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Mechanical properties and damage constitutive model of coal under the coupled hydro-mechanical effect

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Abstract: In order to explore the impact of moisture on the mechanical properties of coal, the triaxial compression tests of raw coal with different moisture contents are carried out by using the triaxial servo-controlled seepage equipment for thermal-hydro-mechanical coupling in coal containing methane. Based on elastic damage mechanics, the damage variables of coal with different moisture contents are deduced, and the damage constitutive model of coal under hydro-mechanical coupling is established, the deformation characteristics of coal with different moisture contents are obtained. The results show that: (1) the deformation and failure process of coal under different moisture contents are similar, which can be divided into pre-peak stress stage, post-peak stress stage and residual stress stage; (2) as the moisture content increases, the peak stress, elastic modulus and brittleness of coal decrease, but the Poisson's ratio increases; (3) the damage constitutive model of coal can better represent the deformation characteristics of coal in the complete stress-strain process under different moisture contents, which is suitable for the analysis of the triaxial compressive stress-strain of coal under different moisture contents; (4) both the damage correction coefficient q and the damage constitutive coefficient n determine the curve shape of the damage constitutive model. The damage correction coefficient reflects the characteristics of residual deformation of coal, and the damage constitutive coefficient reflects different degrees of post-peak strain softening of the stress-strain curve.

Keywords: coal; damage; moisture content; constitutive relation; coupled hydro-mechanical

1 Introduction

Safety, green and innovation are the three major themes of current coal mining industry[1]. After the long-term complex diagenesis, the coal has very strong coupling effect controlled by various geological effects and external environment. Large-scale construction projects such as geothermal engineering and exploitation of mineral resources tend to gradually develop into deep depth. The mechanical characteristics of coal become more and more complicated due to the erosion by natural groundwater or artificial engineering water[2]. Therefore, the study on the mechanical characteristics during the damage and failure process and the damage constitutive model of coal considering the hydro-mechanical coupling effect is helpful to accurately judge the safety and stability of coal and provides theoretical and scientific basis for a series of engineering projects.

Many scholars have established relevant damage models for brittle materials such as coal. Cao et al.[3-4] put forward the concept of rock microelement strength based on the Drucker-Prager criterion and Mohr-Coulomb criterion. They established the rock damage statistic constitutive model based on the strength criterion, assuming that the rock microelement strength obeys the normal distribution. Wang et al.[5] obtained the rock damage constitutive model under the triaxial stress condition considering the Hoek-Brown strength criterion as the statistical distribution variable of rock microelement, whose strength obeys the Weibull distribution. Li et al.[6] modified the Lemaitre strain equivalence hypothesis. Based on the Mohr-Coulomb criterion and using Weibull distribution, they established the rock damage constitutive model which takes into account the sliding friction. Wang et al.[7] carried out dynamic compression tests on granite and discussed the effects of temperature and strain rate on the dynamic properties of granite, and they established the damage constitutive model that can accurately describe the effects of temperature and strain rate on rock stress-strain response. Li et al.[8] summarized the shortcomings of previous rock damage statistic constitutive models and introduced the initial damage coefficient in the newly established rock damage constitutive model that reflected the heterogeneity, nonlinear characteristics and residual strength of rock to some extent. Liu et al.[9] combined the Weibull statistic damage constitutive model with the fracture mechanics model and proposed the irreversible plastic strain model. Their established damage model can reflect the hysteretic

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stress–strain curve and cumulative fatigue plastic deformation of the rock under the cyclic loading. Zhu et al.[10] deemed that the damage of coal is mainly caused by tensile failure, and the failure mode of coal can be judged by the maximum tensile stress criterion and Mohr-Coulomb criterion. They established the staged damage permeability model of coal. Qin et al.[11] studied acoustic emission characteristics of coal with different contents of water under uniaxial compression, and they compared the mechanical properties with the acoustic emission characteristics. Pan et al.[12] carried out the loading and unloading tests on coal with five different water contents to analyze the effect of matrix moisture on the gas diffusion in coal. Based on the theory of damage mechanics, Wang et al.[13] assumed that the strength of rock microelement obeyed the random Weibull distribution, and they introduced the effective stress principle into the pore pressure to establish the rock statistic damage constitutive model.

Many researchers carried out a series of studies to illustrate the influence of moisture content on rock mechanical behaviors. Kang et al.[14] analyzed the influence of water content on the rock mechanical properties using damage mechanics analysis. He considered the volume change caused by rock expansion in the damage variable, and established the damage constitutive model under the relationship between rock state and moisture content. Taking into account the influence of moisture content on the mechanical and deformation characteristics of red sandstone, Hu et al.[15] put forward a damage statistic model considering the effect of moisture, and obtained the mechanical damage law of rock at different water contents. Wang et al.[16] compared the uniaxial compression tests of the raw coal and briquette with different water contents, and studied the differences of their deformation characteristics. They deduced the segmented damage statistic constitutive model considering the water content. Li et al.[17] carried out triaxial compression tests of sandstone under different confining pressures and different water contents. They analyzed the mechanical properties of sandstone under different water contents from the aspect of energy evolution. Zhou et al.[18] carried out experiments about the mechanical characteristics of rocks in different states of saturated water. They studied the shear strength, tensile splitting strength and uniaxial compressive strength at different water saturations, as well as the variation law with the saturated water time. Based on continuum damage mechanics and statistical theory, Deng et al.[19] combined the damage of water-rock interaction caused by cyclic immersion–air drying into the constitutive model, and they established the statistic damage constitutive model of sandstone considering the water-rock interaction. Based on the theory of damage mechanics, Liu[20] established the water damage constitutive equation of rock regarding the immersion time and porosity as the damage variables. Liu et al.[21–22], Fu et al.[23] analyzed the mechanical strength characteristics of sandstone obtained from the Three Gorges Reservoir region under the effect of water-rock interaction based on the rock mechanics test.

The mechanical characteristics of water-bearing coal have been studied experimentally by many researchers, but the influence of hydro-mechanical coupling effect on the mechanical properties of coal requires further studies. In addition, most of the studies applied statistic damage models and there are some differences between model curves and experimental results. The coal is brittle and the traditional statistic damage variables based on the Weibull distribution function can not accurately describe the coal damage characteristics. Based on the Lemaitre strain equivalent hypothesis and elastic damage mechanics, this paper derived the variables of the overall damage in the segmented coal with different moisture contents. The segmented damage model of coal under hydro-mechanical coupling effect was established and the triaxial compression tests under different moisture contents were carried out. The rationality of the model was verified by experiments. Furthermore, the mechanical characteristics and evolution process of damage under different moisture contents were discussed, and the relationship between the mechanical characteristics parameters and water content was analyzed, which can be regarded as the theoretical background for the analysis and design of coal mining engineering affected by water contents.

2 Experimental method

2.1 Specimen preparation

The test coal sample was obtained from the #3 coal seam of Zhaozhuang mine, which belongs to Shanxi Jincheng Anthracite Coal Group Corporation Ltd. The selected test coal sample is the high-order anthracite and there is no obvious crack[24]. Table 1 is the proximate analysis of the studied coal seam. First, the original coal sample obtained is sealed with plastic film and placed into a wooden box. The concrete is then poured, and the core sample with the dimension of ϕ50 mm× 100 mm is taken with a core drilling machine after the concrete has been completely hardened. Then it is polished with a grinder[25]. The samples are dried for 24 hours at 80 ℃ with an oven and they are preserved in a drying tank for experiments.

The detailed preparation process for raw coal samples with different moisture contents are as follows:

(1) The manufactured coal samples are dried for 72 hours in the vacuum drying oven to ensure that the coal samples can be absolutely dried. Then the dry weight M_0 of coal samples is obtained.

(2) The prepared dry coal samples are divided into 3 groups and one group is soaked in a vacuum sealed container filled with pure water to make the coal samples water saturated. Then the weight of the water-bearing sample (M_s) is obtained, and the moisture content (m) of the coal sample is

$$m = \frac{M_s - M_0}{M_0} \times 100\% \qquad (1)$$

(3) The step (2) is repeated in other two groups of

coal samples during the treatment process. All these 3 groups of raw coal samples with different water contents are obtained[26].

Table 1 Proximate analysis of anthracitic coal

Coal sample	Moisture /%	Ash content /%	Volatile matter /%	Fixed carbon /%
Zhaozhuang 3#	1.76	11.84	10.76	75.64

2.2 Test scheme

The triaxial servo seepage test device for thermal-fluid-solid coupling is applied for methane bearing coal[27], as shown in Fig. 1. The CH_4 with the purity of 99.99% is adopted in the experiments and the depth of coal seam is about 1200 m. In order to better simulate the real underground environment of coal samples, the stress at the depth of coal samples is set as the test stress, i.e., the gas pressure is 1 MPa and the confining pressure is 2 MPa, and the temperature is 30°C. The constant displacement (i.e., 0.1 mm/min) control mode is applied in axial compression load on coal samples with the water contents of 0%, 2.87% and 3.39%, respectively, until the damage of the test coal samples. The specific test steps are shown in Xu et al. [28]

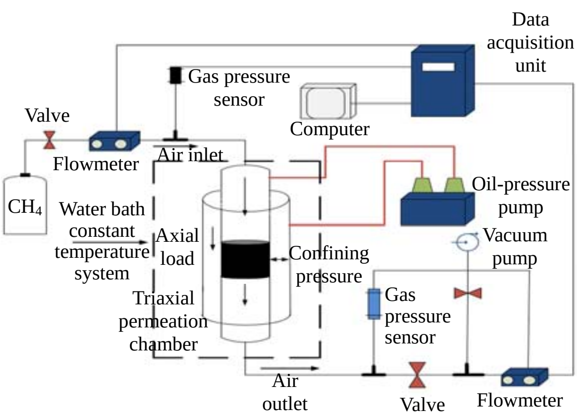

Fig. 1 Schematic diagram for test device system[29]

a) Installation of coal samples. b) Sealing of the apparatus. c) Vacuum degasification. d) Adsorption equilibrium. e) The confining pressure is maintained at 2 MPa, and the gas pressure is maintained at 1 MPa. The experimental temperature is 30 ℃. The axial stress is placed under the displacement control mode with the rate of 0.1 mm/min until the failure of coal, and the deformation characteristics of the coal samples are measured. f) The specimens are replaced and the triaxial compression tests on coal samples with the water contents of 2.87% and 3.39% are carried out.

3 Damage evolution of coal under hydro-mechanical coupling effect

3.1 Damage of coal affected by water content

Different water contents in the internal structure of coal play the significant impacts on the mechanical properties of coal. The mechanical properties of coal, especially the elastic modulus will be degraded by the moisture. According to the theory of macroscopic damage mechanics, in order to characterize the impact of different water contents on coal, the difference in elastic modulus can be used. Assuming that there is no damage of coal when the water content is 0, the variation of elastic modulus under different water contents are used to define the water damage variable as[30]

$$D_W = 1 - \frac{E_W}{E_0} \qquad (2)$$

where D_W is the damage variable of coal with the water content of *W*; E_0 is the elastic modulus of coal with the water content of 0; and E_W is the elastic modulus of coal with the water content of *W*.

3.2 Stress damage

According to the Lemaitre strain equivalence hypothesis[31], the strain caused by the nominal stress acting on the damaged material is equal to the strain caused by the effective stress acting on the intact material, and the following relationship is obtained:

$$[\sigma^*] = [\sigma]/(1 - D_\varepsilon) = [C][\varepsilon]/(1 - D_\varepsilon) \qquad (3)$$

where $[\sigma]$ is the nominal stress tensor; $[\sigma^*]$ is the effective stress tensor; $[\varepsilon]$ is the strain tensor; $[C]$ is the elastic modulus tensor; and D_ε is the damage variable.

Considering that the coal has a certain residual strength after damage, the damage correction coefficient *q* is introduced to modify the damage constitutive model of coal[32]:

$$[\sigma^*] = [\sigma]/(1 - qD_\varepsilon) = [C][\varepsilon]/(1 - qD_\varepsilon) \qquad (4)$$

The damage of micro-elements under the external load is random, and the damage mechanical properties can't be characterized by a single characteristic value. The deformation of coal under external load conditions at the pre-peak stage is regarded as elastic deformation because of the obvious brittleness, and there is no obvious plastic deformation. The traditional statistic damage variables based on Weibull distribution function can't accurately describe the damage and failure characteristics of coal. This paper describes the constitutive model of the micro-element based on elastic damage mechanics. Assuming that the initial strain of coal under load is linear, the damage degradation degree of the micro-element based on the elastic damage constitutive relationship in Fig. 2, can be expressed as [33]

$$D_\varepsilon = \begin{cases} 0 & \varepsilon_1 < \varepsilon_{co} \\ 1 - (\varepsilon_{co}/\varepsilon_1)^n & \varepsilon_{co} \leqslant \varepsilon_1 \leqslant \varepsilon_{cr} \\ 1 - \lambda\varepsilon_{co}/\varepsilon_1 & \varepsilon_1 \geqslant \varepsilon_{cr} \end{cases} \qquad (5)$$

where ε_{co} is the strain at the peak stress; ε_{cr} is the compressive strain at residual compressive strength; λ is the residual strength factor; and *n* is the damage constitutive coefficient.

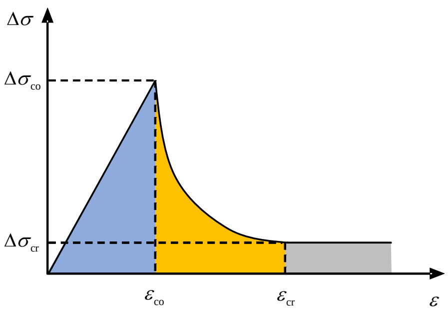

Fig. 2 Elastic damage constitutive law of elements under triaxial compressive stress

In the triaxial compressive test in this paper,

$$\sigma_2 = \sigma_3 \tag{6}$$

$$\Delta\sigma = \sigma_1 - \sigma_3 \tag{7}$$

where $\Delta\sigma$ is the deviatoric stress (MPa); σ_1 is the axial stress (MPa); and σ_3 is the confining pressure (MPa).

Assuming that the properties of coal are isotropic at the macroscopic scale[34], the stress–strain relationship of coal at the elastic stage follows the generalized Hooke's law[35]. According to Eqs. (4) and (7), the coal damage constitutive equation can be written as

$$\Delta\sigma = E\varepsilon_1(1-qD_\varepsilon)+(2u-1)\sigma_3 \tag{8}$$

where E is the elastic modulus (MPa); u is the Poisson's ratio; and ε_1 is the axial strain.

3.3 Hydro-mechanical coupling damage model

In order to consider the influence of moisture on coal damage constitutive relationship, the elastic modulus can be obtained by Eq. (2):

$$E = E(W) = E_W = (1-D_W)E_0 \tag{9}$$

Under the hydro-mechanical coupling effect, the coal has different damage characteristics. Substituting Eq. (9) into Eq. (8) yields

$$\begin{aligned}\Delta\sigma = E_0\varepsilon_1(1-D_W)(1-qD_\varepsilon)+(2u-1)\sigma_3 = \\ E_0\varepsilon_1(1-D)+(2u-1)\sigma_3\end{aligned} \tag{10}$$

The damage variable of the overall coal damage under different water contents can be expressed as

$$D = D_W + qD_\varepsilon - qD_\varepsilon D_W \tag{11}$$

By combining Eqs. (5), (10) and (11), the segmental damage constitutive model of coal under the hydro-mechanical coupling can be obtained as

$$\Delta\sigma = \begin{cases} E_0\varepsilon_1(1-D_W)+(2u-1)\sigma_3 & \varepsilon_1 < \varepsilon_{co} \\ E_0\varepsilon_1\left\{1-\left[D_W+q-q(\varepsilon_{co}/\varepsilon_1)^n - qD_W + qD_W(\varepsilon_{co}/\varepsilon_1)^n\right]\right\}+(2u-1)\sigma_3 & \varepsilon_{c0} \leqslant \varepsilon_1 \leqslant \varepsilon_{cr} \\ E_0\varepsilon_1\left[1-(D_W+q-q\lambda\varepsilon_{co}/\varepsilon_1 - qD_W + qD_W\lambda\varepsilon_{co}/\varepsilon_1)\right]+(2u-1)\sigma_3 & \varepsilon_1 \geqslant \varepsilon_{cr} \end{cases} \tag{12}$$

4 Results analysis and model verification

4.1 Experimental results and analysis

According to the triaxial compression tests, the deviatoric stress–strain curves of coal at the gas pressure of 1 MPa, the confining pressure of 2 MPa, the temperature of 30 ℃, and the water contents of 0, 2.87%, and 3.39% can be obtained, as shown in Fig. 3.

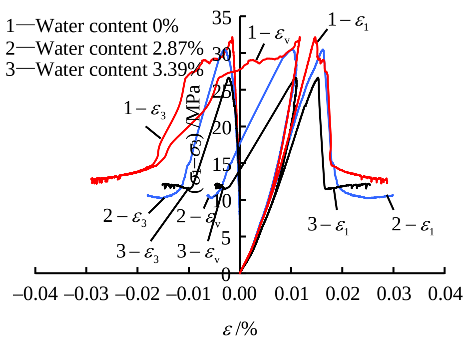

Fig. 3 The deviatoric stress–strain curves of coal with different moisture contents

Under the conditions of constant temperature, gas pressure, and confining pressure, as the water content in coal increases, the triaxial compressive strength of coal decreases. The variation characteristics under the water contents of 0, 2.87%, and 3.39% are basically similar during the deformation and failure process. This is consistent with the previous results[36–38], which reflects the damage effect of moisture on the mechanical properties of coal and the stress–strain curve is shown in Fig. 4.

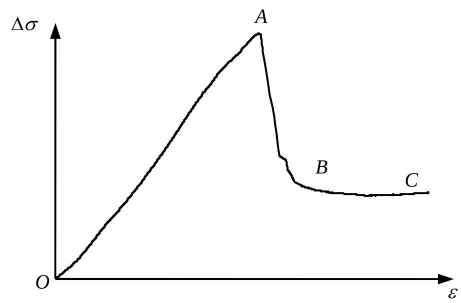

Fig. 4 Schematic diagram of coal deformation and failure process

The whole stress–strain curve of coal under triaxial compression can be divided into three stages: pre-peak stage (*OA*), including initial compaction, linear elasticity and yield, post-peak stress drop stage (*AB*) and residual strength stage (*BC*).

(1) Pre-peak stage. During the initial compaction stage of coal, micro-pores and micro-cracks develop inside the coal. These micro-defects are compacted and closed as the axial stress increases. At the linear

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elastic stage, as the axial stress rises, the coal exhibits similar elastic deformation characteristics. The mechanical properties of coal are relatively stable, and the elastic modulus remains basically constant. Due to the obvious brittleness of coal, large pores and cracks are formed at the yield stage of the pre-peak period. They continue to develop towards macroscopic fractures. It can be seen from Figs. 3 and 4 that the whole stress–strain curve of coal at the pre-peak stage is basically linear. Therefore, the deformation of coal under external load conditions at the pre-peak stage is regarded as elastic deformation. The damage variable that characterizes the damage and degradation degree of coal can be regarded as 0.

(2) Post-peak stress drop stage. When the stress is loaded to the compressive strength, the failure occurs. With the increase of the axial strain, the axial stress drops significantly, which is caused by the obvious brittleness of coal. Under the continuous action of axial stress, a large number of micro-cracks in the coal coalesce to form macro-cracks, resulting in the loss of partial bearing capacity and the occurrence of stress drop.

(3) Residual strength stage. With the further development of deformation, the coal still has a certain bearing capacity at the residual strength stage after failure. The concave and convex parts of the internal structure are worn or sheared with the further development of deformation. The crack aperture is reduced. The destroyed coal shows a certain degree of compaction and closure under the action of confining pressure. The obvious deformation occurs after it attains to the residual strength[39].

Figure 3 shows the strength and deformation of raw coal with the water contents of 0%, 2.87%, and 3.39%, respectively. Their respective deformation parameters are also calculated. Figures 5–7 are the variation trends of elastic modulus, peak stress and Poisson's ratio with water content in coal. It is shown that the peak stress and the elastic modulus decrease as the moisture content in the coal sample grows, but the Poisson's ratio rises. The elastic moduli of coal with the moisture contents of 0%, 2.87%, and 3.39% are 2360.0, 2076.8, and 1935.2 MPa, respectively. The elastic modulus of coal with the water content of 2.87% is about 12% lower than that of the sample with the water content of 0, while the elastic modulus of coal with the water content of 3.39% is about 6.8% lower than that of the sample with the water content of 2.87%. The peak stresses of coal samples with the water contents of 0%, 2.87%, and 3.39% are 31.52, 30.47, and 26.59 MPa, respectively. The peak deviatoric stress of coal with the water content of 2.87% is about 3.3% lower than that of the sample with the water content of 0. The peak deviatoric stress of coal with the water content of 3.39% is about 12.7% lower than that of the sample with the water content of 2.87%. As the water content rises from 2.87% to 3.39%, the Poisson's ratio also increases from 0.25 to 0.3 with a significant increase rate of 20%.

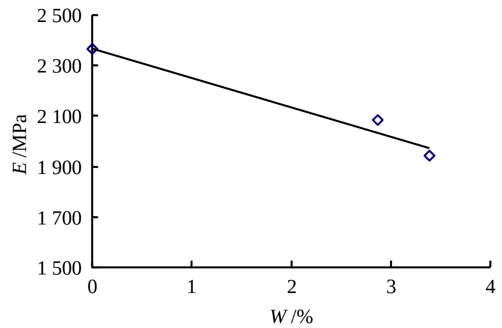

Fig. 5 Relationship between elastic modulus and moisture content

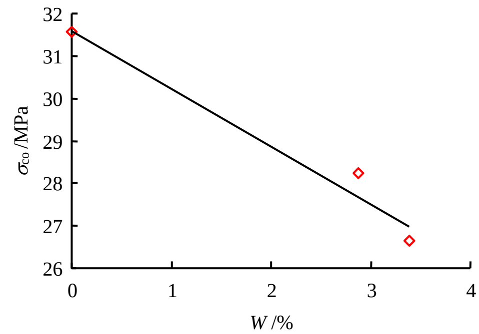

Fig. 6 Relationship between peak stress and moisture content

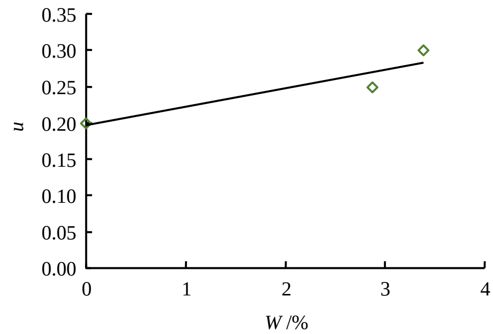

Fig. 7 Variation of Poisson's ratio with moisture content

The damage effect of water on coal is mainly due to:

(1) Damage caused by bound water. The bound water is the water bound on the surface of coal rock due to the adsorption of coal to water exceeding its own gravity. The water adsorbed on the surface of coal will cause the hydrolysis reaction between the colloid and soluble salt. The mechanical strength of coal will be reduced because of the decrease in the connection force and friction between molecules of coal.

(2) Damage caused by free water. Free water is not subjected to force and is mainly affected by gravity. Free water produces water pressure on the pores of coal. When the coal is under a certain load, the water can't be discharged in time, which will cause high pore pressures in the pores and cracks. It makes the ends of micro-cracks in the coal structure stay at a state of tension with concentrated stress, which leads to the expansion in the coal.

The bound water causes the initial damage, and the free water causes superimposed damage during the loading process. The combined action of them aggravates the damage of coal[40].

4.2 Verification of damage constitutive model

To explain the rationality of the constitutive model of coal under different water contents based on elastic damage mechanics, the obtained damage statistic parameters are substituted into the constitutive model, and the model curves are drawn in turn. The conventional triaxial compression test curves of coal under three water contents are compared. Table 2 lists the parameter values in coal damage constitutive model under different water contents.

Table 2 Parameters in the coal damage constitutive model with different moisture contents

W /%	$\Delta\sigma_{co}$ /MPa	ε_{co} /%	ε_{cr} /%	D_W	u	q	n	λ	E /MPa
0.00	31.52	0.014	0.018	0.00	0.20	0.90	5	0.47	2 360.0
2.87	28.17	0.016	0.019	0.12	0.25	0.90	6	0.34	2 076.8
3.39	26.59	0.015	0.017	0.18	0.30	0.90	9	0.39	1 935.2

The elastic modulus of coal under three different water contents is calculated by using test data. The test data is substituted into Eq. (2), and the damage variable D_W at different water contents of coal is calculated. The deviatoric stress of the damage constitutive model under the hydro-mechanical coupling effect can be obtained by substituting relevant test data into Eq. (12). The parameters in the damage constitutive model with different water contents are listed in Table 2. Using the established damage constitutive model of coal under hydro-mechanical coupling effect, the theoretical curves of deviatoric stress–strain with water contents of 0, 2.87%, and 3.39% are calculated, respectively. The theoretical curves and experimental curves of deviator stress–strain at different water contents are compared and analyzed. Figure 8 shows the comparison between the deviatoric stress-strain test curve and the theoretical curves of coal under different water contents.

From Fig.8, it can be observed that the segmented damage constitutive model of coal established in this paper under the hydro-mechanical coupling can better capture the variation of coal strength under different water contents. At the pre-peak stage, the test and theoretical curves under different water contents show good consistency. The axial strain basically increases linearly with the increase of axial stress. At the post-peak stress drop stage, as the axial strain increases, the internal damage of coal continues to develop. Both the theoretical and test curves deviate from the straight line and show a slight downward bending trend. The peak strength decreases with the increase of water content. The peak stress and strain in the experimental and theoretical curves are basically the same, reflecting the rationality of established model. With the further development of deformation, the coal still has a certain bearing capacity at the residual strength stage after failure. The destructed coal has a certain degree of compaction and closure affected by the confining pressure. From the variation trend of theoretical and experimental curves, the stress–strain curves of coal with different stages during the deformation and failure process can be better characterized by the theoretical curve.

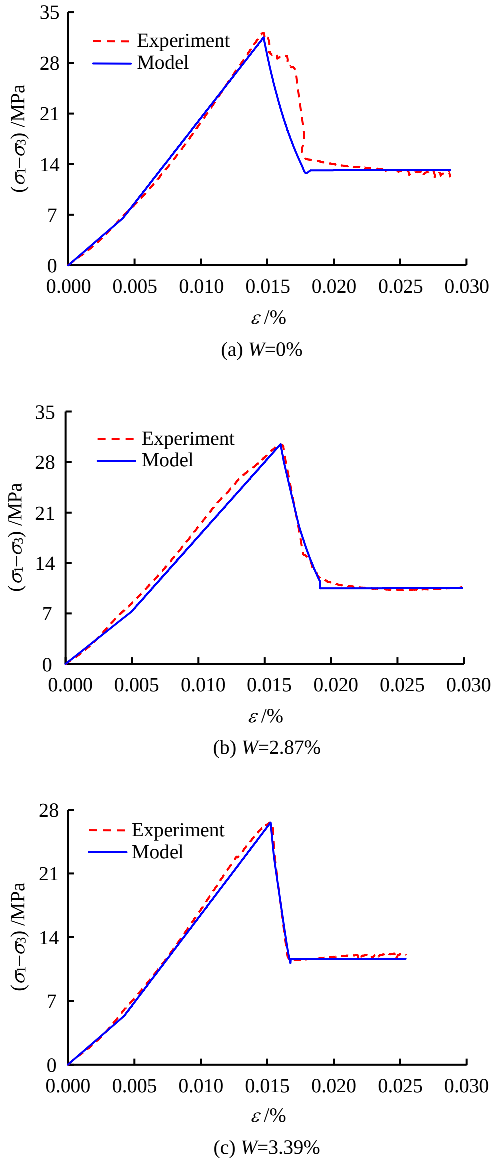

Fig. 8 Comparison between experimental and theoretical curves in coal damage constitutive model

4.3 Effect of model parameters

On the basis of model verification, the model parameters are analyzed to further verify the rationality of the model. Figures 9 and 10 show the influences of parameters q and n on the theoretical curve of the coal segmental damage constitutive model when other variable parameters remain unchanged.

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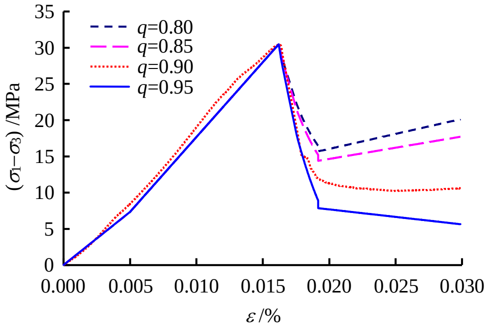

Fig. 9 Effect of parameter *q* on theoretical deviatoric stress–strain curves

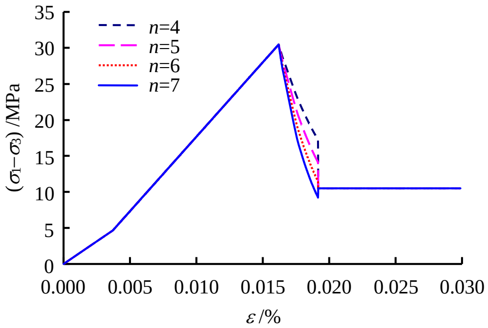

Fig. 10 Effect of parameter *n* on theoretical deviatoric stress–strain curves

It can be seen from Fig.9 that q can reflect the post-peak shape of the theoretical curve in the constitutive model. With the decrease of damage correction coefficient q, the post-peak curve of the model firstly slows down and then steepens, and the stress drop rate slows down. The parameter q can be used to measure the strength of the damaged rock at the post-peak. It can be found that q mainly reflects the residual deformation characteristics of coal. It can be noticed from Fig.10 that the similar macroscopic stress–strain curve can be obtained by using three different damage constitutive coefficients n. Comparing these three curves in Fig.10 shows that the peak stress and initial elastic modulus are approximately the same. They have little impact on the pre-peak stress stage and the residual stage. But there are certain differences in the post-peak region of these stress-strain curves. Three different damage constitutive coefficients reflect different softening degrees after peak. The curve shape of damage constitutive model established in this paper is mainly determined by the parameters q and n.

5 Conclusions

In order to study the evolution law of coal damage characteristics under hydro-mechanical coupling, the overall damage variables of segmented coal under different water contents are derived based on elastic damage mechanics. The segmental coal damage constitutive model under hydro-mechanical coupling is established and some conclusions can be drawn:

(1) The deformation and failure process of coal at different water contents can be divided into pre-peak stress stage, post-peak stress stage and residual stage. The mechanical characteristics of deformation and failure are basically similar. The initial damage process caused by bound water is combined with the superimposed damage caused by free water during the loading process. The combined action of bound water and free water aggravate the damage of coal.

(2) As the moisture content increases, the peak stress of raw coal affected by moisture decreases, the Poisson's ratio increases, the elastic modulus decreases linearly, and the brittleness gradually decreases.

(3) The established damage constitutive model of segmental coal under the hydro-mechanical coupling is in good agreement with the test curve, which is capable for analyzing the triaxial compressive stress and strain problems under different moisture conditions.

(4) The analysis and comparison of different parameters in the damage constitutive model suggest that q reflects the characteristics of residual deformation of coal and n reflects different softening degrees of the stress–strain curve at the post-peak. The curve shape of the established damage constitutive model is mainly determined by the parameters q and n.

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