} \\ - \dfrac{b\cos^4\alpha}{(b+c)S_1k_{n1}} - \dfrac{b\sin^2\alpha\cos^2\alpha}{(b+c)S_1k_{s1}}\end{array}\right] \tag{14}$$

Through formula (13) and (14), the E and μ of cleats combined coal body can be defined.

4. EXAMPLE CALCULATION

In order to prove the accuracy of the model referred in this paper, comparing the experimental data of any coal seam of Jin Cheng mining area with the model calculation results, the comparing results are shown in Table **1**.

Model calculation parameters are determined by indoor experiments of coal sample, well logging interpretation and core description data. Coal rock elastic modulus average value is E_s=3.5×10^{3}MPa, Poisson's ratio average value is μ_s=0.33, the average spacing value of butt cleats is S_1=0.05m, the normal stiffness average value is k_{n1}=3.5×10^{4}MPa/m, the average shear stiffness value of butt cleat is k_{s1}=5.3×10^{3}MPa/m, average length of single butt cleat is b=0.012m, average spacing between two cleats is c=0.03m, the average spacing value of face cleats is S_2=0.03m, the average normal stiffness value of face cleat is k_{n2}=8.0×10^{3}MPa/m, the average shear stiffness value of face cleat is k_{s2}=1.7×10^{3}MPa/m, the included angle of face cleat and minimum horizontal principal stress direction is α=82°.

Table 1. The Mechanical Parameters Experimental Results of Coal Bed

Coal Sample Number	Elastic Modulus (MPa)	Poisson's Ratio
1	1587	0.37
2	1683	0.34
3	1866	0.31
4	1587	0.35
5	1418	0.39
6	1529	0.34
7	1654	0.36
8	1814	0.34
9	1784	0.35
10	1489	0.36
Average Value	**1641**	**0.35**

From the model calculation results, it could be obtained that elastic modulus of coal body was 1.56×10^{3}MPa, Poisson's ratio was 0.36. Experimental results were that the average elastic modulus of coal mining area was 1.64×10^3 MPa, average Poisson's ratio was 0.35. So the model calculation results are in good agreement with the experimental results, the relative error of elastic modulus and Poisson's ratio were 4.94% and 2.86% respectively within the error range permitted in engineering application.

5. THE RELATIONSHIP BETWEEN ELASTIC PARAMETERS OF COAL BODY AND COAL ROCK, FACE CLEATS AND BUTT CLEATS

In order to analyze the elastic modulus and Poisson's ratio of coal body changing with the coal rock, face cleats and butt cleats parameters, take corresponding calculation parameters in section 4 if no special instructions referred.

5.1. The Relationship Between Elastic Modulus of Coal Body And Coal Rock, Face Cleats and Butt Cleats

From the calculation results shown in Fig. (**2**), it could be obtained that the elastic modulus of coal body increased with the increasing of that of coal rock, but the increase rate decreased, and the elastic modulus of the coal body is much smaller than that of coal rock when the inclination of face cleat was 82°, it also reflected that the cleats had bigger influence on the elastic modulus of coal body. The influence of the normal stiffness and shear stiffness of face cleats and butt cleats on the elastic modulus of coal body (as were shown in Figs **3**, **4**, **6**) and the elastic modulus of coal rock were similar, but the elastic modulus of coal body decreased with the increasing of normal stiffness. From Fig. (**5**), it could be known that the elastic modulus of coal body increased with the increasing of the shear stiffness of cleats, but the amplitude decreased.

As is shown in Fig. (**7**), when the spacing between butt cleats is definite, the elastic modulus of coal body initially

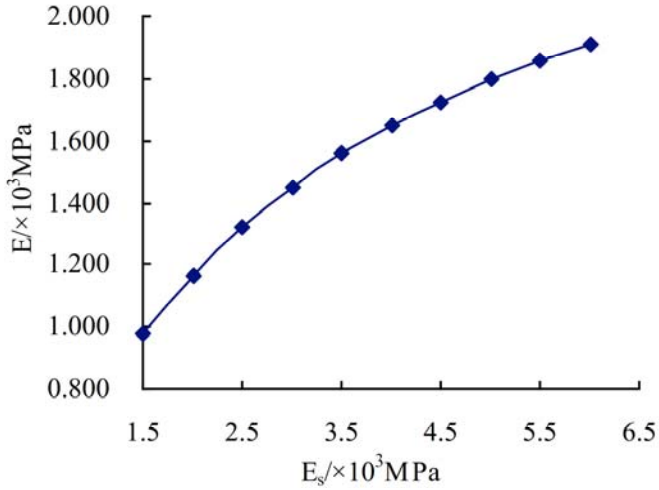

Fig. (2). The relationship between the elastic modulus E of coal body and the elastic modulus E_s of coal rock block.

slightly decreased then increased rapidly with the increasing of the inclination of face cleat. When α was 90° the elastic modulus reached the maximum, while α was 0°, face cleats paralleled to the horizontal direction, and the elastic modulus of coal body only depended on elastic modulus of coal rock, the normal stiffness and the spacing of face cleats. When the inclination of face cleats is definite, the calculation results of elastic modulus of coal body according to different butt cleats spacing were generally the same, which indicated that the influence of butt cleat spacing on elastic modulus of coal body was small.

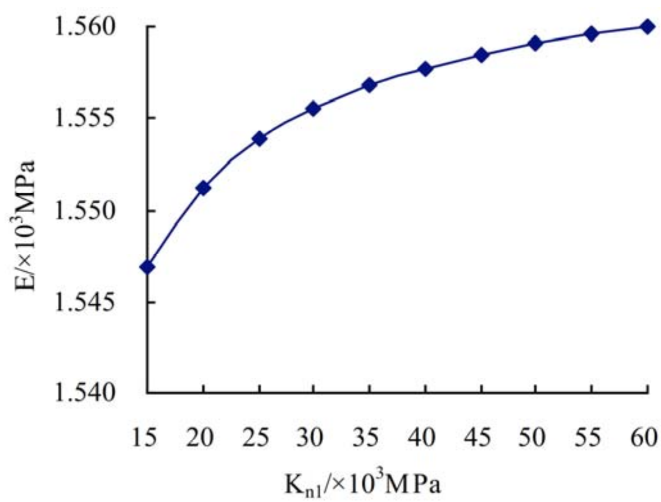

Fig. (3). The relationship between the elastic modulus E of coal body and the normal stiffness $k_{n1}$of butt cleat.

From the calculation results shown in Fig. (**8**), it could be obtained that when the spacing between face cleats is definite, the elastic modulus of coal body initially slightly decreased then increased rapidly with the increasing of the inclination of face cleat. When α was 90° the elastic modulus reached the maximum, equaled to the elastic modulus of coal rock. It is mainly due to the following reasons. When the inclination initially increased from 0°, the shear stiffness of face cleat began to affect the elastic modulus of coal body and made it decreasing. And once the inclination increased to a certain value, the normal and shear stiffness of butt cleat

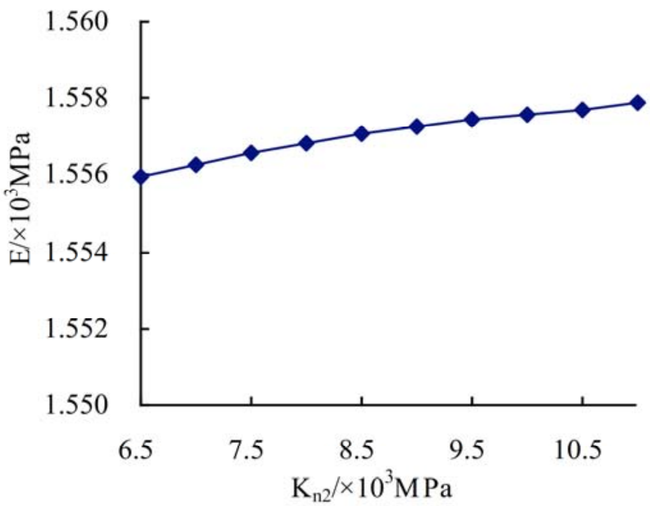

Fig. (4). The relationship between the elastic modulus *E* of coal body and the normal stiffness k_{n2} of face cleat.

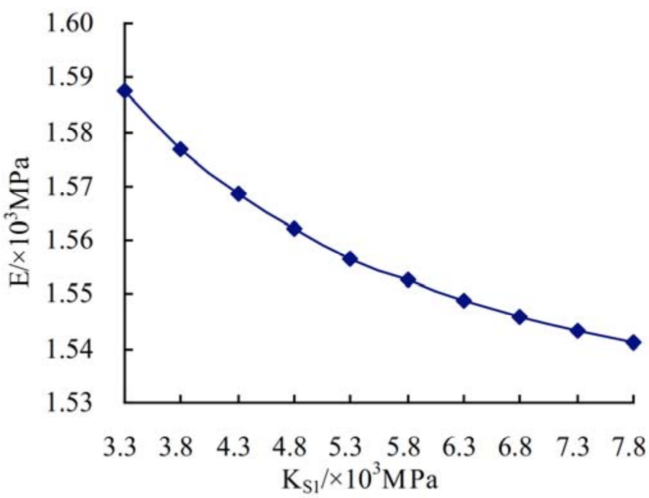

Fig. (5). The relationship between the elastic modulus *E* of coal body and the shear stiffness k_{s1} of butt cleat.

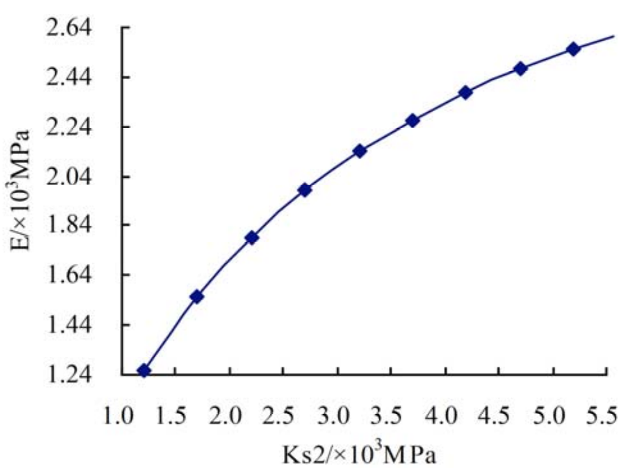

Fig. (6). The relationship between the elastic modulus *E* of coal body and the shear stiffness k_{s2} of face cleat.

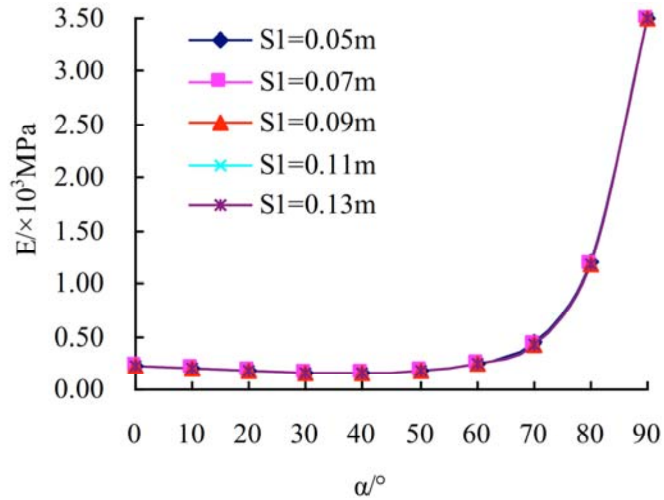

Fig. (7). The relationship among the elastic modulus *E* of coal body, inclination α of face cleat and the distance S_1 between butt cleats.

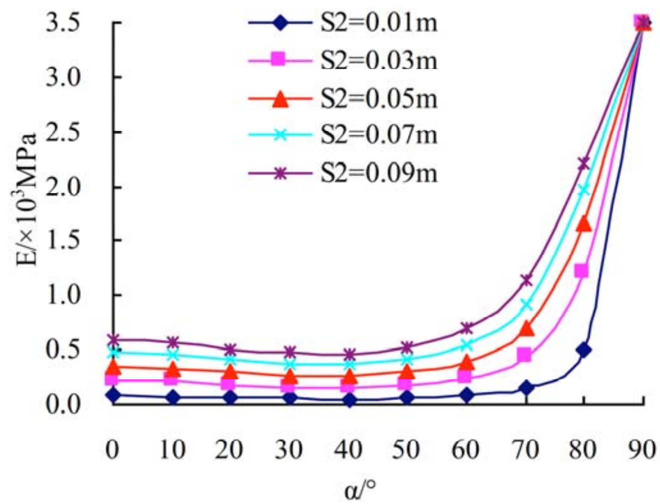

Fig. (8). The relationship among the elastic modulus *E* of coal body, inclination α of face cleat and the distance S_2 between face cleats.

played a main role in the influential factors of the elastic modulus of coal body, while the normal and shear stiffness of butt cleat were much bigger than that of face cleat, and made the elastic modulus increasing. When the inclination of face cleats is definite, the elastic modulus of coal body increased with the increasing of face cleats, which also indicated that the elastic modulus of coal body increased with the decreasing of face cleats density.

In order to analyze the influence of connectivity rate on the elastic modulus of coal body, supposing that the length of butt cleats *b* was 0.012m, the spacing of the parallel butt cleats *c* arranged from 0.028 to 0.108 m, and increased connectivity rate from 0.1 to 0.3, then calculated the elastic modulus after the connectivity rate had changed, and drew the Fig. (**9**). The changing rule of the curve in Fig. (**9**) was similar to that of Fig. (**7**), when the inclination of face cleats was definite, the elastic modulus only slightly increased almost unchanged with the increasing of connectivity rate, which indicated that the connectivity rate of butt cleats had little effects on the elastic modulus.

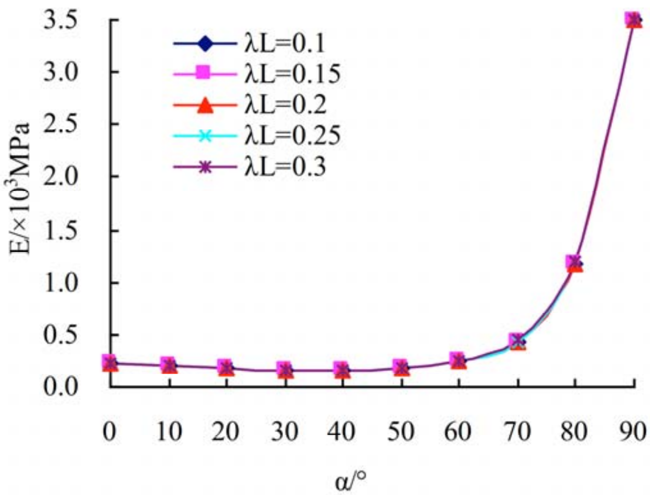

Fig. (9). The relationship among the elastic modulus E of coal body, inclination α of face cleat and the connectivity rate λ_L of butt cleats.

5.2. The Relationship Between Poisson's Ratio of Coal Body and Coal Rock, Face Cleats and Butt Cleats

The analyzing method of Poisson's Ratio to coal body with cleats is the same as that of elastic modulus. Applying the calculation model, corresponding change rule can be obtained, so it is no longer stated here. Through the results, it could be found that the Poisson's ratio of coal rock had relatively obvious effects on that of coal body, and the Poisson's ratio of coal body increased linearly with that of coal rock. In addition, the Poisson's ratio of coal body increased with the shear stiffness of butt cleats, and decreased with the shear stiffness face cleat, and it was opposite to the changing rule of elastic modulus.

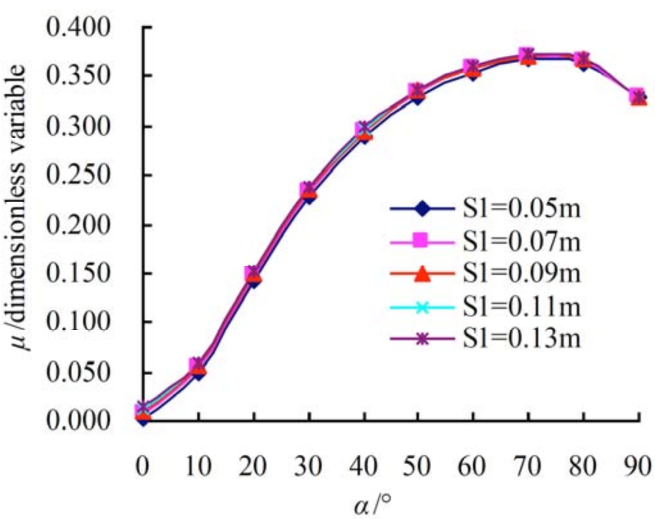

Fig. (10). The relationship among the Poisson's ratio μ of coal body, inclination α of face cleat and the distance S_1 between butt cleats.

Fig. (**10**) reflected that the relations between the Poisson's ratio of coal body, the inclination of face cleats and the spacing between butt cleats. It could be obtained that when the spacing is definite, with the increasing of the inclination, the Poisson's ratio initially increased then decreased, and the maximum value could be obtained. The Poisson's ratio reached the maximum value when the inclination α was around 70° according to different spacing. When the inclination α was 0°, the Poisson's ratio of coal body was determined by the elastic modulus and the Poisson's ratio of coal rock, the spacing between butt cleats, the spacing between face cleats, the shear stiffness of butt cleats, the shear stiffness of face cleats and the connectivity rate of butt cleats. When the parameters mentioned above were definite, the Poisson's ratio of cleats combined coal body could be defined. When α was 90°, the Poisson's ratio of coal body was the same as that of coal rock, and it was 0.33. When the inclination was definite, the Poisson's ratio increased only slightly increased almost unchanged with the increasing of the spacing between butt cleats, which indicated that while the distribution density of butt cleats, the Poisson's ratio of cleats combined coal body increased, but the changes were small.

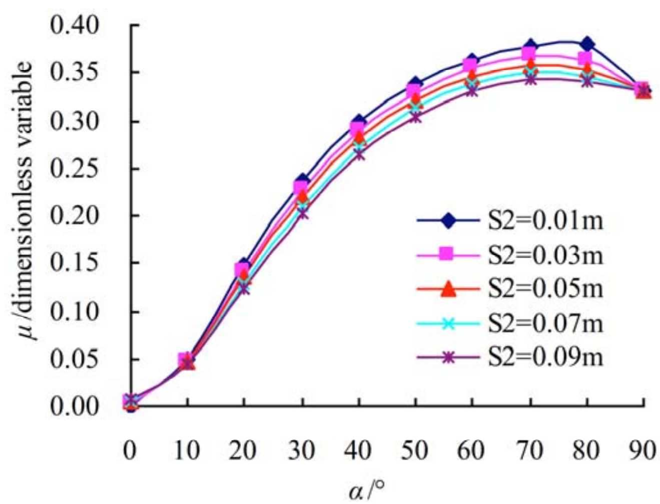

Fig. (11). The relationship among the Poisson's ratio μ of coal body, inclination α of face cleat and the distance S_2 between face cleats.

Fig. (**11**) showed that the relations between the Poisson's ratio of cleat combined coal body, the inclination of face cleats and the spacing between face cleats. It could be known that when the spacing was definite, the Poisson's ratio of coal body initially increased then decreased. It was mainly due to the following reasons. When the inclination initially increased from 0°, the shear stiffness of butt cleat began to affect the Poisson's ratio of coal body, and its normal stiffness was an order of magnitude larger than its shear stiffness, this led to the Poisson's ratio rapidly increase. With the inclination increasing, the Poisson's ratio of coal body was determined by the normal stiffness and shear stiffness of face cleats and butt cleats and other factors. And once the inclination increased to a certain level, the shear stiffness of face cleat had relatively obvious influence on the Poisson's ratio of coal body, while the value of shear stiffness were much smaller than that of normal stiffness. As a result, the inclination increased while the Poisson's ratio decreased. And when α was less than 10°, the changing curves of different cleats spacing intersected, and when α was more than 10°, the inclination of face cleat was definite, the Poisson's ratio decreased with the increasing of face cleat spacing, namely the Poisson's ratio increased with the increasing of the distribution density of face cleats.

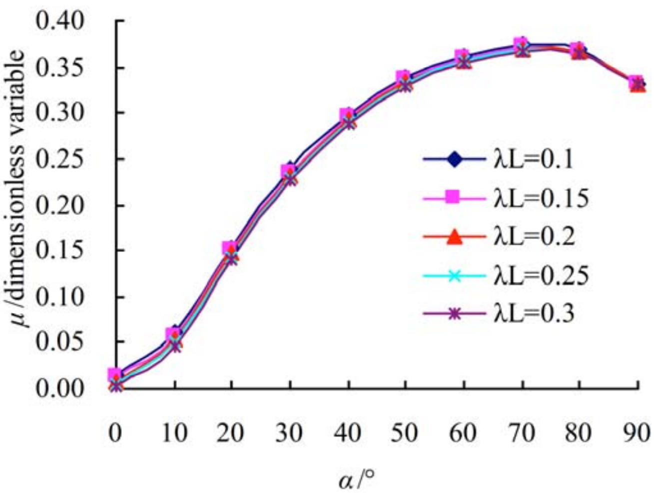

Fig. (12). The relationship among the Poisson's ratio μ of coal body, inclination α of face cleat and the connectivity rate λ_L of butt cleats.

Fig. (**12**) showed that when the connectivity rate was definite, the Poisson's ratio initially increased then decreased with the increasing of the inclination of face cleats. When the inclination was definite, the Poisson's ratio decreased with the increasing of the connectivity rate of butt cleats, but the decreasing rate was relatively uniform, approximately linear decreasing.

6. CONCLUSIONS

1. Comparing model calculation results with the actual measured results, it confirmed that the model developed in this paper could be used to analyze and calculate delivered two-dimensional face cleats and butt cleats combined coal body.

2. Upon discussing the relationship among elastic modulus of cleats combined coal body, coal rock mechanical parameters, face cleats and butt cleats mechanical parameters, it proved that the influences of the connectivity rate and spacing of butt cleats on the elastic modulus were minor. When α was 90°, the elastic modulus of coal body reached to maximum and equaled to that of coal rock. When α was 0°, face cleats paralleled to the horizontal direction. The elastic modulus of coal body was exclusively dependent on elastic modulus of coal rock, the normal stiffness and the distance between.

3. After analyzing the changing law of Poisson's ratio of cleats combined coal body with coal rock mechanical parameters, face cleats and butt cleats mechanical parameters, it indicated that when the spacing was definite, with the increasing of the inclination of face cleats, the Poisson's ratio initially increased then decreased. The distribution density of butt cleats had little influence on it. The Poisson's ratio increased with face cleats distribution density. When the inclination of face cleats was definite, the Poisson's ratio decreased when increasing the connectivity rate of butt cleats. But the decreasing rate was relatively uniform, approximately linear decreasing.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

The support of the National Natural Science Foundation of China (No. 51274067) is gratefully acknowledged.

REFERENCES

[1] Yang, T.; Chen, S.; Zhu, W. Coupled model of gas-solid in coal seams based on dynamic process of pressure relief and gas drainage. *Rock Soil Mech*., **2010**, *31*(7), 2247-2252.

[2] Yin. G.; Jiang, C.; Xu, J. Experimental study of influences for water content in coalbed gas reservoirs on methane seepage. *Chin. J. Rock Mech. Eng.*, **2011**, *30*, 3401-3406.

[3] Goodman, R.E.; Taylor, R.L.; Brekke, T.L. A model for the mechanics of jointed rock. *J. Soil Mech. Found. Div.*, **1968**, *94*(3), 637-659.

[4] Fred, H.; Kulhawy, M. Geomechanical model for rock foundation settlement. *J. Geotech. Eng.,* **1978**, *104*(2), 211-227.

[5] Yan, S.; Huang, Y.; Chen, C. An Equivalent model for jointed rock mass with persistent joint and its elastic parameters. *J. Huazhong Univ. Sci. Technol.,* **2001**, *29*(6), 60-63.

[6] Yan, S.; Pan, P.; Wu, D. Estimation of 3-D equivalent elastic constants of penetrative jointed rock mass by FEM. *J. Wuhan. Univ. Technol.*, **2003**, *25*(4), 47-50.

[7] Yan, S.; Huang, Y.; Chen, C. An equivalent model for jointed rock mass with planar nonpenetrative joint and its elastic parameters. *J. Huazhong Univ. Sci. Technolog*. **2001**, *29*(6), 64-67.

[8] Han, J.; Li, S.; Li, S. Study of deformation characteristic of rock mass with multiple persistent crack sets. *Chin. J. Rock Mech. Eng.*, **2011**, *30*, 3319-3325.

[9] Yang, Y.; Song, Y.; Chen, S. Test study of coal's strength and deformation characteristics under triaxial compression. *J. China Coal Soc.*, **2006**, *31*(2), 150-153.

[10] Guan, L.; Tian, H.; Chen, W. Research on mechanical properties of coal and its application. *Rock Soil Mech.*, **2009**, *30*(12), 3715-3719.

[11] Duan, P.; Wang, Z. Experimental investigation on mechanics properties and failure of coal in HanCheng. *Coal Geol. Explor.*, **2012**, *40*(4), 39-42.

[12] Zuo, J.; Xie, H.; Wu, A. Investigation on failure mechanisms and mechanical behaviors of deep coal-rock single body and combined body. *Chin. J. Rock Mech. Eng.*, **2011**, *30*(1), 85-92.

[13] Guo, D.; Zuo, J.; Zhang, Y. Research on strength and failure mechanism of deep coal-rock combination bodies of different inclined angles. *Rock Soil Mech.*, **2011**, *32*(5), 1333-1339.

[14] Liu, X.; Wang, Y.; Zhang, Z. Crack density evolution model of rock and coal. *J. Liaoning Tech. Univ.*, **2011**, *30*(2), 161-163.

[15] Duan, P.; Wang, Z. Experimental investigation on mechanics properties and failure of coal in Hancheng. *Coal Geol. Explor.*, **2012**, *40*(4), 39-42.

[16] Medhurst, T.P.; Brown, E.T. A Study of the mechanics behavior of coal for pillar design. *Int. J. Rock Mech. Mining Sci.*, **1998**, *35*(8), 1087-1104.

[17] Shen, W.; Zhang, B. Testing study on mechanics parameters of coal. *Chin. J. Rock Mech. Eng.*, **2000**, *19*, 860-862.

[18] Shkuratnik, V.L.; Filimonov, Y.L.; Kuchurin, S.V. Experimental investigations into acoustic emission in coal samples under uniaxial loading. *J. Mining Sci.*, **2004**, *40*(5), 458-464.

[19] Shkuratnik, V.L.; Filimonov, Y.L.; Kuchurin, S.V. Regulations of acoustic emission in coal samples under triaxial compression. *J. Mining Sci.*, **2005**, *41*(1), 44-52.

[20] Su, C.; Zhai, X.; Li, Y. Study on deformation and strength of coal samples in triaxial compression. *Chin. J. Rock Mech. Eng.*, **2006**, *25*, 2963-2968.

[21] Du, C. Study on theoretics of hydraulic fracturing in coal bed and applicatons. PhD Thesis, China University of Mining and Technology, **2008**.

Received: July 28, 2013 Revised: September 24, 2013 Accepted: September 26, 2013