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

Zhongzhong Liu¹,² · Hanpeng Wang¹,² · Su Wang¹,² · Yang Xue¹,² · Chong Zhang¹,²

Received: 6 January 2021 / Accepted: 7 July 2021 / Published online: 20 July 2021
© Saudi Society for Geosciences 2021

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 a 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 the 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

Introduction
Coal and gas outburst is a common dynamic disaster in the coal mine, which is a physicochemical phenomenon of extreme complexity (Sobczyk 2014; Wold et al. 2008; Li et al. 2018; 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 the 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; Müller et al. 2018; Sormunen 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 (Zhou et al. 2011; Deng and Gu 2011; Wang et al. 2020). The isotropic elastic damage statistical constitutive model established by Cao et al. (Cao and Li 2008) can well simulate the axial strain softening under compression but cannot reflect the volumetric dilatancy characteristics. Turichshev and Hadjigeorgiou (Turichshev and Hadjigeorgiou 2016) developed synthetic rock mass bonded block models to simulate the behavior of intact veined rock. Unteregger et al. (Unteregger et al. 2015) presented a constitutive model for describing the nonlinear mechanical behavior of different types of intact rock subjected to complex 3D stress states. Pourhosseini and Shabanimashcool (Pourhosseini and Shabanimashcool 2014) developed a constitutive model to describe the nonlinear behavior of intact rocks under static loading.
Wei et al. (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. (Gao et al. 2011) defined the damage variable of coal rock structure and established the corresponding elastoplastic damage constitutive model. Yang et al. (Yang et al. 2018a) 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.

The gas adsorbed on the coal matrix causes the adsorption expansion stress, which leads to the change of micro-cracks and pores, and finally leads to the deterioration of its mechanical properties. In view of the gas adsorption, Perera and Sampath (Perera and Sampath 2019) established a mechanical model of dual-porosity medium considering the mechanical deterioration effect caused by gas adsorption. Ranathunga et al. (Ranathunga et al. 2016) deduced a new nonlinear damage constitutive model of coal containing gas. Hu et al. (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. (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. (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. (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.

**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 \( n \) direction is \( A \), the effective bearing area in this direction is \( A_e \), and the defect area is \( A_D \), we can get

\[
Ae = A - AD
\]  

And then, the damage variable \( D \) can be defined as

\[
D = \frac{A_D}{A} = \frac{A-Ae}{A}
\]  

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 \( n \). When \( D = 0 \), it corresponds to the nondestructive state of the coal body, and \( D = 1 \) corresponds to the complete fracture state of the 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 \( \sigma_e \) increases. The effective stress \( \sigma_e \) can be expressed as

\[
\sigma_e = \frac{\sigma}{1-D}
\]

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 \( \sigma \) acting on the damaged material is equivalent to the strain caused by the effective stress \( \sigma_e \) acting on the undamaged material. For example, the one-dimensional linear elastic relationship of the damaged material can be expressed as

\[
\varepsilon = \frac{\sigma_e}{E} = \frac{\sigma}{E(1-D)}
\]  

![Fig. 1 Isotropic damage element of the coal body](image)
where $E$ is the elastic modulus of undamaged state of the material, $E_e$ is the elastic modulus of the damaged state of the material, and $\varepsilon$ is strain. The damage of material is considered in the elastic modulus:

$$E_e = (1-D)E$$  \hspace{2cm} (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. Comparing 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:

$$\sigma_1 A_1 = \sigma_2 A_2$$  \hspace{2cm} (6)

$$\varepsilon = \frac{\sigma_1}{E_2} = \frac{\sigma_2}{E_1}$$  \hspace{2cm} (7)

where $\sigma_1, A_1, E_1, \sigma_2, A_2, E_2$ are the effective stress, the effective bearing area, and the elastic modulus of two damaged states, respectively.

The research issue in this paper is the damage and deterioration of coal caused by gas adsorption expansion and stress loading, and the research object is the same kind of coal. Different from the previous research methods, based on the Lemaitre strain equivalent principle, this paper transforms the degradation effect of adsorbed gas and free gas on coal into the change of elastic modulus before and after the action of gas, which can be indirectly measured. 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 $\sigma_0$ 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 $\sigma_p$ and $A_p$. Then, Eq. (8) can be got:

$$\sigma_0 A_0 = \sigma_p A_p$$  \hspace{2cm} (8)

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

$$D_p = \frac{A_0 - A_p}{A_0}$$  \hspace{2cm} (9)

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

$$\sigma_p = \frac{\sigma_0}{(1-D_p)}$$  \hspace{2cm} (10)

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

$$\varepsilon = \frac{\sigma_0}{E_p} = \frac{\sigma_p}{E_0}$$  \hspace{2cm} (11)

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

$$E_p = E_0(1-D_p)$$  \hspace{2cm} (12)

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

$$\sigma_p = E_0(1-D_p)\varepsilon_p$$  \hspace{2cm} (13)

Similarly, according to the assumption of strain equivalence, the state of the 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:

$$\sigma = E_p(1-D_F)\varepsilon$$  \hspace{2cm} (14)

where the $D_F$ is the damage variable of the loading state.

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

$$\sigma = E_0(1-D_p)(1-D_F)\varepsilon$$  \hspace{2cm} (15)

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

$$\sigma = E_0(1-D_{co})\varepsilon$$  \hspace{2cm} (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):

$$D_p = 1 - \frac{E_p}{E_0}$$  \hspace{2cm} (17)

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

$$\frac{dD_F}{d\varepsilon} = \varphi(\varepsilon)$$  \hspace{2cm} (18)
Since the material strength obeys the 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):

$$D_F = 1 - e^{-(\frac{\varepsilon}{n})^k}$$  \hspace{1cm} (19)

where $n$ is the shape parameter, and $k$ is the scale parameter. The damage evolution equation can be deduced as

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

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

By integrating Eq. (18), we can get

$$D_F = \int_0^{E_0} \phi(x) \, dx = 1 - e^{\frac{1}{k} \left(\frac{\varepsilon}{\varepsilon_{\text{max}}}\right)^k}$$  \hspace{1cm} (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:

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

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

Fig. 3 The (a) picture and (b) structure of the test apparatus
When only stress loading is considered, \( E_p = E_0 \), we can get

\[
D_{co} = 1 - \frac{E_p}{E_0} e^{-\epsilon / \epsilon_{\text{max}}} = D_p
\]  

(23)

When only stress loading is considered, \( E_p = E_0 \), we can get

\[
D_{co} = 1 - \frac{E_0}{E_0} e^{-\epsilon / \epsilon_{\text{max}}} = 1 - e^{-\epsilon / \epsilon_{\text{max}}} = D_F
\]  

(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 the coal body and shows an 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.

Model application and verification

Equations (22) and (16) are the damage evolution equation and constitutive equation of the 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 pressures.

Test apparatus

The self-developed visual constant volume gas–solid coupling test system is used for the test (Zhang et al. 2020). The size of the apparatus is 340 mm × 340 mm × 460 mm (length × width × height). The axial loading on the coal sample is given by the press machine with the help of the axial loading piston. The coal sample is loaded in the couple loading chamber, and the high-pressure gas is injected with the gas injection pipe. The silicone rubber sealing cover and the sealing ring are used to seal the high-pressure gas in the coupling loading chamber. 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 axial loading piston 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. The apparatus picture is shown in Fig. 3.

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 (Xu et al. 1993; Yin et al. 2009; Wang et al. 2015). Several standard briquette samples were made using the method raised by Wang et al. (Wang et al. 2015). The pulverized coal used in the test was taken from the B6 coal seam of the Xinzhuangzi mine. The sodium humate was taken as the binder, and the forming pressure was 15 MPa. The main processes are as follows, and the coal samples are shown in Fig. 4.

1. The raw coal was crushed and sieved with a standard screen.
2. The aggregate, binder, and water were weighed according to the ratio.

| Table 1. Preparation parameters of the samples |
| Sample size | Particle size distribution (0–1 mm:1–3 mm) | Concentration of cementing agent (%) | Precast strength (MPa) | Density (kg/m\(^2\)) | Cohesion (MPa) | Porosity (%) |
|-------------|----------------------------------------|---------------------------------|----------------------|-------------------|----------------|--------------|
| ø50×100 mm | 0.76:0.24 | 3.25 | 1.00 | 13.8 | 0.049 | 10 |

Fig. 4 The coal samples used in the test
The binder was dissolved in the water and mixed with the aggregate.

The mixed materials were loaded into the mold and pressed for 10 min.

The samples were unloaded from the mold and then were labeled and cured.

The preparation parameters of the samples are shown in Table 1.

Test scheme

During the test, CO₂ was selected as the test gas and the equilibrium pressure of gas adsorption was taken as 0.0 MPa, 0.4 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa, and 2.0 MPa. In order to avoid temperature interference, the tests were carried out at a constant temperature of 25°C. The axial loading adopts displacement control mode, and the loading speed is 1 mm/min. 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, and the preload is 0.1 MPa. After vacuumizing for 4 h, CO₂ with certain pressure was injected and adsorbed for 24 h.

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

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.

The damage evolution curves of the coal body at different adsorption pressures and stress loading processes are calculated, as shown in Fig. 5.

It can be seen from Fig. 5 that under different adsorption pressures, the calculated damage of the 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, and 2.0 MPa, the initial damage variables of adsorption were 0, 0.206, 0.280, 0.457, 0.515, and 0.558, respectively. The initial damage variable at 2.0 MPa adsorption pressure is 2.7 times that at 0.4 MPa.

| Adsorption pressure (MPa) | \( \sigma_{\text{max}} \) (MPa) | \( \varepsilon_{\text{max}} \) | \( E_0 \) (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           |
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 the coal body is the most obvious when the adsorption pressure is 0.0–1.2 MPa, 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.

By comparing the stress–strain curve with the damage evolution curve of the coal body, Fig. 6 is obtained. It shows that the micro-damage stage of the 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 micropores 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 corresponds to the rapid expansion stage of coal damage, and the meso-level of the 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 the coal body. It corresponds to the damage stage of the coal body in the meso-level.

According to the damage constitutive relation shown in Eq. (16) and the stress–strain curves under different adsorption pressures.

Fig. 7 Comparison of stress–strain curves between uniaxial compression test and model calculation (a) 0.0 MPa (b) 0.4 MPa (c) 0.8 MPa (d) 1.2 MPa (e) 1.6 MPa (f) 2.0 MPa
pressures obtained in the test, the comparison curves between the test and model calculation under different adsorption pressures shown in Fig. 7 are obtained. Also, in order to verify the accuracy of this model, the corresponding comparison with the damage model proposed by Liu is made (Liu et al. 2018). In terms of elastic stage and peak strength, the model proposed in this paper is basically consistent with that proposed by Liu because both of them take into account the damage of gas adsorption on coal. However, when it comes to the yield stage and post-peak plastic stage, because Liu’s model does not consider the superposition of stress loading, its curve tends to be stable, which is quite different from the test results. The model proposed in this paper, based on the Weibull distribution and strain equivalence principle, can be well consistent with the test results in the plastic stage. Through the comparison, it can be seen that under the joint action of gas adsorption and stress loading, the results of the 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.

**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 pressures was carried out, and the damage evolution characteristics of the coal body in different adsorption pressures and loading processes were obtained. Through the comparative analysis of model calculation results and test results, the results of the 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 the damage evolution equation with the test results, it is concluded that the calculated damage of the 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 the 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 the elastic stage to the 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 instability failure, corresponding to the damage stage of the coal body.

Funding This research was funded by the Natural Science Foundation of Shandong Province (ZR2017MEM023, 2019GSF111036) and the National Natural Science Foundation of China (51427804).

Declarations

Conflict of interest The authors declare that they have no competing interests.

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, Valet 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 Soil Mech 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. J China Coal Soc 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

Lemaître J (1972) Evaluation of dissipation and damage in metals submitted to dynamic loading. Evaluation of dissipation and damage in metals submitted to dynamic loading, 16

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 70:291–308

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 198:1–13

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
Liu LY, Zhu WC, Wei CH, Ma XH (2018) Mechanical model and numerical analysis of mechanical property alterations of coal induced by gas adsorption. Rock Soil Mech 39(4):1500–1508
Müller C, Frühwirt T, Haase D, Schlegel R, Konietzky H (2018) Modeling deformation and damage of rock salt using the discrete element method. Int J Rock Mech Min 103:230–241
Perera MSA, Sampath KHSM (2019) Modelling of free and adsorbed CO2-induced mechanical property alterations in coal. Int J Coal Geol 217:103348
Pourhosseini O, Shabanimashcool M (2014) Development of an elastoplastic constitutive model for intact rocks. Int J Rock Mech and Min Sci (Oxford, England : 1997) 66(66):1–12
Ranathunga AS, Perera M, Ranjith PG (2016) Influence of CO2 adsorption on the strength and elastic modulus of low rank Australian coal under confining pressure. Int J Coal Geol 167:148–156
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
Sormunen O, Castren A, Romanoff J, Kujala P (2016) Estimating sea bottom shapes for grounding damage calculations. Mar Struct 45:86–109
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
Turichshev A, Hadjigeorgiou J (2016) Development of synthetic rock mass bonded block models to simulate the behaviour of intact veined rock. Geotech Geol Eng 35(1):1–23
Unteregger D, Fuchs B, Hofstetter G (2015) A damage plasticity model for different types of intact rock. Int J Rock Mech and Min Sci (Oxford, England : 1997) 80:402–411
Wang HP, Zhang QH, Yuan L, Xue JH, Li QC, Zhou W, Li JM, Zhang B (2015) Development of a similar material for methane-bearing coal and its application to outburst experiment. Rock Soil Mech 36(6):1676–1682
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
Wei MY, Wang CG, Cui GL, Tan YL, Zhang SW (2016) Influences of damage and shear dilation on permeability evolution of fractured coal. Rock Soil Mech 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. 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. J Chongqing Univ (05):42–47
Yang XB, Xia YJ, Wang XJ (2012) Investigation into the nonlinear damage model of coal containing gas. Saf Sci 50(4):927–930
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 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. J Nat Gas Sci Eng 50:157–165
Yang PY, Wu XE, Chen JH (2018a) Elastic and plastic-flow damage constitutive model of rock based on conventional triaxial compression test. Int J Heat Technol 36(3):927–935
Yang PY, Wu XE, Chen JH (2018b) Elastic and plastic-flow damage constitutive model of rock based on conventional triaxial compression test. Int J Heat Technol 36(3):927–935
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. Chin J Rock Mech Eng 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):20190272
Zhou HW, Wang CP, Han BB, Duan QZ (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 permeabil-