Investigation into the gas adsorption-loading coupling damage constitutive model of coal rock

Zhongzhong Liu
Shandong University
Hanpeng Wang (whp@sdu.edu.cn)
Shandong University https://orcid.org/0000-0002-4622-2229
Su Wang
Shandong University
Yang Xue
Shandong University
Chong Zhang
Shandong University

Research Article

Keywords: Coal and gas outburst, Stress loading, Gas adsorption, Coupling damage, Damage constitutive equation, Damage evolution equation

Posted Date: April 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-351996/v1

Investigation into the gas adsorption-loading coupling damage constitutive model of coal rock

Zhongzhong Liu [1,2], Hanpeng Wang [1,2,*], Su Wang [1,2], Yang Xue [1,2], Chong Zhang [1,2]

[1] Geotechnical and Structural Engineering Research Centre, Shandong University, Jinan 250061, China

[2] School of Qilu Transportation, Shandong University, Jinan, Shandong 250061, China

[*] Corresponding author

ORCID iD

Zhongzhong Liu: https://orcid.org/0000-0002-2872-4970

Hanpeng Wang: https://orcid.org/0000-0002-4622-2229

Corresponding author at:

School of Qilu Transportation, Shandong University, No.17923, Jingshi Road, Jinan, Shandong 250061, China. Tel.: +86 531 88399182; fax: +86 531 88395428. E-mail address: whp@sdu.edu.cn (Hanpeng Wang)

Abstract: Coal and gas outburst is the result of comprehensive action of in-situ stress, gas and mechanical properties of coal rock. The coupling effect of loading and gas adsorption eventually leads to the coal rock failure. Based on the principle of strain equivalence and considering the coupling effect of gas adsorption and stress loading, an adsorption-loading coupling damage model is established which breaks through the bottleneck of only considering single influencing factor. Taking briquette samples with controllable properties as the research object, uniaxial compression tests of coal rock at different gas adsorption pressures are carried out, and the model is verified based on the test results. The results of model calculation and tests show that the meso damage stage of coal body can well correspond to the macroscopic deterioration phenomenon and it is in good agreement with the stress-strain curve. It is proved that the model has good applicability and can accurately describe the damage and failure process of coal rock.

Keywords: Coal and gas outburst; Stress loading; Gas adsorption; Coupling damage; Damage constitutive equation; Damage evolution equation

1. Introduction

Coal and gas outburst is a common dynamic disaster in coal mine, which is a physicochemical phenomenon of extreme complexity (Li et al. 2018; Sobczyk 2014; Wold et al. 2008; Yang et al. 2017). There are many primary micro cracks and micro holes in the coal body. Under the combined action of load and gas adsorption, the primary defects expand and penetrate until macro cracks are produced, which eventually leads to the instability and failure of engineering structure. The establishment of a constitutive model which can accurately describe the deformation and failure process of coal rock is of great significance to study the physical and mechanical properties of coal containing gas and guide the safety production of mine theoretically.

Based on the phenomenological statistical damage mechanics theory, some scholars have carried out a lot of researches on the damage constitutive model of the coal rock (Bale et al. 2016; Liu et al. 2016).

In view of the stress loading, some scholars established the rock damage constitutive model, selecting different statistical distribution variables and strength criteria based on the statistical characteristics of rock micro element strength failure (Deng and Gu 2011; Wang et al. 2020; Zhou et al. 2011). The isotropic elastic damage statistical constitutive model established by Cao and Li (2008) can well simulate the axial strain softening under compression, but cannot reflect the volumetric dilatancy characteristics. Wei et al. (2016) established a damage constitutive model of coal rock considering volume strain increment to study the influence of coal rock damage and shear expansion effect on coal permeability. Gao et al. (2011) defined the damage variable of coal rock structure and established the corresponding elastoplastic damage constitutive model. Yang et al. (2018) summarized the stress-strain relationship of rock under conventional triaxial compression, and improved the classical plastic statistical damage model considering the advantages and disadvantages of the classical constitutive model.

In view of the gas adsorption, Perera and Sampath (2019) established a mechanical model of dual porosity medium considering the mechanical deterioration effect caused by gas adsorption. Hu et al. (2016) established a mechanical model for the degradation of coal rock mechanical properties caused by gas adsorption based on the relevant theory of elastic wave velocity, and carried out uniaxial compression failure experiments under different pore gas pressures to verify the model. Yang et al. (2015) established an energy-damage coupling model of coal rock under creep condition and triaxial compression condition respectively, which used dissipative energy to characterize the damage variable and considered the initial damage of coal rock. Zhu et al. (2018) pointed out that the adsorption damage of coal rock was mainly caused by tensile failure, and the piecewise damage numerical model of coal rock was established based on the maximum tensile-stress criterion and Mohr-Coulomb criterion. Yang et al. (2012) proposed the concept of compression energy and established the nonlinear constitutive relationship considering the nonlinear deformation characteristics of coal rock.

To sum up, the existing damage constitutive models mainly focused on either stress loading or gas adsorption, the damage constitutive model which can comprehensively consider the effect of stress and gas adsorption is relatively less. In this paper, a gas adsorption-loading coupling damage constitutive model of coal rock was established based on macroscopic phenomenological damage mechanics, and the rationality of the model was verified by experiment and numerical calculation.

2. Gas adsorption-loading coupling damage constitutive model

The continuous damage mechanics method describes the material damage process with continuous and variable damage variables, which provides a theoretical framework for describing the nonlinear stress-strain relationship of coal caused by cracks (Tang et al. 2002). Under the assumption of isotropy, a point inside the coal body is randomly selected to represent the volume unit. As shown in Fig. 1, the section area perpendicular to $\boldsymbol{n}$ direction is A, the effective bearing area in this direction is A_e and the defect area is A_D, we can get：

$$A_e = A - A_D \tag{1}$$

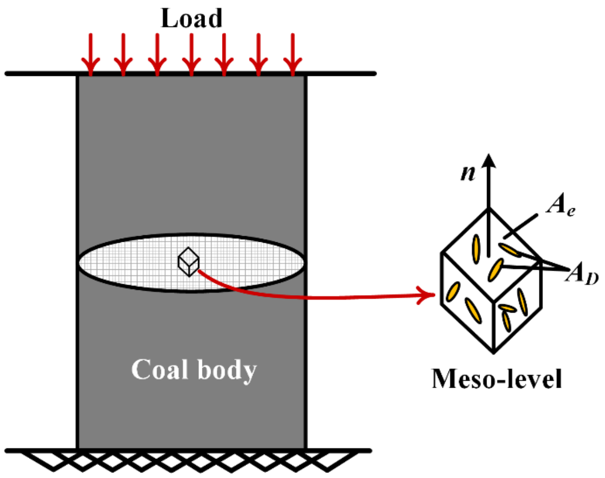


Fig. 1. Isotropic damage element of coal body

And then, the damage variable D can be defined as：

$$D = \frac{A_D}{A} = \frac{A - A_e}{A} \tag{2}$$

It can be seen from the above analysis that the damage variable D does not change with the section direction, that is, it has nothing to do with $\boldsymbol{n}$. When D=0, it corresponds to the non-destructive state of coal body, and D=1 corresponds to the complete fracture state of coal body.

When the coal body is subjected to the combined action of load and gas adsorption, the effective bearing area

A_e decreases and the effective stress σ_e increases. The effective stress σ_e can be expressed as:

$$\sigma_e = \frac{\sigma}{1-D} \tag{3}$$

It should be noted that it is very difficult to determine the effective bearing area by analyzing each defect form and damage mechanism from the meso level. In order to overcome this difficulty, Lemaitre (Lemaitre 1972) proposed the strain equivalence principle: the strain caused by the stress σ acting on the damaged material is equivalent to the strain caused by the effective stress σ_e acting on the undamaged material. For example, the one-dimensional linear elastic relationship of the damaged material can be expressed as：

$$\varepsilon = \frac{\sigma_e}{E} = \frac{\sigma}{E_e} = \frac{\sigma}{(1-D)E} \tag{4}$$

Where E is the elastic modulus of undamaged state of material, E_e is the elastic modulus of damaged state of material, ε is strain. The damage of material is considered in the elastic modulus:

$$E_e = (1-D)E \tag{5}$$

According to the above analysis, the strain caused by the external load F on the damaged coal is equivalent to the strain caused by the effective stress in the undamaged condition. Compare two damaged states arbitrarily, the strain caused by the effective stress of the first damaged state acting on the second damaged state is equivalent to the strain caused by the effective stress of the second damaged state acting on the first damaged state:

$$\sigma_1 A_1 = \sigma_2 A_2 \tag{6}$$

$$\varepsilon = \frac{\sigma_1}{E_2} = \frac{\sigma_2}{E_1} \tag{7}$$

Where σ_1, A_1, E_1, σ_2, A_2, E_2 is the effective stress, the effective bearing area and the elastic modulus of two damaged states, respectively.

The "non adsorption state" of coal in atmospheric air is defined as the first damaged state, and its effective stress and effective cross-sectional area are σ_0 and A_0; The "state after gas adsorption" is defined as the second damaged state, and its effective stress and effective cross-sectional area are σ_p and A_p. Then Eq. (8) can be got:

$$\sigma_0 A_0 = \sigma_p A_p \tag{8}$$

D_p is defined as the adsorption damage variable, which is related to the adsorption pressure and gas properties:

$$D_p = \frac{A_0 \text{-} A_p}{A_0} \tag{9}$$

Eq. (10) can be obtained by simultaneous Eq. (8) and Eq. (9):

$$\sigma_p = \frac{\sigma_0}{\left(1\text{-}D_p\right)} \tag{10}$$

Eq. (11) can be obtained according to Eq. (7):

$$\varepsilon = \frac{\sigma_0}{E_p} = \frac{\sigma_p}{E_0} \tag{11}$$

Eq. (12) can be obtained by simultaneous Eq. (10) and Eq. (11):

$$E_p = E_0\left(1\text{-}D_p\right) \tag{12}$$

Both sides of Eq. (12) are multiplied by the adsorption damage strain ε_p to obtain the damage constitutive relation of coal rock considering gas adsorption:

$$\sigma_p = E_0\left(1\text{-}D_p\right)\varepsilon_p \tag{13}$$

Similarly, according to the assumption of strain equivalence, the state of coal body after "gas adsorption" can be assumed as the first damaged state, and the state in the coupling effect of "gas adsorption and loading" can be regarded as the second damaged state. Then we can get the damage constitutive relation of coal under the condition of gas adsorption and loading:

$$\sigma = E_p\left(1\text{-}D_F\right)\varepsilon \tag{14}$$

Where the D_F is the damage variable of the loading state.

Eq. (15) can be obtained by simultaneous Eq. (12) and Eq. (14):

$$\sigma = E_0\left(1\text{-}D_p\right)\left(1\text{-}D_F\right)\varepsilon \tag{15}$$

Define the coupling damage variable as D_{co}, and $D_{co}=D_P+D_F-D_PD_F$, then Eq. (15) can be simplified as Eq. (16).

$$\sigma = E_0\left(1 - D_{co}\right)\varepsilon \tag{16}$$

The damage variable is the macroscopic description of the irreversible meso structure change in materials. The response of macroscopic physical and mechanical properties of materials can represent the internal deterioration degree of materials. The elastic modulus of coal can be obtained by monitoring and calculating in the degradation experiment. We can get Eq. (17) by rewriting Eq. (12).

$$D_p = 1 - \frac{E_p}{E_0} \tag{17}$$

The damage unit of coal body in Fig. 1 is regarded as a micro unit. In the process of stress loading, the damage degree of micro unit reflects the macro deterioration degree of coal body, and the accumulation and superposition amount of damage eventually lead to the deterioration of macro performance of coal body. The damage rate of micro unit in coal under stress loading is defined as $\varphi(\varepsilon)$ (Ahmed et al. 2020; Yang et al. 2018), and the relationship between damage variable D_F and micro element can be expressed as:

$$\frac{dD_F}{d\varepsilon} = \varphi(\varepsilon) \tag{18}$$

Since the material strength obeys Weibull distribution of probability statistics in the process of loading, it can be considered that the damage variable also obeys the distribution (Chen et al. 2018). Then the stress loading damage variable D_F can be described as Eq. (19):

$$D_F = 1 - e^{-\left(\frac{\varepsilon}{n}\right)^k} \tag{19}$$

Where n is the shape parameter and k is the scale parameter. The damage evolution equation can be deduced as:

$$D_F = 1 - e^{-\frac{1}{k}\left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^k} \tag{20}$$

Where ε_{max} is the strain value corresponding to the peak strength point of coal in degradation test, and k is the characteristic parameter of coal damage evolution (El-Zohairy et al. 2020; Li et al. 2014), k=1/ln($E_0\varepsilon_{max}/\sigma_{max}$), σ_{max} is the peak strength during coal loading.

By integrating Eq. (18) we can get:

$$D_F = \int_0^{\varepsilon} \varphi(x)dx = 1\text{-}e^{-\frac{1}{k}\left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^k} \tag{21}$$

By substituting Eq. (21) and Eq. (17) into Eq. (16), the damage evolution equation considering the coupling effect of gas adsorption and stress loading can be obtained:

$$D_{co} = 1\text{-}\frac{E_p}{E_0} e^{-\frac{1}{k}\left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^k} \tag{22}$$

It can be seen from Eq. (22) that the stress-strain relationship at any point in the coal body is related to the elastic modulus and the corresponding strain. When only gas adsorption damage is considered, the stress loading strain is 0. We can get:

$$D_{co} = 1\text{-}\frac{E_p}{E_0} e^{-\frac{1}{k}\left(\frac{0}{\varepsilon_{\max}}\right)^k} = 1\text{-}\frac{E_p}{E_0} = D_p \tag{23}$$

When only stress loading is considered, E_p=E_0, we can get:

$$D_{co} = 1\text{-}\frac{E_0}{E_0} e^{-\frac{1}{k}\left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^k} = 1\text{-}e^{-\frac{1}{k}\left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^k} = D_F \tag{24}$$

The expression of coupling damage variable D_{co} shows that the joint action of gas adsorption and stress loading aggravates the total damage of coal body, and shows obvious nonlinear relationship, as shown in Fig. 2. The damage model reflects the macro and micro mechanical properties of coal in the process of gas adsorption induced coal damage, and can truly reveal the damage evolution law and damage degradation mechanism of adsorbed coal in the process of loading degradation.

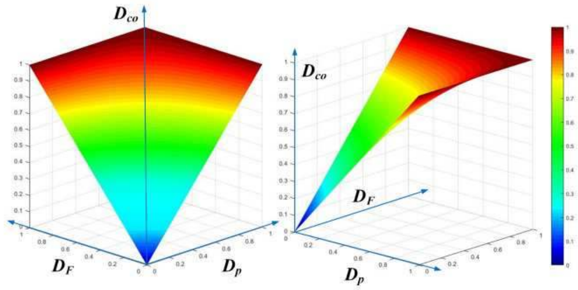


Fig. 2. Change image of coupling damage variable under gas adsorption and stress loading

3. Model application and verification

Eq. (22) and Eq. (16) are the damage evolution equation and constitutive equation of coal body under the coupling effect of gas adsorption and stress loading respectively. The applicability of the model is verified by the damage degradation test of coal under different gas adsorption pressure.

3.1. Test apparatus

The self-developed visual constant volume gas-solid coupling test system is used for the test (Zhang et al. 2020). The constant volume structure of the apparatus ensures that the axial loading is not affected after gas injection, and eliminates the test error caused by the change of air pressure in the coupling loading chamber caused by the pressure head rise and fall during the loading and unloading process. Through the circumferential displacement test device and visualization window, the real-time monitoring of the deformation of the test sample, the development and deterioration of coal cracks and other characteristic parameters are realized.

3.2. Sample preparation

It is difficult to prepare raw coal standard samples, and the dispersion of strength and deformation characteristics is high, which is not convenient for the analysis of test results. The coal samples used in the test are the briquette materials which have good consistency with the mechanical properties of raw coal (Wang et al. 2015; Xu et al. 1993; Yin et al. 2009). Several standard briquette samples were made using the method raised by Wang et al. (2015), and the preparation parameters of the samples are shown in Table 1.

Table 1. Preparation parameters of the samples

Sample size	Particle size distribution (0-1mm:1-3mm)	Concentration of cementing agent (%)	Precast strength (MPa)
φ50×100 mm	0.76:0.24	3.25	1.00

3.3. Test scheme

During the test, CO_2 was selected as the test gas, and the equilibrium pressure of gas adsorption was taken as 0.0, 0.4, 0.8, 1.2, 1.6 and 2.0 MPa. Six groups of tests were conducted and the test process was as follows：

(1) The standard briquette samples were loaded into the coupling loading chamber of the test apparatus. After vacuumizing for 4 h, CO_2 with certain pressure was injected and adsorbed for 24 h.

(2) After adsorption equilibrium, uniaxial compression test was carried out to monitor the uniaxial compressive strength and elastic modulus of the samples.

3.4. Test result and discussion

Through the degradation test of coal at different adsorption pressures, the damage evolution characteristics were obtained. The damage parameters of coal are shown in Table 2.

Table 2. Damage parameters of coal at different adsorption pressures

Adsorption pressure (MPa)	σ_{max}	ε_{max}	E_0 (MPa)	E_p (MPa)	Value of k
0.0	1.011	0.0279	67.06	67.06	1.625
0.4	0.841	0.0278	67.06	53.23	1.256
0.8	0.737	0.0269	67.06	48.27	1.117
1.2	0.659	0.0256	67.06	36.43	1.044
1.6	0.601	0.0227	67.06	32.51	1.076
2.0	0.523	0.0243	67.06	29.63	0.878

The damage evolution curves of coal body at different adsorption pressure and stress loading process are calculated, as shown in Fig. 3.

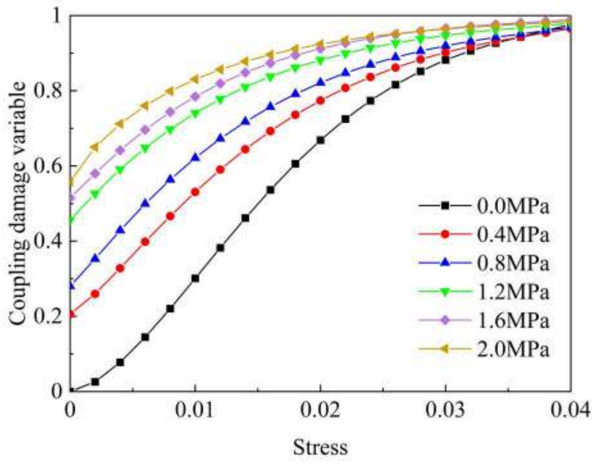


Fig. 3. Coupling damage variable evolution curves

It can be seen from Fig. 3 that under different adsorption pressures, the calculated damage of coal body model increases with the increase of coal body strain, and the coal body damage variables eventually tend to 1. In addition, it can be seen from the curve in the figure that the initial adsorption damage variable of coal increases with the increase of adsorption pressure. When the adsorption pressure was 0 MPa, 0.4 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa, 2.0 MPa, the initial damage variables of adsorption were 0, 0.206, 0.280, 0.457, 0.515, 0.558, respectively. The initial damage variable at 2.0 MPa adsorption pressure is 2.7 times of that at 0.4 MPa adsorption pressure. With the increase of adsorption pressure, the damage variable increases rapidly at first and then slows down. The results show that the damage of coal body is the most obvious when the adsorption pressure is 0.0-1.2, while the change tends to be stable when the adsorption pressure is 1.2-2.0 MPa. The stage of damage rapid propagation is significantly shortened, which shows that the coal is closer to the instability failure under the action of gas adsorption when the adsorption pressure is high.

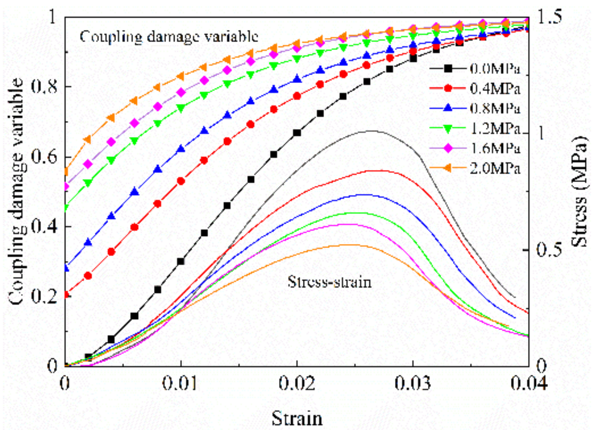
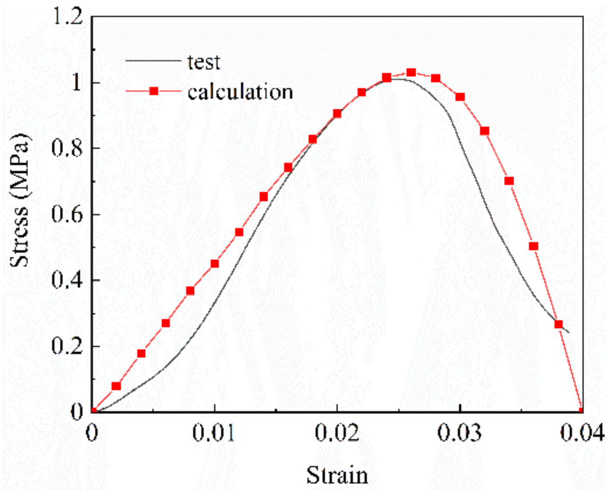
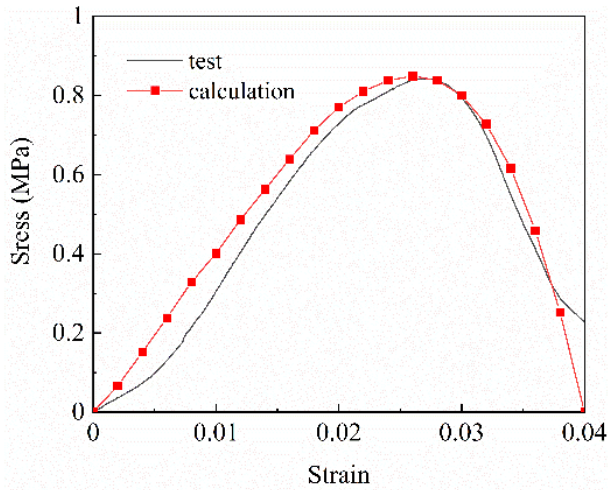


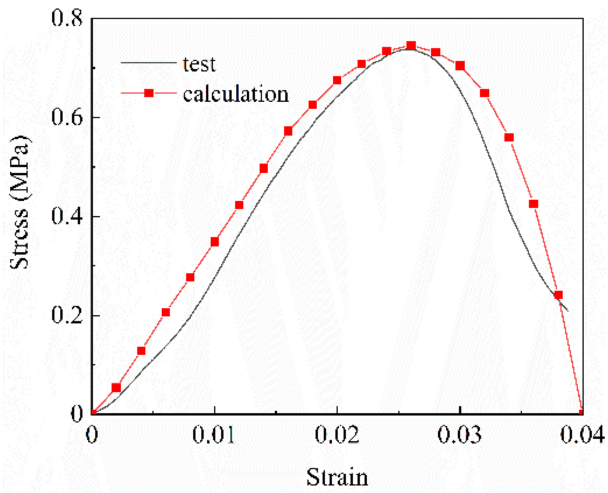
Fig. 4. Damage evolution and stress-strain curves of coal under different adsorption pressures

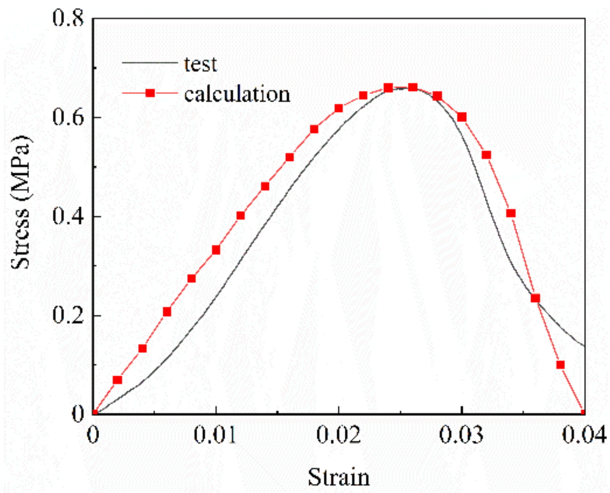
By comparing the stress-strain curve with the damage evolution curve of coal body, Fig. 4 is obtained. It shows that the micro damage stage of coal body can well correspond to the macroscopic deterioration phenomenon. At the beginning of loading, the coal body is in the stage of volume compaction, which corresponds to the closure of micro pores and micro cracks in the meso level. In the middle stage of loading, the coal body changes from the compaction state to the elastic stage, and then enters the post peak expansion stage. At this time, it corresponding to the rapid expansion stage of coal damage, and the meso level of coal body is in the stage of damage evolution and stable expansion. At the end of loading, a large number of macro cracks appear in the coal body, and the coal skeleton is difficult to resist the external load, and finally reaches the bearing limit, which leads to the failure stage of coal body. It corresponds to the damage stage of coal body in the meso level.





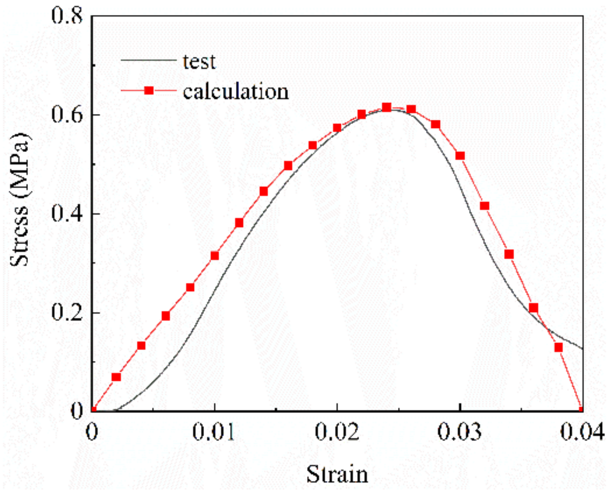
(a) 0.0 MPa (b) 0.4 MPa



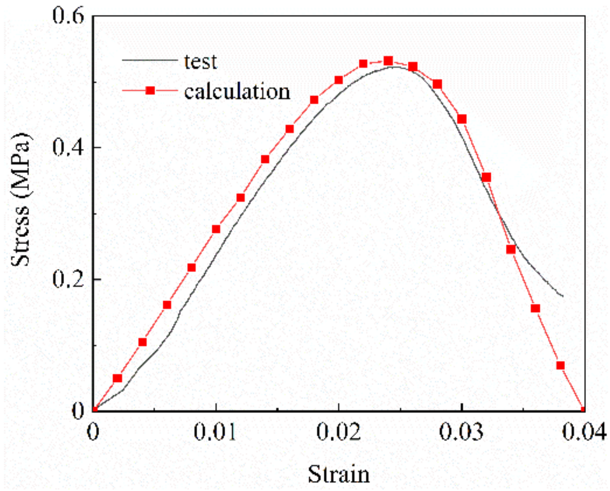


(c) 0.8 MPa

(d) 1.2 MPa



(e) 1.6 MPa



(f) 2.0 MPa

Fig. 5. Comparison of stress-strain curves between uniaxial compression test and model calculation

According to the damage constitutive relation shown in Eq. (16) and the stress-strain curves under different adsorption pressures obtained in the test, the comparison curves between the test and model calculation under different adsorption pressures shown in Fig. 5 are obtained. Through the comparison, it can be seen that under the joint action of gas adsorption and stress loading, the results of damage evolution model can be well consistent with the test results, and the meso damage characteristics of coal can reasonably predict and reveal the macroscopic deterioration phenomenon of coal body.

4. Conclusion

(1) Based on macroscopic phenomenological damage mechanics, considering stress loading damage and gas adsorption damage comprehensively, the bridge between them is built by strain equivalent theory, and the damage evolution equation and damage constitutive equation are deduced. The coal deterioration test with different adsorption pressure was carried out, and the damage evolution characteristics of coal body in different adsorption pressure and loading process were obtained. Through the comparative analysis of model calculation results and test results, the results of damage evolution model and test results can be well consistent, which proves that the model has good applicability and can accurately describe the damage and failure process of coal rock.

(2) By comparing the calculation results of damage evolution equation with the test results, it is concluded that the calculated damage of coal body model increases with the increase of coal body strain, and the initial adsorption damage variable of coal increases with the increase of adsorption pressure. With the increase of adsorption pressure, the stage of rapid damage propagation is obviously shortened, which indicates that the coal is closer to the instability failure under the action of adsorption damage when the adsorption pressure is high.

(3) Through the comparative analysis of damage constitutive equation calculation results and test results, it is concluded that the meso damage stage of coal body can well correspond to the macroscopic deterioration phenomenon. At the beginning of loading, the coal body is in the stage of volume compaction, corresponding to the initial damage stage. In the middle stage of loading, the coal body changes from elastic stage to post peak expansion stage, which corresponds to the rapid expansion stage of coal damage. At the end of loading, a large number of macro cracks appear in the coal body, which leads to the instability failure, corresponding to the damage stage of coal body.

Funding

This research was funded by Natural Science Foundation of Shandong Province (ZR2017MEE023, 2019GSF111036), National Natural Science Foundation of China (51427804).

Conflict of interest

The authors declare no conflict of interest.

Availability of data and material

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

Consent for publication

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

References:

Ahmed Z, Wang SH, Hashmi MZ, Zhang ZS, Zhu CJ (2020) Causes, characterization, damage models, and constitutive modes for rock damage analysis: a review. Arab J Geosci 13(16).

Bale JS, Valot E, Monin M, Polit O, Soemardi T (2016) Experimental analysis of thermal and damage evolutions of DCFC under static and fatigue loading. Revue Des Composites Et Des Matériaux Avancés 26(2):165-184.

Cao WG, Li X (2008) A new discussion on damage softening statistical constitutive model for rocks and method for determining its parameters. Rock and Soil Mechanics 29(11):2952-2956.

Chen S, Qiao CS, Ye Q, Khan MU (2018) Comparative study on three-dimensional statistical damage constitutive modified model of rock based on power function and Weibull distribution. Environ Earth Sci 77(3):108.

Deng J, Gu DS (2011) On a statistical damage constitutive model for rock materials. Comput Geosci-Uk 37(2):122-128.

El-Zohairy A, Hammontree H, Oh E, Moler P (2020) Temperature Effect on the Compressive Behavior and Constitutive Model of Plain Hardened Concrete. Materials 13(280112).

Gao F, Xu AB, Zhou FB (2011) Research on the coal and rock damage and gas permeability in the protective seams mining. Journal of China Coal Society 36(12):1979-1984.

Hu SB, Wang EY, Liu XF (2016) Effective stress of gas-bearing coal and its dual pore damage constitutive model. Int J Damage Mech 25(4):468-490.

Lemaitre J (1972) Evaluation of dissipation and damage in metals submitted to dynamic loading. Evaluation of dissipation and damage in metals submitted to dynamic loading16.

Li LJ, Ruan SH, Zeng L (2014) Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles. Constr Build Mater 70291-308.

Li W, Ren T, Busch A, Hartog SAMD, Cheng Y, Qiao W, Li B (2018) Architecture, stress state and permeability of a fault zone in Jiulishan coal mine, China: Implication for coal and gas outbursts. Int J Coal Geol 1981-13.

Liu XS, Ning JG, Tan YL, Gu QH (2016) Damage constitutive model based on energy dissipation for intact rock subjected to cyclic loading. Int J Rock Mech Min 85: 27-32.

Perera MSA, Sampath KHSM (2019) Modelling of free and adsorbed CO2-induced mechanical property alterations in coal. Int J Coal Geol 217: 103348.

Sobczyk J (2014) A comparison of the influence of adsorbed gases on gas stresses leading to coal and gas outburst. Fuel 115(2):288-294.

Tang CY, Shen W, Peng LH, Lee TC (2002) Characterization of Isotropic Damage Using Double Scalar Variables. Int J Damage Mech 11(1):3-25.

Wang CL, He BB, Hou XL, Li JY, Liu L (2020) Stress–Energy Mechanism for Rock Failure Evolution Based on Damage Mechanics in Hard Rock. Rock Mech Rock Eng 53(3):1021-1037.

Wang HP, Zhang QH, Yuan Liang, Xue JH, Zhang B (2015) Development of a similar material for methane-bearing coal and its application to outburst experiment. Rock and Soil Mechanics 36(6):1676-1682.

Wei MY, Wang CG, Cui GL, Tan YL, Zhang SW (2016) Influences of damage and shear dilation on permeability evolution of fractured coal. Rock and Soil Mechanics 37(2):275-283.

Wold MB, Connell LD, Choi SK (2008) The role of spatial variability in coal seam parameters on gas outburst behaviour during coal mining. Int J Coal Geol 75(1):1-14.

Xu J, Xian XF, Du YG, Zhang GY (1993) An experimental study on the mechanical property of the gas-filled coal. Journal of Chongqing University 05:42-47.

Yang DD, Chen YJ, Tang J, Li XW, Jiang CL, Wang CJ, Zhang CJ (2017) Experimental research into the relationship between initial gas release and coal-gas outbursts. Journal of Natural Gas Science & Engineering 50:157-165.

Yang PY, Wu XE, Chen JH (2018) Elastic and plastic-flow damage constitutive model of rock based on conventional triaxial compression test. International Journal of Heat and Technology 36(3):927-935.

Yang SQ, Xu P, Ranjith PG (2015) Damage model of coal under creep and triaxial compression. Int J Rock Mech Min 80:337-345.

Yang XB, Xia YJ, Wang XJ (2012) Investigation into the nonlinear damage model of coal containing gas. Safety Sci 50(4):927-930.

Yin GZ, Wang DK, Zhang DM, Wang WZ (2009) Test analysis of deformation characteristics and compressive strengths of two types of coal specimens containing gas. Chinese Journal of Rock Mechanics and Engineering 28(2):410-417.

Zhang B, Wang HP, Yuan L, Li SC, Zhang C (2020) A Novel Apparatus for Dynamic-Static Coupling Tests on Gas-Adsorbed Coal. Geotech Test J 43(6):1353-1367.

Zhou HW, Wang CP, Han BB, Duan ZQ (2011) A creep constitutive model for salt rock based on fractional derivatives. Int J Rock Mech Min 48(1):116-121.

Zhu WC, Liu LY, Liu JS, Wei CH, Peng Y (2018) Impact of gas adsorption-induced coal damage on the evolution of coal permeability. Int J Rock Mech Min 101:89-97.

Figures

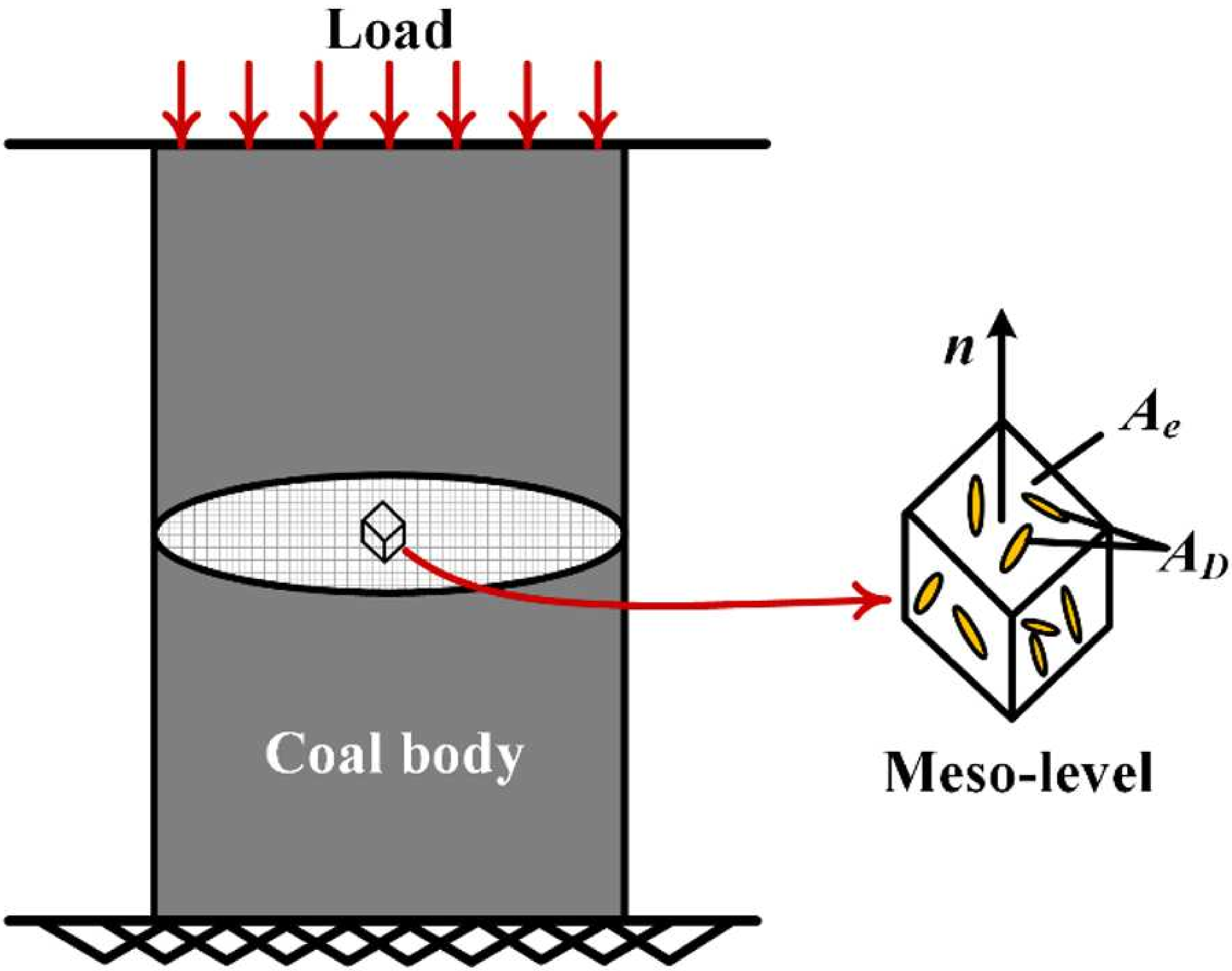


Figure 1

Isotropic damage element of coal body

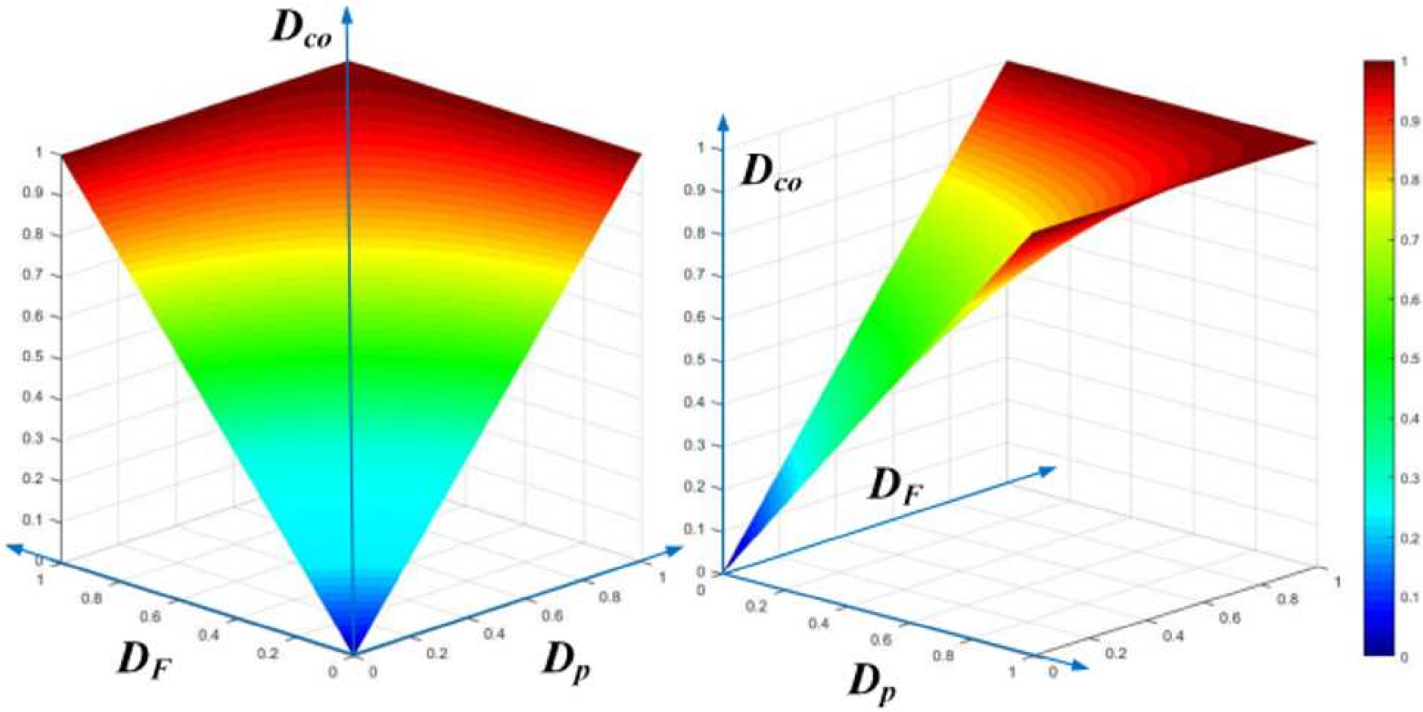


Figure 2

Change image of coupling damage variable under gas adsorption and stress loading

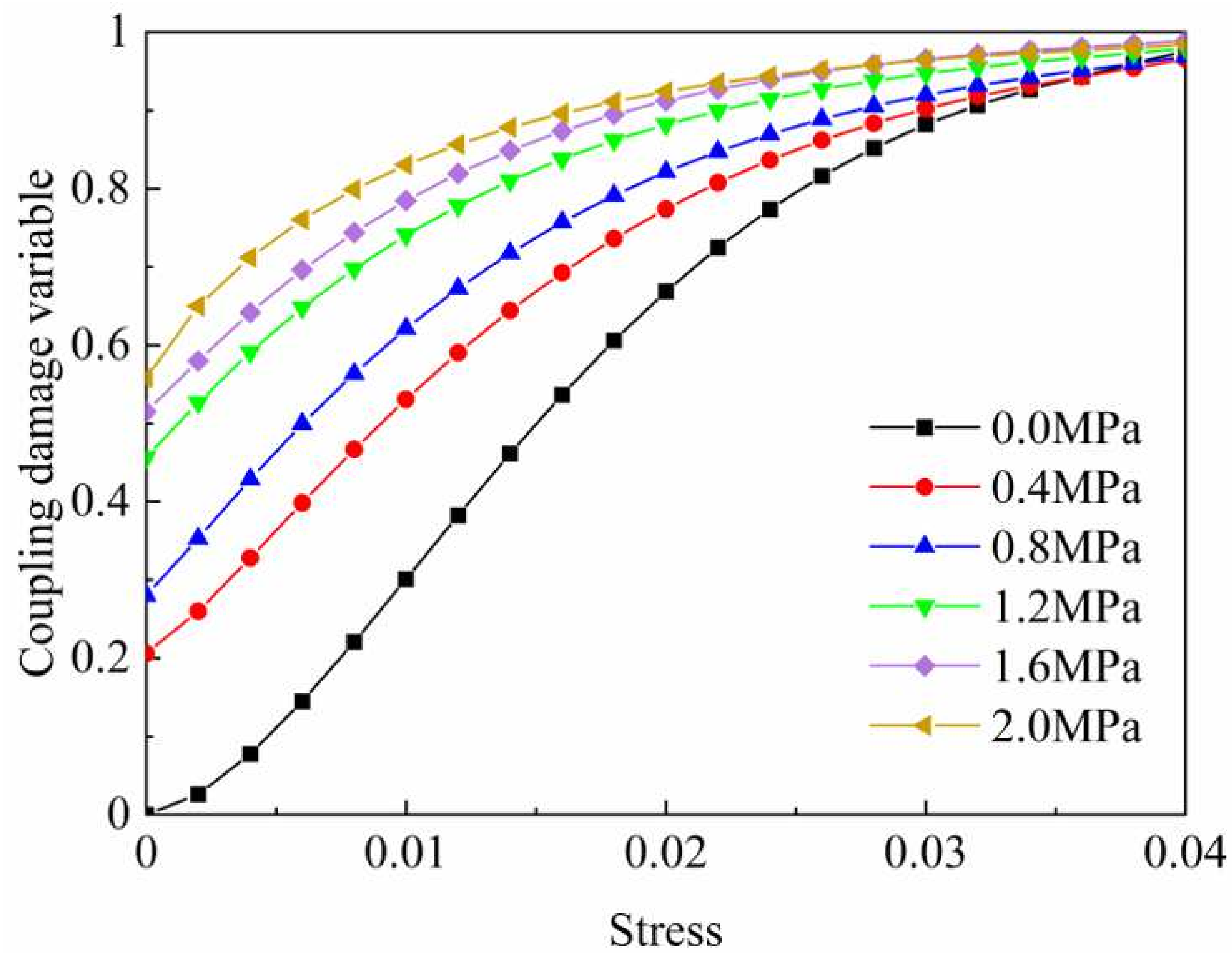


Figure 3

Coupling damage variable evolution curves

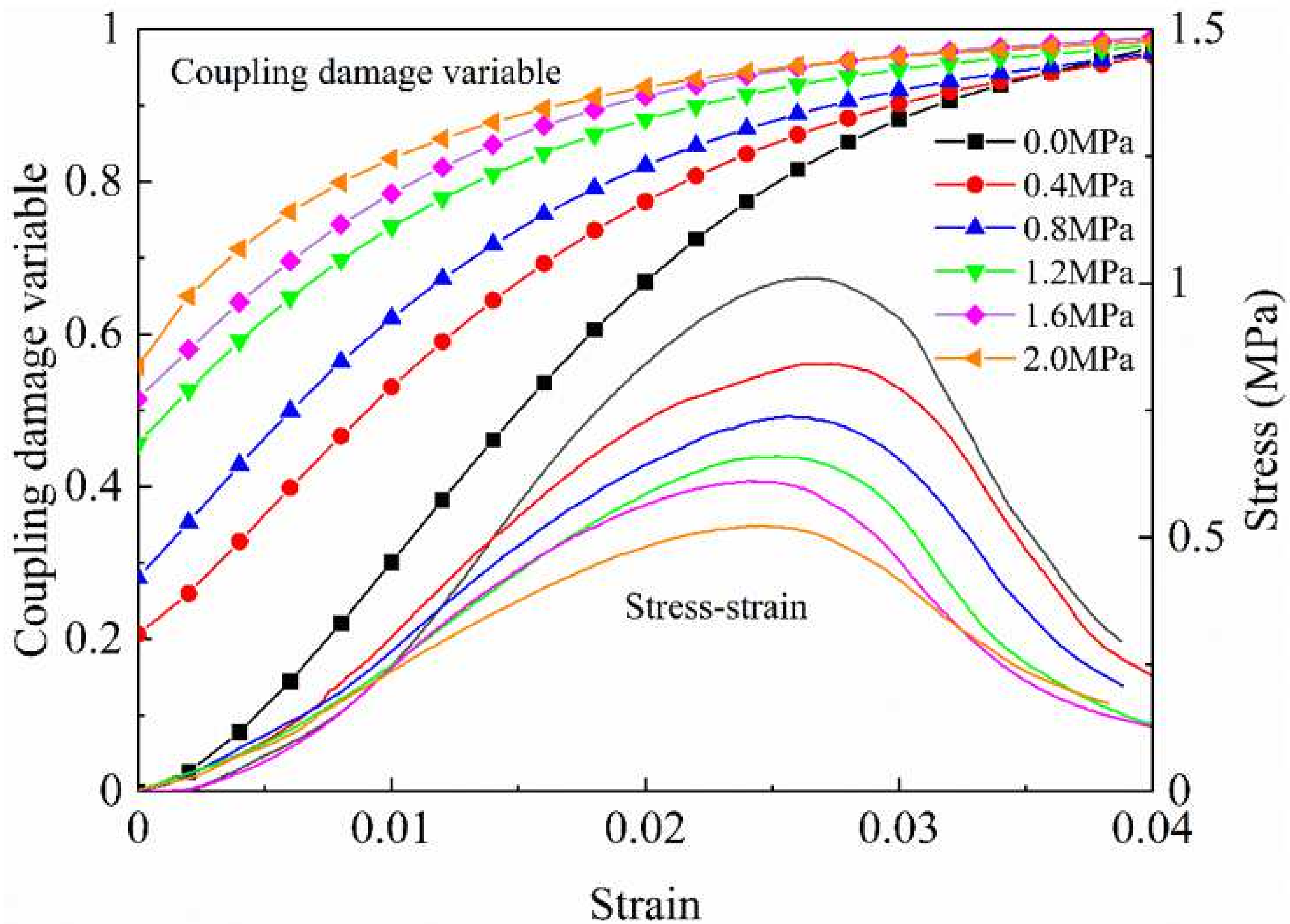


Figure 4

Damage evolution and stress-strain curves of coal under different adsorption pressures

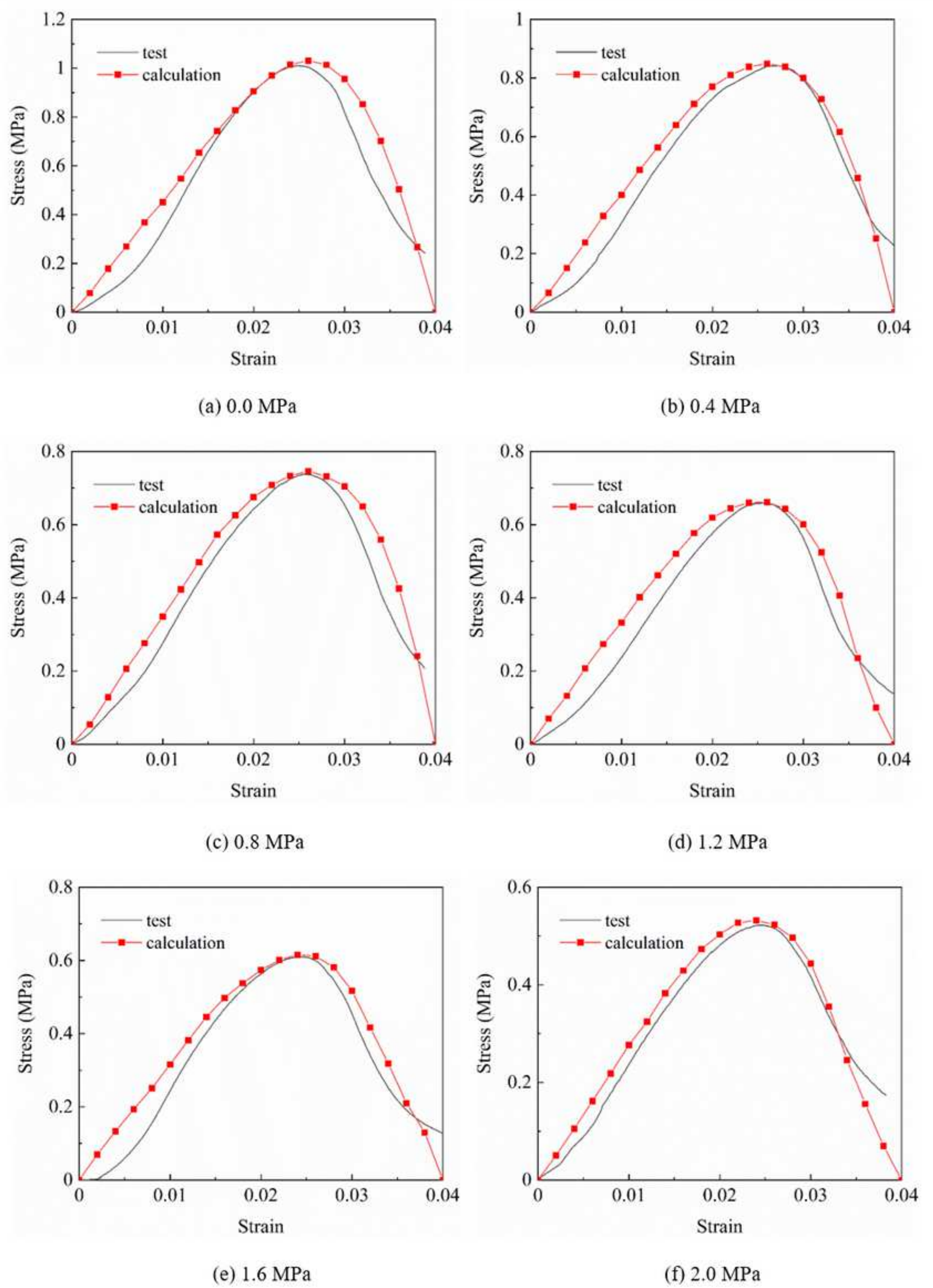


Figure 5

Comparison of stress-strain curves between uniaxial compression test and model calculation