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ORIGINAL PAPER

The nonlinear creep behavior and creep damage constitutive model of coal rock

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Abstract
The creep behavior of coal rock is one of the most important factors which impacts on the stability of coal mine. In this study, the raw coal blocks mined from Baode coal mine in Shanxi were collected and prepared into briquette coal specimens. And the creep behavior of coal rock was accurately analyzed. Results show that the stress levels have a significant effect on coal rock creep processes; the complete three stage of creep process only occur at relatively high stress level. And the ratio of creep deformation to the total strain shows a trend of decreasing firstly and then increasing, which indicated the damage effect caused and accumulated by creep. Moreover, the failure angle decreases with the increase of the confining pressure, indicating the deformation increasement of specimens, which is consistent with the larger increase of radial deformation in the test results. An elastic–plastic damage body was proposed based on the tests and the damage mechanics theory and then replace the viscous element in Nishihara model to construct a new nonlinear creep damage constitutive model. Comparative analysis of experimental data and fitting results found that the model can better reflect the three stage of creep process (decelerating creep stage, stable creep stage, accelerating creep stage) and the nonlinear creep damage behavior of coal rock. The new model can provide theoretical basis for further revealing the creep damage behavior of gas well coal rock.

Keywords Briquette · Creep · Damage mechanics · Confining pressure · Constitutive model

Introduction

In underground mining engineering, coal rock creep can lead to large deformation and even destabilization damage, which often results in serious production disasters and human casualties. However, as a double-pore medium (Guo et al. 2018), the properties of coal rock are influenced by various factors: the initial damage state of the material, strength, stress environment, and so on. The strength of raw coal specimens cut from natural coal rock has great dispersion properties, so it is of great significance to prepare briquette coal specimens to study the mechanical properties and creep behavior of coal rocks (Meng et al. 2021; Gan et al. 2021).

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In practical engineering, rocks are subjected to three-dimensional stress; it is very necessary to study long-term deformation properties through indoor creep tests. Over the past years, researchers have carried out a lot of studies on the large deformation properties of rocks based on creep tests (Liu et al. 2019b, a; Zhao et al. 2021, 2017). The geological environment is complex and variable, which lead to a certain amount of microfractures within the rock (Zhang et al. 2020). As a high-accident rate industry (Xue et al. 2022), coal mining requires special attention to safety risks which associated with the changes of coal rock properties. Due to the tests obtained from raw coal specimens are discrete (Liu et al. 2021b, a), the indoor creep tests with briquette coal specimens are needed to investigate coal rock creep properties.

In recent years, many scholars have obtained a lot of research results by studying the various properties of rocks under different environmental conditions (Zhou et al. 2022; Li et al. 2022; Gao et al. 2022), among which the time-dependent properties of rocks have been fully verified (Cheng et al. 2021; Li et al. 2017; Ramesh and Hajibeygi 2021). As one of the hot topics, the creep behavior has been mainly studied by creep curve characters (Zuo et al. 2000), proposed physical creep models which were based on the theory of mechanics (Zhang et al. 2019; Cao et al. 2020), and improving elements to simulate creep processes (Zhou et al. 2013; Liu et al. 2020). To better understand the creep behavior of rock, it is very necessary to build a creep model to describe the whole creep process, while current creep models are limited by linear elements. Therefore, combining with damage mechanics theory and based on the damage effects accumulated during the creep tests to improve one or more elements and rebuilding a creep damage model seems an urgent mission for characterizing creep behavior of rock mass.

In this study, the briquette coal specimens were taken from coal rock blocks from the Baode coal mine in Shanxi Province; then triaxial compression tests and triaxial-graded loading creep tests were conducted to obtain the mechanical and creep behavior. Combining with the damage mechanics theory, an elastic–plastic damage body was proposed to describe the accelerating creep stage, and the creep damage constitutive model was established by replacing the viscous element in the Nishihara model. It is found that the model can better reflect the whole process of coal rock creep behavior compare with the Nishihara model, and the rationality and validity of the model was verified.

Materials and methods

Test equipment

The creep tests of coal rock are performed in TFD-2000 microcomputer servo-controlled triaxial rheological testing machine, as shown in Fig. 1. The testing machine mainly comprises the following parts: the axial pressure loading system, the confining pressure loading system, the software control system, and the data acquisition system. It can perform uniaxial compression test, triaxial compression test, and triaxial creep test and has two kinds of control model, which are displacement control and load control. The main technical parameters of the testing machine are its maximum axial force is 2000 kN, the maximum confining pressure is 80 MPa, the maximum axial deformation is 50 mm, and the maximum radial deformation is 25 mm. The deformation of those specimens can be measured by axial and radial sensor. The precision of all measured parameters is 0.5%. The measurement is collected by software control system automatically to eliminate manual error.

Specimen preparation

Coal rock blocks were prepared from the Baode coal mine in Shanxi Province, China. Due to the low success rate of specimen processing and the existence of many impurities and natural cracks, the raw coal specimens cannot be regarded as homogeneous materials (Liu et al. 2021b, a); in order to obtain a homogeneous and continuous rock material, theoretically, it should be reshaped; therefore, briquette coal specimen is selected for tests; the specific procedures for the specimen preparation are as follows (Zhang et al. 2020; Liu et al. 2020):

Step 1: Crushed the raw coal block into coal powder with different particle sizes, put it into the vibrating sifter and sieved it for half an hour, as shown in Fig. 2a. The 0.18–0.25-mm (60–80 mesh) coal powder was took as the

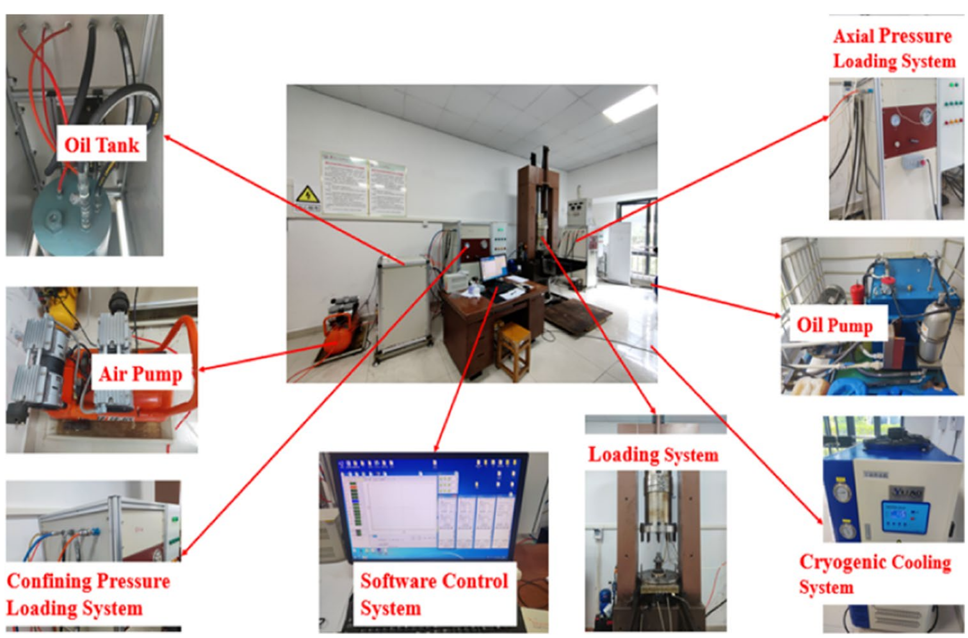


Fig. 1 Triaxial creep testing equipment

main test material. Twenty-eight grams of coal powder was mixed with 3 g of water until it did not adhere to the inside of the container and then put it into the mold, as shown in Fig. 2b.

Step 2: Used the load control to slowly apply the forming pressure to 100 MPa (Liu et al. 2020), after reaching the set value, the pressure will be lasted for 1 h. Then a briquette coal specimen with 25-mm diameter and 50-mm high was reshaped according to the International Society for Rock Mechanics (ISRM).

Step 3: The specimen was placed in a room temperature environment and dried naturally for 9 h (Liu et al. 2020), and then, a group of specimens with approximately equal acoustic wave velocity were selected by acoustic wave tester, as shown in Fig. 2c.

Preliminary experiments

The depth of the raw coal mine is known to be approximately 300 m; then, based on a vertical stress gradient γ of 25 kPa/m and considering the effect of the unloading envelope caused by the mining process, it is decided that the test confining pressures were 2, 4, 6, and 8 MPa, respectively. In order to better simulate the actual working conditions. The test procedures are listed in Table 1.

Before the creep test, the triaxial compression tests were conducted at a loading rate of 0.5 MPa/s (Zhao et al. 2021), and the loading rate was proven feasible through pre-tests. The basic physical and mechanical parameters of coal rock are shown in Table 2, and the stress–strain curves of the triaxial compression tests of coal rock are given in Fig. 3.

Creep test procedure

It can be easily found from the numerical span of the elasticity modulus in Table 2 that the specimen is more sensitive when the confining pressure is 4 and 6 MPa, so the triaxial-graded loading creep tests were conducted under the confining pressure of 4 and 6 MPa. The main steps of the triaxial-graded loading creep tests are as follows:

Table 1 Basic parameters of the specimens and test procedures

Specimen no	*H*/mm	*D*/mm	*W*/g	Test type	σ_3/MPa
S1	50.97	25.25	28.9	Triaxial compression	2
S12	51.96	25.51	29.9		4
S10	51.07	25.53	29.9		6
S13	51.06	25.33	29.9		8

Step 1: Put the briquette coal specimen into the loading chamber as shown in Fig. 4. A loading rate of 0.5 MPa/s (Zhao et al. 2021) was used to apply the axial loads and confining pressures until the specimen reach hydrostatic pressure condition ($\sigma_1 = \sigma_3$). Keep the confining pressure at a constant value and then applied axial loads to the predetermined value (40% of the peak strength) with the same loading rate; keep this axial stress constant and lasted for 12 h; meanwhile, the axial and radial strains were recorded automatically.

Step 2: The 10% of the peak strength of the triaxial compression tests was chosen as the stress increasement, and the triaxial-graded loading creep tests were conducted under the same loading rate of 0.5 MPa/s and the same confining pressures. The detailed loading stress values are shown in Table 3. It should be mentioned that each stress level lasted for 12 h and then applied next loading level until failure occurs.

Step 3: The acquisition interval is 10 s; the data can be collected more frequently and uniformly, allowing for the observation of subtle changes in stress–strain during the rheological process.

Results and discussion

Analysis of coal rock creep behavior under graded loading

The creep test curves are shown in Fig. 5. It was found that the complete creep failure time of coal rock is approximately 58.65 h under the confining pressure of

(**a**) Sieving (**b**) Briquette mold (**c**) Briquette specimen

Fig. 2 Preparation process of briquette coal specimens

Table 2 Triaxial compression results of coal rock under different confining pressures

Confining pressure (MPa)	Peak strength (MPa)	Axial peak strain (%)	Radial peak strain (%)	Volumetric peak strain (%)	Elasticity modulus (MPa)
2	6.79	2.109	−3.270	−4.431	4.042
4	11.18	2.876	−2.652	−2.427	4.522
6	14.76	2.912	−3.807	−4.703	7.078
8	17.15	3.903	−4.556	−5.209	7.500

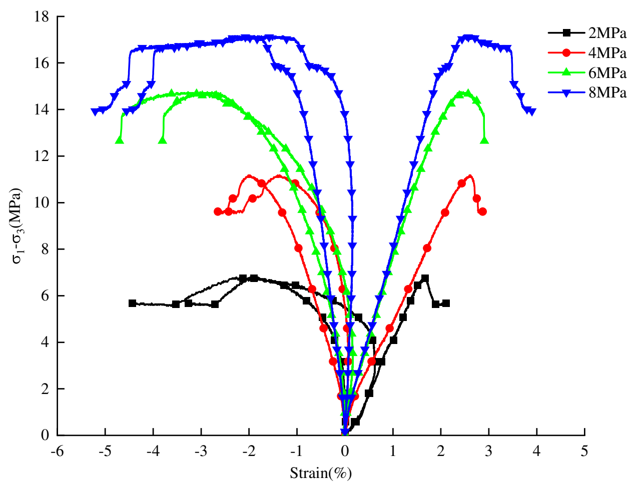


Fig. 3 Stress–strain curves under different confining pressures

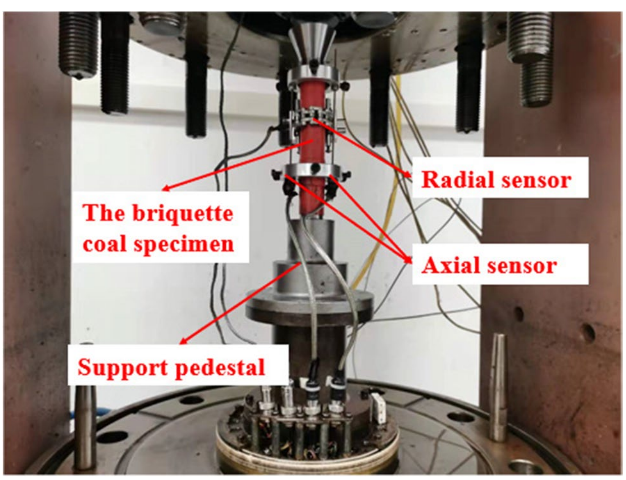


Fig. 4 Loading schematic

6 MPa, the axial failure creep deformation is 0.390%, the radial failure creep deformation is – 22.906%, and the failure stress is 6.51 MPa. Under the confining pressure of 4 MPa, the complete creep failure time of coal rock is approximately 54.33 h, the axial failure creep deformation is 0.386%, the radial failure creep deformation is – 11.394%, and the failure stress is 5.30 MPa. This phenomenon indicates that an increase in the confining pressure will increase the strength and enhances the ability to resist deformation of coal rock. The creep parameters under different confining pressure are listed in Table 3.

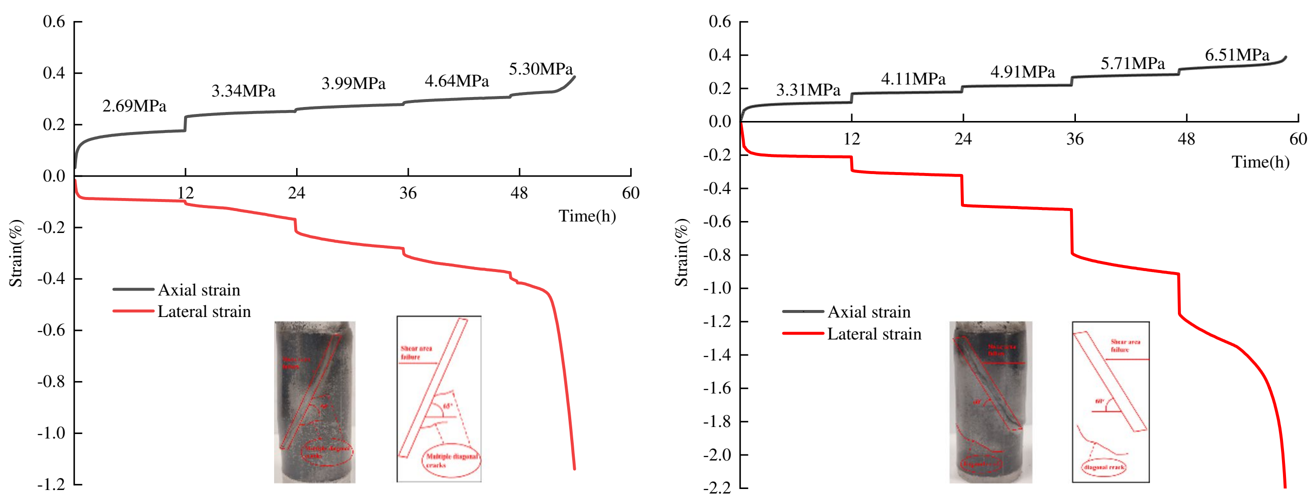
It can be seen from Fig. 5 that the radial creep behavior is relatively obvious than the axial one, which presents a radial expansion effect. This is because the radial binding force provided by the confining pressure plays an obvious role, which can effectively curb the rapid increase of radial deformation. The radial creep deformation in the early part is provided by the closure of pores inside the specimen, while the development and expansion of cracks provide the radial creep deformation in the later part. Like axial creep curve, the ratio of irreversible creep deformation to total strain in the radial creep curve also decreases firstly and then increases, and the creep deformation in the accelerating creep stage is more pronounced when the stress level is higher. Therefore, it is necessary to analyze the effect of the damage caused and accumulated by creep deformation when coal rock is failure.

It is also can been obtained from Fig. 5 that the stress levels have a significant effect on coal rock creep processes. When the confining pressure is constant and the stress levels are graded raised, it was found that the creep deformation and the ratio of creep deformation are both decreased firstly and then increased when stress level is less than 80% of the peak strength. In other words, only decelerating creep and stable creep occur under a relatively low stress level. While the accelerating creep stages occurs when the stress level is 80% of the peak strength, both the axial and radial strains increased rapidly until failure of specimens at this stress level. So, it can be generalized that the coal rock creep enters the decelerating creep and then stable creep stage with time when the stress remains constant at relatively low stress level. The accelerating creep stage only occurs when the stress level is at a relatively high stress level (Liu et al. 2019b, a).

Although the axial deformation increases with the stress level in general, the ratio of creep deformation to total strain shows a trend of decreasing firstly and then increasing. This phenomenon indicates the internal cracks within

Table 3 Creep parameters under different confining pressure

σ_3/MPa	Level (%)	$\sigma_1-\sigma_3$/MPa	Axial deformation (%)		The ratio of creep deformation to total strain
			Total	Creep	
4	40	2.69	0.176	0.144	0.816
	50	3.34	0.251	0.021	0.086
	60	3.99	0.278	0.021	0.074
	70	4.64	0.307	0.022	0.072
	80	5.30	0.386	0.073	0.188
6	40	3.31	0.116	0.103	0.892
	50	4.11	0.179	0.011	0.061
	60	4.91	0.219	0.009	0.040
	70	5.71	0.284	0.018	0.062
	80	6.51	0.390	0.076	0.195



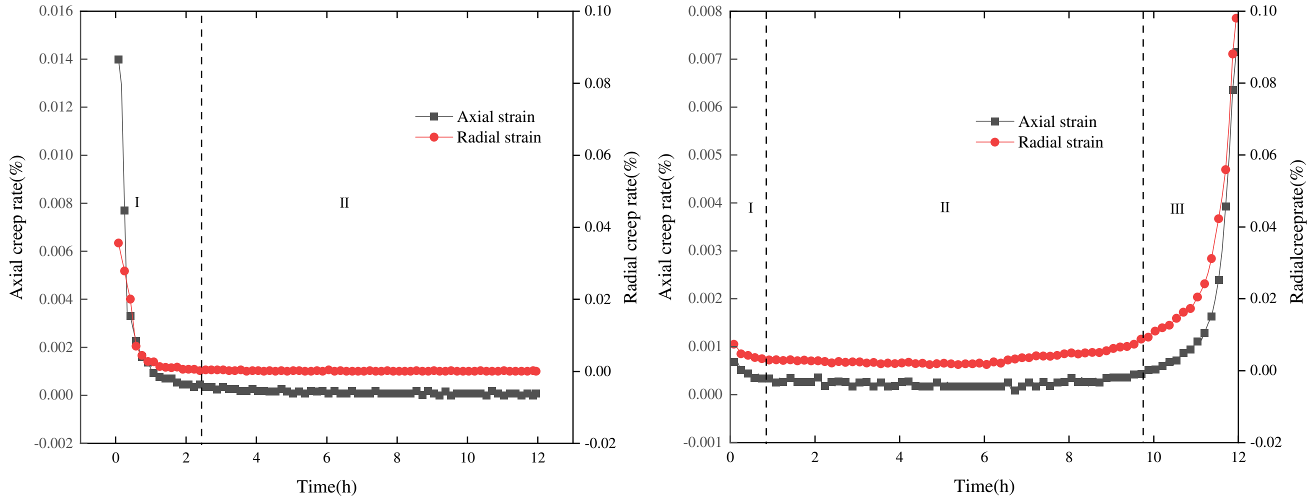
(**a**) σ_3 = 4 MPa (**b**) σ_3 = 6 MPa

Fig. 5 Creep test curves

coal rock develop and expand as the stress levels increase, causing the creep deformation (irreversible viscoelastic strain) to increase continuously, and the axial and radial deformations of the rocks also increased dramatically. It results in continuous damage, significant deterioration processes occur in the internal micro-elements of coal rock, and failure occurs when the damage accumulates to a certain level within coal rock.

Take the creep test results of coal rock under the confining pressure of 6 MPa as an example; Fig. 6 shows creep rate curve of coal rock when stress level is 3.31 MPa and 6.51 MPa, respectively. When the stress level is 3.31 MPa, the specimen first experiences a short instantaneous deformation and then enters decelerating creep stage (I); after 2.49 h, the specimen enters stable creep stage (II). There is no accelerating stage creep due to the relatively low stress level. When the stress level is 6.51 MPa, after 0.86 h of decelerating creep stage (I), the specimen enters stable creep stage (II), which lasted for 8.83 h, and then enters accelerating creep stage (III), which maintain for 2.30 h before failure occurs.

From Fig. 6, the radial creep rate is greater than the axial creep rate, indicating that radial creep of coal rock is more sensitive than axial creep. In the case of constant confining pressure and increasing stress level, the outside environment provides more energy to the interior of the system. Then, the volumetric deformation starts to expand swiftly due to the rapid increase of radial deformation, and the expansive radial creep could be related to creep-induced fractures. Therefore, it is more reasonable to use the radial creep characteristics to determine whether creep damage occurs in the rock.



(**a**) σ_1-σ_3 = 3.31 MPa (**b**) σ_1-σ_3 = 6.51 MPa

Fig. 6 Creep rate curve under the confining pressure of 6 MPa

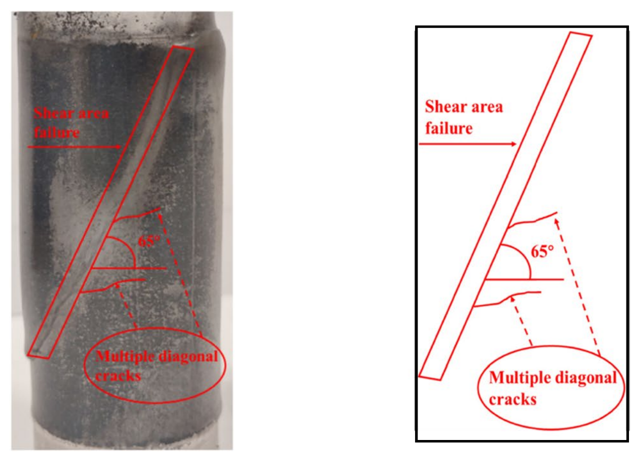
Coal rock failure modes

Sketches of the failure to the briquette coal specimen can be drawn after triaxial-graded loading creep tests, the failure modes of specimens as shown in Fig. 7.

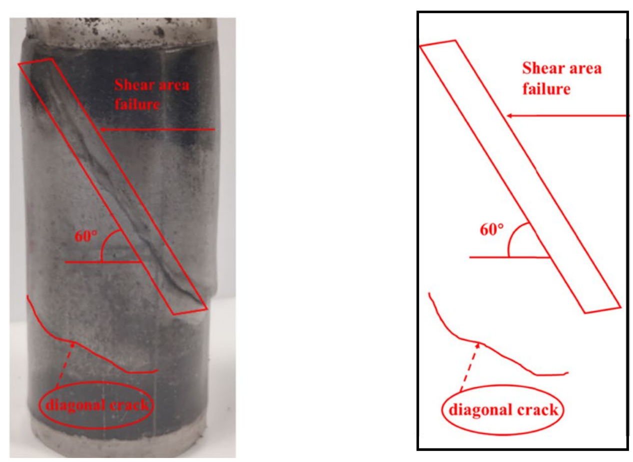
When the confining pressure is 4 MPa, a combined mechanism of the shear failures and the multiple diagonal cracks were observed in the specimen and indicating a plastic failure with a failure angle of 65° (Abolfazl and Davood 2021). The radial deformation of the specimen was greater than the axial deformation due to the specimen undergoes a large plastic deformation. It reflected in a bulge in the middle of the specimen, which also proves that shear damage has occurred. The skeleton could not continue to carry the force when the damage accumulated to a certain extent, and the shear surface is further extended, forming a macroscopic misshapen damage surface.

When the confining pressure is 6 MPa, a combined mechanism of the shear area failure and the diagonal crack was observed in the specimen and indicating a plastic failure with a failure angle of 60°, it is found that a small amount of tiny cracks appears next to the main oblique shear damage cracks. It indicates that the increase of confining pressure caused the larger energy required for deformation and damage of the specimen, so more energy is absorbed and dissipated. And more energy is required for the development and expansion of cracks within coal rock due to the limitation of the confining pressure, which creates more micro-cracks on a macro scale.

Comprehensively, it can be seen that the creep failure of the briquette coal specimen is in the form of overall fragmentation, mainly with obvious oblique penetration through the shear area failure and accompanied by a small



(**a**) σ_3 = 4 MPa



(**b**) σ_3 = 6 MPa

Fig. 7 Failure modes and sketches in creep tests amount of secondary diagonal tensile crack failure along the main crack. The specimens' main crack runs through the rock mass, which is caused by the crack expansion after failure (Shen et al. 2022). And the failure angle decreases as the confining press increases, which indicated that the deformation increasement of specimens is consistent with the lager increase of radial deformation in the test results. Therefore, the specimens are predominantly shear damaged with a small amount of tensile damage.

The nonlinear creep damage constitutive model of coal rock

Nishihara model

Coal rock creep processes exhibiting significant cohesive-elastic–plastic behavior have been showed in many studies (Yan et al. 2020; Lin et al. 2020). And among the traditional creep models, the Nishihara model can well-express the creep behavior, as shown in Fig. 8.

The Nishihara model creep equation is

$$\varepsilon = \begin{cases} \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left[1 - \exp\left(-\frac{E_1}{\eta}t\right)\right] & (\sigma \le \sigma_s) \\ \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left[1 - \exp\left(-\frac{E_1}{\eta}t\right)\right] + \frac{\sigma-\sigma_s}{\eta_2}t & (\sigma > \sigma_s) \end{cases} \quad (1)$$

where ε is the strain of rock; σ is the load stress on the rock; and t is the time.

Creep constitutive model based on damage mechanics theory

Establishment of an elastic–plastic damaged body

The Nishihara model is still composed of linear components; existing studies have pointed out (Yu et al. 2020; Liu et al. 2021b, a; Liu and Li 2018) that the Nishihara model has limitations in describing the accelerating creep stage. While, coal rock, as a typical soft rock, shows instantaneous deformation, decelerating creep, and stable creep when the applied load is less than the long-term strength, however, the deformation is reversible; then, coal rock does not accumulate damage. On the other hand, an irreversible creep deformation of coal rock occurs when the load applied exceeds the long-term load. Damage within coal rock begins to accumulate and an accelerating phase occurs; eventually, the macroscopic failure occurs. The description of the accelerating creep has always been a difficult problem (Wang et al. 2019, 2016), so the damage mechanics theory was used to characterize the effect of damage on the accelerating creep stage and then uses an elastic–plastic damage body to describe the accelerating creep stage.

The elastic–plastic damage body is shown in Fig. 9, where the total micro-element body N is divided into two parts, one is the undamaged linear elastic part N_1; the other is the damaged micro-element N_2:

$$N = N_1 + N_2 \quad (2)$$

Assuming that the elastic–plastic damaged body is subjected to an average stress of σ_0, the damaged part of the micro-element body cannot bear the load, so the load is all borne by the undamaged part, which is subjected to a stress of σ'_0. Therefore, according to the micro-element physical equilibrium and geometric relationship, it can be expressed as:

$$\sigma_0 N = \sigma'_0 N_1 \quad (3)$$

The damage variable or damage factor D can be defined as

$$D = 1 - N_1/N \quad (4)$$

When $D = 0$ and $N_2 = 0$, the rock is in the elastic deformation stage, the deformation can still be recovered after the pressure is removed, and no damage accumulates inside the specimen.

When $D = 1$ and $N_1 = 0$, the rock cannot continue to bear the load; then, the specimen damage occurs. Therefore, the damage variable D should satisfy $D \in [0,1]$.

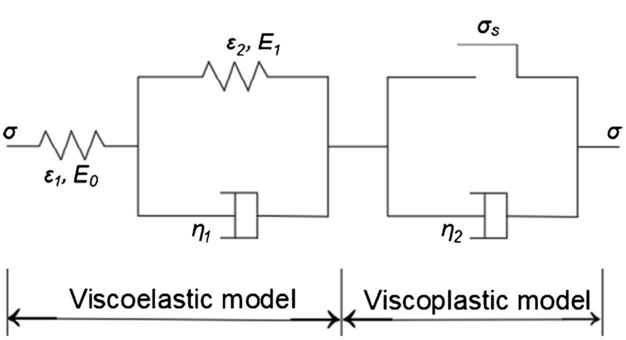


Fig. 8 Nishihara model

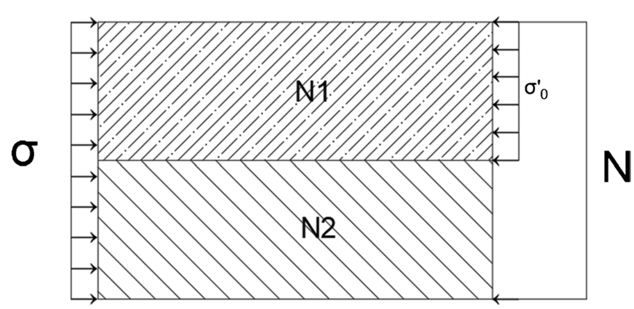


Fig. 9 Elastic–plastic damage body

Combining Eqs. (2), (3), and (4) results in

$$\sigma_0 = \sigma_0^{'}(1 - D) \tag{5}$$

Based on the principles of continuum damage mechanics and strain equivalence,

$$\begin{cases} \sigma = E\varepsilon(1 - D) \\ \varepsilon_{ep} = \varepsilon_{ep}^{'} \end{cases} \tag{6}$$

where ε_{ep} is the total strain of the micro-element, and the strain of the undamaged part of the micro-element is ε'_{ep}.

Then, combining Eqs. (5) and (6) results in

$$\sigma_0 = E_0\varepsilon_{ep}(1 - D) \tag{7}$$

Since rock creep damage is related to loading time, combined with the results of Kachanov (1992) and based on the effective stress,

$$[\sigma_0^*] = [\sigma]/(1 - D) \tag{8}$$

Then, set the rock creep damage rate as

$$\frac{dD}{dt} = Ce^{\left(\frac{\sigma_0}{1-D}\right)^V} \tag{9}$$

where C and V are the rock material parameters.

By deducing the mathematical formula, the creep damage variable can therefore be obtained as a function of time and lifetime as follows:

$$D = 1 - \left(1 - \frac{t}{t_F}\right)^{\alpha} \tag{10}$$

where $\alpha = (1 - V)^{-1}$ and t_F is the rock creep complete damage time (lifetime).

According to existing tests and studies (Ge et al. 2022; Liu et al. 2020; Chen et al. 2020), as coal rock is a typical soft rock, the yield strength is generally equated to the long-term strength, so rock creep will only occur and accumulate damage when the constant stress loaded during rock creep is greater than the yield strength σ_s, so the constitutive model of the elastic–plastic damage body is

$$D = \begin{cases} 0 & (\sigma \le \sigma_s) \\ 1 - \left[1 - \frac{t}{t_F}\right]^{\alpha} & (\sigma > \sigma_s) \end{cases} \tag{11}$$

Substituting Eq. (11) into Eq. (7) can obtain the rock creep constitutive model for an elastic–plastic damaged body as

$$\varepsilon_{ep} = \begin{cases} \frac{\sigma_0}{E_0} & (\sigma \le \sigma_s) \\ \frac{\sigma_0}{E_0}\left[1 - \frac{t}{t_F}\right]^{-\alpha} & (\sigma > \sigma_s) \end{cases} \tag{12}$$

Establishment of the nonlinear creep damage model for coal rock

The above damage evolution model for the elastic–plastic damage body was replaced by the viscous element in the Nishihara model, and the replacement physical model is shown in Fig. 10.

By controlling the participation of the elastic–plastic damage body in the creep constitutive model through the plastic element, the creep constitutive model of the rock in the one-dimensional state can be obtained as

$$\varepsilon = \begin{cases} \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left[1 - \exp\left(-\frac{E_1}{\eta}t\right)\right] & (\sigma \le \sigma_s) \\ \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left[1 - \exp\left(-\frac{E_1}{\eta}t\right)\right] + \frac{\sigma}{E_2}\left(1 - \frac{t}{t_F}\right)^{-\alpha} & (\sigma > \sigma_s) \end{cases} \tag{13}$$

Using the theory of elasticity, the one-dimensional model was converted into a three-dimensional model and a nonlinear creep damage constitutive model based on damage mechanics theory was obtained as

$$\varepsilon = \begin{cases} \frac{\sigma_1-\sigma_3}{3G_0} + \frac{\sigma_1+2\sigma_3}{9K} + \frac{\sigma_1-\sigma_3}{3G_1}\left[1 - \exp\left(-\frac{G_1}{\eta}t\right)\right] & (\sigma \le \sigma_s) \\ \frac{\sigma_1-\sigma_3}{3G_0} + \frac{\sigma_1+2\sigma_3}{9K} + \frac{\sigma_1-\sigma_3}{3G_1}\left[1 - \exp\left(-\frac{G_1}{\eta}t\right)\right] + \frac{\sigma_1-\sigma_3}{3G_2}\left(1 - \frac{t}{t_F}\right)^{-\alpha} & (\sigma > \sigma_s) \end{cases} \tag{14}$$

where G_0, G_1, and G_2 are the shear modulus and K is the bulk modulus.

Creep model parameter identification and model validation

The quasi-Newton nonlinear optimization algorithm (BFGS) was used to identify the parameters of the nonlinear creep damage constitutive model to ensure the stability of the experimental data, and the fitted parameters are shown in Table 4.

The parameters, which were obtained from the inversion of creep tests at different confining pressures, were substituted into the nonlinear creep damage equation obtained in the previous section to verify the correctness and reasonableness of the model, and strain–time curves were plotted, as shown in Fig. 11.

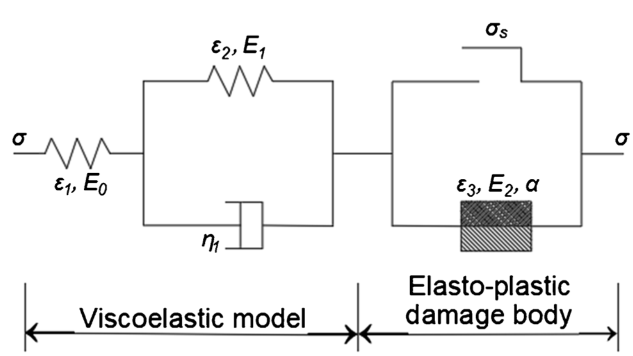


Fig. 10 Nonlinear creep damage model

Figure 11 shows that the experimental curves and the model curves were fitted very well. The resulting nonlinear creep damage constitutive model can not only reflect the creep behavior of decelerating creep stage and stable creep stage, but also can simulate the accelerating creep stage better. The superiority and reasonableness of the present model can be clearly seen in comparison with the Nishihara model in the accelerating creep stage.

As a model of clean utilization of coal resources, there are many studies that have demonstrated the advantages of underground coal gasification technology (UCG) in mining engineering, so it has great development space. The technical principle of UCG is the conversion of coal into a combustible gas by controlled combustion underground. This requires an effective constitutive model to analyze the stability of the underground gas wells.

The above obtained results and findings can prove the correctness and reasonableness of the nonlinear creep damage constitutive model of coal rock, which has certain guiding value in solving the long-term stability problems of the confining pressure in UCG practical engineering.

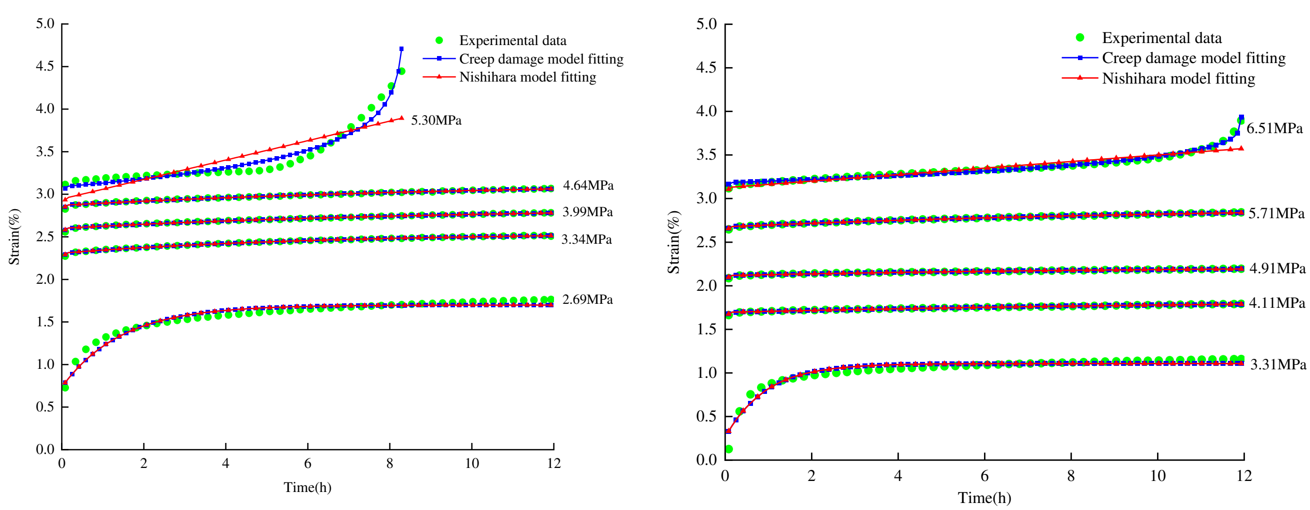
Table 4 Axial creep model parameters for graded loading at a confining pressure condition of 6 MPa

$\sigma_1-\sigma_3$/MPa	3.31	4.11	4.91	5.71	6.51
G_0/GPa	2.058	2.348	2.988	3.267	2.931
G_1/GPa	1.629	1.982	2.651	3.170	2.518
K/GPa	2.572	3.553	2.648	2.829	2.941
η/GPa·h	289.791	307.614	270.922	308.629	151.211
G_2/GPa	—	—	—	—	2.632
a	—	—	—	—	0.182
t_F/h	—	—	—	—	58.647
R^2	0.917	0.993	0.991	0.996	0.986

Conclusions

In this study, the triaxial compression tests and triaxial-graded loading creep tests on briquette coal specimens were conducted, a nonlinear creep damage constitutive model was established in combination with damage mechanics theory to describe the creep behavior of coal rock, and the reasonableness of the model was verified. The following conclusions are drowned from this work.

- Stress levels have a significant effect on coal rock creep processes, only decelerating creep and stable creep stages occur under relatively low stress levels (50%, 60%, and 70% of peak strength), and the creep deformation under each stress level gradually decreases. The decelerating creep, stable creep, and accelerating creep stages occur under stress level of 80% of the peak strength. And the ratio of creep deformation shows a trend of decreasing firstly and then increasing which indicated that the damage effect caused and accumulated during the creep process.
- The radial creep behavior is relatively obvious than the axial one, and the radial creep rate is greater than the axial creep rate, indicating that radial creep of coal rock is more sensitive than axial creep. The reason is that the radial binding force provided by the confining pressure plays an obvious role, which can effectively curb the rapid increase of radial deformation.
- The failure angle decreases as the confining press increases, indicating the deformation increasement of specimens, which is consistent with the lager increase of radial deformation in the test results. Therefore, the



(**a**) $\sigma_3 = 4$ MPa (**b**) $\sigma_3 = 6$ MPa

Fig. 11 Comparison curve between tests and simulation specimens are predominantly shear damaged with a small amount of tensile damage.

- Based on the damage mechanics which can better describe the accelerating creep, an elastic–plastic damage body was constructed. By using the damage body to replace the viscous element in the Nishihara model, then a nonlinear creep damage constitutive model was established. And the applicability of the model was verified through the comparison of experimental data and fitting results.

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Data Availability The figures and tables used to support the findings of this study are included in the article.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abolfazl E, Davood A (2021) Failure analysis of clay soil-rubber waste mixture as a sustainable construction material. Constr Build Mater 2021:310

Cao WG, Chen K, Tan X et al (2020) A novel damage-based creep model considering the complete creep process and multiple stress levels. Comput Geotech 124:103599.1–103599.7

Chen Y, Zhu SY, Wang ZG et al (2020) Deformation and failure of floor in mine with soft coal, soft floor, hard roof and varying thicknesses of coal seam. Eng Fail Anal 115

Cheng L, Liu JF, Ren Y et al (2021) Study on very long-term creep tests and nonlinear creep-damage constitutive model of salt rock. Int J Rock Mech Min Sci 146

Gan QQ, Xu J, Peng SJ et al (2021) Effect of heating on the molecular carbon structure and the evolution of mechanical properties of briquette coal. Energy 237(Dec.15 Pt.2):121548.1–121548.13

Gao RB, Wu F, Chen J et al (2022) Study on creep characteristics and constitutive model of typical argillaceous salt rock in energy storage caverns in China. J Energy Storage 50

Ge LN, Yi F, Du CB et al (2022) Deformation localization and damage constitutive model of raw coal and briquette coal under uniaxial compression. Geofluids 2022:12

Guo ZH, Vu PNH, Hussain F (2018) A laboratory study of the effect of creep and fines migration on coal permeability during single-phase flow. Int J Coal Geol 20061-76

Kachanov M (1992) Effective elastic properties of cracked solids: critical review of some basic concepts. Appl Mech Rev 45:8

Li XC, Yang CL, Ren T et al (2017) Creep behaviour and constitutive model of coal filled with gas. Int J Min Sci Tech 27:5

Li XB, Liu XS, Tan YL et al (2022) (2022) Creep constitutive model and numerical realization of coal-rock combination deteriorated by immersion. Minerals 12(3):292–292

Lin H, Zhang X, Cao RH et al (2020) Improved nonlinear Burgers shear creep model based on the time-dependent shear strength for rock. Environ Earth Sci 79:6

Liu Y, Li ZD (2018) Nonlinear variation parameters creep model of rock and parametric inversion. Geotech Geol Eng 36:5

Liu WB, Zhang SG, Sun BY (2019a) Energy evolution of rock under different stress paths and establishment of a statistical damage model. KSCE J Civ Eng 23:10

Liu WB, Zhang SG, LI RM (2019) Accelerated creep model of rock based on energy dissipation theory. J China Coal Soc 44(09):2741–2750 (in Chinese)

Liu D, Wang YB, Ni XM et al (2020) Classification of coal structure combinations and their influence on hydraulic fracturing: a case study from the Qinshui Basin. China Energies 13:17

Liu ZZ, Wang HP, Wang S et al (2021a) Investigation into the gas adsorption-loading coupling damage constitutive model of coal rock. Arab J Geosci 14:15

Liu DF, Yan WX, Yan S et al (2021b) Study on the effect of axial and hydraulic pressure coupling on the creep behaviors of sandstone under multi-loading. Bull Eng Geol Environ 80:8

Meng H, Yang YZ, Wu LY (2021) Strength, deformation, and acoustic emission characteristics of raw coal and briquette coal specimens under a triaxial compression experiment. ACS Omega 6:47

Ramesh KK, Hajibeygi H (2021) Multiscale simulation of inelastic creep deformation for geological rocks. J Comput Phys 440

Shen WB, Yu WJ, Pan B et al (2022) Rock mechanical failure characteristics and energy evolution analysis of coal-rock combination with different dip angles. Arab J Geosci 2022(15):1

Wang QY, Zhu WC, Xu T et al (2016) Numerical simulation of rock creep behavior with a damage-based constitutive law. Int J Geomech 17:1

Wang RF, Li L, Simon R (2019) A model for describing and predicting the creep strain of rocks from the primary to the tertiary stage. Int J Rock Mech Min Sci 123(C)

Xue CC, Cao AY, Guo WH et al (2022) Mechanism and energy evolution characteristics of coal burst in mining thick, deep, and large inclined coal seams: a case study from a Chinese coal mine. Geofluids 2022:18

Yan BQ, Guo QF, Ren FH et al (2020) Modified Nishihara model and experimental verification of deep rock mass under the water-rock interaction. Int J Rock Mech Min Sci 128(C)

Yu MY, Liu BG, Sun JL et al (2020) Study on improved nonlinear viscoelastic-plastic creep model based on the Nishihara model. Geotech Geol Eng 38(3):3203–3214

Zhang SG, Liu WB, Lv HM (2019) Creep energy damage model of rock graded loading. Results Phys 12:1119–1125

Zhang L, Li XC, Ren T (2020) A theoretical and experimental study of stress–strain, creep and failure mechanisms of intact coal. Rock Mech Rock Eng 53

Zhao BY, li YF, Huan W et al (2021) Experimental study on mechanical properties of shale rock and its strength criterion. Arab J Geosci 14:4

Zhao YL, Wang YX, Wang WJ et al (2017) Modeling of non-linear rheological behavior of hard rock using triaxial rheological experiment. Int J Rock Mech Min Sci 9366-75

Zhou HW, Wang CP, Mishnaevsky L et al (2013) A fractional derivative approach to full creep regions in salt rock. Mech Time-Depend Mat 17:3

Zhou XP, Pan XK, Berto F (2022) A state-of-the-art review on creep damage mechanics of rocks. Fatigue Fract Eng M 45:3

Zuo M, Chiovelli S, Nonaka Y (2000) Fitting creep-rupture life distribution using accelerated life testing data. J Press Vess-T Asme 122(4):482–487