Creep characteristics and constitutive model of coal under triaxial stress and gas pressure

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Abstract

Creep behavior is one of the most important mechanical behaviors of coal. In the present study, we systematically carried out a series of creep experiments of briquette samples under triaxial compression and gas pressure. The experimental results showed that the creep deformation characteristics of coal were related to deviatoric stress and gas pressure. The accelerating creep stage initiated when the deviatoric stress reached or exceeded the yield stress until failure took place. In contrast, when the deviatoric stress was less than the yield strength, only transient and steady creep stage occurred. Besides, gas pressure played a positive role in the creep process of coal. The axial strain of coal slightly increased with gas pressure (range from 0.13 to 0.40 MPa) when the effective triaxial stress remained constant. For example, in the steady creep stage ($\sigma_\text{1} = 9$ MPa, $p = 0.13$ MPa), the axial strain of sample S\textsubscript{1} is 2.710$\%$ and that of sample S\textsubscript{2} is 3.361$\%$, that is, coal samples with high gas pressure have higher axial strain. Moreover, gas pressure has two main effects on the mechanical behavior of coal. One is that the coal adsorbs gas molecules resulting in swelling strain and swelling stress, and the other is that the gas pressure may compress the coal particles. Considering the swelling stress and gas pressure, we intensively studied the effective stress formula of coal containing gas. Then, the effective stress was taken into consideration in the nonlinear Nishihara creep model. Furthermore, the tertiary creep factor $n$ was introduced in the nonlinear model to control the creep deformation evolution with time so that the nonlinear model could accurately describe the full creep stage of coal. In contrast, due to the lack of such a controlling parameter, the Nishihara model failed to reproduce the accelerating creep stage.

KEYWORDS

coal, creep model, effective stress, gas pressure, swelling stress, triaxial compression

1 INTRODUCTION

Creep behavior is one of the fundamental mechanical properties of coal or rock, associated with the stability of many buildings and underground structures in mining and rock engineering, such as roadways, tunnels, and dams. It is important to have a precise understanding of the creep or time-dependent behavior of coal or rock, which may prevent coal
and gas outburst\textsuperscript{1} as well as explain the mechanism of the stability of underground galleries.\textsuperscript{2}

The time-dependent deformation of coal or rock under the axial or triaxial compression has been exhaustively studied by numerous scientists and engineers in decades. In general, the creep behavior of rock or coal exhibits a pattern of three stages, that is, the primary (or transient) creep stage, the secondary (or steady) creep stage, and the tertiary (or accelerating) creep stage.\textsuperscript{3,6} Also, scholars have developed a broad array of creep models, which can be classified into three categories, that is, empirical models, micromechanism-based models, and component models.

Based on the analysis of rheological test data, the empirical model describing the relationship between creep strain and time is established via the fitting results. For example, Cruden\textsuperscript{7} studied the creep law of rock under the uniaxial compression and found that the power law of transient creep appeared to fit all the data satisfactorily without the addition of any components of steady-state creep. Shear stress-strain-time models for soils were examined in terms of undrained triaxial compression tests on the reconstituted specimens of kaolinite and Cucaracha shale. The multiloading experiments and the constant deformation rate tests were separately performed by Mesri et al.\textsuperscript{8} And they found that the strain-time relation can be expressed by a power function. The Mesri creep model is mainly applicable to the creep behavior of saturated soils. Based on the unsaturated creep tests of weak intercalated soils, an improved Mesri creep model was established by Zhu and Yu\textsuperscript{9} using GDS triaxial apparatus. They subsequently carried out the compressive trials of two kinds of gangue and found that the logarithmic function is suitable for describing its equal-time stress-strain relationship. Guo et al\textsuperscript{10} subsequently modified the Singh-Mitchell creep model and proposed the stress-strain-time relationship based on the analysis of the test result. Guedes\textsuperscript{11} proposed the power law compared against cubic polynomial and found that the above two functions can describe the primary and secondary creep. The empirical models with simple creep equation forms and only a few parameters appear to have the capability to describe the creep behaviors of specific rock or coal fairly well and may play an important role in engineering practice. However, the empirical models have an obvious defect that the physical meaning of model parameters is still unknown.

The micromechanism-based creep models considering the progressive evolution of microstructure could be the reflection of the accelerating creep stage of geomaterials (such as rock, coal, and concrete). Mazzotti and Savoia\textsuperscript{12} proposed the isotropic model for the creep damage of concrete under uniaxial compression. Shao et al\textsuperscript{13} discovered that time-dependent deformation is the macroscopic consequence of microstructural evolution (ie, microcracking, clay sheet sliding, and dissolution). Then, they performed the creep and relaxation tests and proposed the constitutive model for argillite rock. Pietruszczak et al\textsuperscript{14} assumed that the development of creep strain in geomaterials is associated with a progressive evolution of microstructure. And they presented a mathematical framework for modeling the creep phenomenon in frictional materials exhibiting a strong inherent anisotropy. Wang\textsuperscript{15} established a new constitutive model to describe the anisotropic damage in brittle rocks. Giorla and Dunant\textsuperscript{17} investigated the microstructure effects on the simulation of creep for the concrete and derived the constitutive law of creep for the cement paste.

Because the physical properties of parameters are explicit, the model construct is flexible. The component models are widely studied, popularized, and applied in the investigation of coal and rock creep under uniaxial (or triaxial) compression. According to the difference of mechanics mechanism in components, the component models generally can be divided into two kinds: classical constitutive models (also called linear creep models) and nonlinear constitutive models. Based on the combination of standard elements, such as the Hookean solid, the Newtonian fluid, and the St. Venant plastic body, a large number of models were proposed. Subsequently, the remarkable progress was made with the establishment of representative models, such as the Maxwell model, the Kelvin model, the Bingham model, the Burgers model, and the Nishihara model.\textsuperscript{18-21} However, because the composite components are linear, the classical constitutive models are not able to describe the three creep stages of rock or coal, especially the accelerating creep phase. Therefore, proposing the nonlinear creep model becomes the goal of coal (or rock) creep research. There are usually two ways to establish the nonlinear creep model: replacing the linear element (eg, the Newtonian dashpot) with the nonlinear element (eg, the fractional derivative Abel dashpot),\textsuperscript{3,22-31} or taking the damage mechanics and endochronic theory\textsuperscript{32-37} into consideration. On the one hand, combining with the nonlinear viscous element,
the multiple rheological models are proposed to describe the accelerating creep stage of rock or coal. On the other hand, based on the damage mechanics and endochronic theory, the nonlinear creep models are also established.

Generally, the researches on the creep behavior and constitutive model of coal are far less fruitful than that of rock, especially the triaxial compression experiments on coal under different gas pressure conditions. Moreover, many researchers seemed to neglect the differences between gas-filled coal and rock as well as soil when studying the effective stress of coal and also ignored the effective stress when investigating the creep model of coal or rock. Therefore, in this study, we firstly carried out a series of creep experiments on coal under triaxial and different gas pressures. Then, the nonlinear Nishihara creep model was presented based on the classical Nishihara model. Furthermore, we intensively studied the effective stress formula of gas-filled coal, which was also considered in the nonlinear creep model to enrich previous researches. Finally, based on the present experimental data, the nonlinear creep model was validated and the parameters were determined. The findings in the present research have an important implication for the prevention of coal and gas outburst as well as enhanced coalbed methane recovery.38-42

2 | MATERIALS AND METHODS

2.1 | Specimen preparation

The original coal blocks were collected from the 3rd coal seam of Ywu coal mine in Shanxi Province, China. But the untreated coal blocks were too soft to drill into cylindrical samples via the core drill machine in the laboratory. Moreover, the existence of many primary fissures and pores may have an irreversible influence on the internal stress and strain states. The individual differences in raw coal samples should not be ignored. There are complex and different pore or crack structures within the raw coal. On the contrary, the pore structure of the briquette is more uniform because the briquette used in the test was mainly made from coal particles (with the size of 40-80 mesh). Furthermore, the briquette can also reflect the evolution of coal creep. Thus, we used the briquette coal samples instead of the raw coal samples to perform the creep experiments. Besides, the existing research suggests that it is feasible to discuss the general law of mechanical properties of gas-contained coal samples using briquette samples instead of raw coal samples.43

To minimize the dispersion of samples caused by the production process of briquette, we used a uniform particle size pulverized coal particles. The detailed introduction to the production process of briquette is as follows. First, the raw coal was crushed, and the pulverized coal particles with a size of 40-80 mesh were selected. Then, the pulverized coal particles were mixed with a small amount of pure water and then they were placed into the forming die. Finally, the standard briquette coal samples (Φ 50 × 100 mm) were pressed under the pressure of 100 MPa on a 200 tons rigid testing machine. Besides, the upper surface and lower surface of the specimens were flatted as nearly parallel as possible to avoid the bending of the specimens under the axial compression.4 Therefore, the briquette coal samples were dried in the vacuum drying oven at 105°C for 24 hours. The dimensions of each sample used in the creep tests are listed in Table 1, and some of the specimens are shown in Figure 1.

2.2 | Experimental methods

The autonomous and auto-compensated hydro-mechanical coupling system (Figure 2), designed by China University of Mining and Technology (Beijing), was used in the creep experiments. All tests were performed with the same confining pressure (2 MPa) and temperature (25°C) to well identify the effects of deviatoric stress and gas pressure on creep responses.

Before carrying out experiments, a potential problem which should be taken into consideration is that the variability of natural sample means that multiple tests must be performed to yield consistent results. Heap et al.44 have demonstrated that the use of the stress-stepping creep experiment can successfully overcome this issue. Hence, the stress-stepping methodology was adopted to investigate the time-dependent creep of briquette at different gas pressures.

Once this experimental system had been established, a series of conventional triaxial creep experiments were carried out under different gas pressures. In the beginning, the coal specimens were placed in the triaxial chamber, and

| TABLE 1 Loading procedure for triaxial creep tests |
| Specimen | Length (mm) | Diameter (mm) | Confining pressure σ2 = σ3 (MPa) | Gas pressure p (MPa) | Axial stress levels σ1 (MPa) |
|----------|-------------|---------------|-------------------------------|-------------------|-----------------------------|
| S1       | 103.60      | 52.02         | 2                             | 0.13              | 6, 9, 12, 15               |
| S2       | 103.60      | 51.40         | 2                             | 0.20              | 6, 9, 12, 15               |
| S3       | 103.80      | 54.04         | 2                             | 0.30              | 3, 6, 9, 12, 15, 18        |
| S4       | 103.10      | 51.30         | 2                             | 0.40              | 3, 6, 9, 12, 15            |
then, the methane was injected into the chamber from its upper termini. The adsorption equilibrium state of coal samples would be reached after 24-hours gas adsorption.\(^4\) It is known to all that the CH\(_4\) is very dangerous and explosive. Considering the safety during the tests and on-site gas pressure (range from 0.13 to 0.60 MPa), so we set the largest gas pressure at 0.40 MPa (almost four times as large as of atmospheric pressure). During the adsorption process, the gas pressure was kept constant at the corresponding pressure (0.13, 0.20, 0.30, and 0.40 MPa, respectively). Because of the homogeneity and isotropy of briquette, the adsorption equilibrium was reached soon. The gas flow by the lower termini of the chamber was stable after about 10 hours. Furthermore, each coal sample was first subjected to the hydrostatic pressure of 2 MPa and then deviatoric stress was applied. Each specimen deformed for approximately 12 hours under the triaxial compression, and then, the next level axial stress would be applied. Last but not least, the above procedures were repeated until the failure of coal occurred. It should be noted that the constant gas pressure at the upper termini of the chamber was achieved during the creep experiments. The direction of gas flow was the same as that of axial stress, and the gas flow would seep out from the lower termini of the chamber (Figure 3). Due to the complex mechanical property of coal, we finally obtained four groups of triaxial creep tests on briquettes at different gas pressures (0.13, 0.20, 0.30, and 0.40 MPa, respectively), as shown in Table 1. In all experiments, the axial strain was continuously measured with JC-4A static stress-strain gauge. In addition, the instantaneous gas flow seeping out by the lower termini of the chamber was measured by CS200 mass flow meter. Finally, the creep curves of each specimen would be plotted on the graph using MATLAB (MathWorks).

3 | EXPERIMENTAL RESULTS

According to the Boltzmann overlapping principle, the deformation caused by the load applied at a certain moment in the past is equal to the sum of the deformation caused by the different loads at that moment.\(^1\) Therefore, the results can be given in Figure 3, which shows the creep strain-time curves from four groups of comparative experiments.

As shown in Figure 3A-D, when the deviatoric stress was less than the yield strength, the axial strain increased quickly in the initial compression phase. Then, the axial strain was kept constant after about 2-8 hours. With the deviatoric stress level rose, the increments in the axial strain increased gradually over time. In contrast, when the stress level reached the yield stress level, the accelerating creep stage occurred and the rupture of coal specimen took place in the end. Besides, the axial strain increased sharply during the accelerating creep phase.

The accelerating creep or failure deformation occurred in specimens S\(_1\), S\(_2\), and S\(_4\) at constant axial stress \(\sigma_1 = 15\) MPa. But the failure formation appeared in specimen S\(_3\) under the axial stress of \(\sigma_1 = 18\) MPa. Besides, an interesting phenomenon was observed with the specimen S\(_4\) under \(p = 0.40\) MPa and \(\sigma_1 = 15\) MPa. As illustrated in Figure 3D, the creep curve of sample S\(_4\) showed two stages that the creep rate increased slightly first and then increased sharply after about 12 min. Compared with the other three specimens (S\(_1\), S\(_2\), and S\(_3\)), sample S\(_4\) relatively exhibited the instantaneous deformation, stable creep, and accelerating creep following the last-step loading. In contrast, the other three specimens presented rapid deformation in a short time and had no obvious decelerating or steady-state creep. The creep duration of four specimens (S\(_1\), S\(_2\), S\(_3\), and S\(_4\)) under the last-loading stress is approximately 4.27, 4.46, 8.60, and 15.49 min, respectively. Brittle failure over a short time at the onset of the accelerating creep.
stage occurred quickly in samples $S_1$, $S_2$, and $S_3$. When the applied stress was larger than the yield stress, the fractures within the coal grew rapidly, and the shear stress led to coal failure in the end.

In addition, the gas pressure may affect the axial strain of briquettes during the creep process. From Figure 3A,B, under the 3rd stress level ($\sigma_1 = 12$ MPa), the axial strain of samples $S_1$ and $S_2$ at the steady creep state was 4.4% and 5.3%, respectively. From Figure 3C,D, under the 4th stress level ($\sigma_1 = 12$ MPa), the axial strain of sample $S_4$ at the steady creep state was 5.62%, which was 1.22 times as large as that of sample $S_3$. The failure stress level, the initiation, propagation, and coalescence of microcracks occurred resulting in the growth of facilitating macroscopic cracks when the deviatoric stress level reached or exceeded. These macroscopic cracks extended toward the end of the samples until its final failure. Under the same triaxial stress, the axial creep strain tended to increase with the increase of gas pressure. For example, the axial strain of sample $S_4$ at the 5th stress level ($\sigma_1 = 15$ MPa) increased continuously until rupture occurred, but that of sample $S_3$ was found to keep constant ($\varepsilon = 6.40\%$) in the end. The gas pressure may play a positive role in the creep deformation of briquettes, which will be discussed further in the following section.

4 | NONLINEAR CREEP MODEL FOR COAL CONTAINING GAS

4.1 | One-dimensional nonlinear creep model for coal or rock

To simulate the time-dependent creep behaviors of coal, we will establish a macroscopic constitutive model, which can describe three creep stages, especially the accelerating creep stage.

As shown in Figure 4, the traditional Nishihara model is composed of a Hooke body, a Kelvin body, and an ideal visco-plastic body in series, where $E_0$ stands for the elastic modulus, $E_1$ denotes the viscoelastic modulus, and $\eta_1$ and $\eta_2$ are the viscosity coefficients of the dashpot.

Let $\sigma$ denotes the total stress, $\varepsilon$ represents the total strain, and $\sigma_y$ denotes the yield stress; $\sigma$ and $\varepsilon$ with the subscripts $e$, $ve$, and $vp$ stand for the stress and strain of the Hooke body, the Kelvin body, and the ideal visco-plastic body, respectively. When $\sigma < \sigma_y$, the Nishihara model satisfies the following stress-strain relations:

\[
\sigma = E_0 \varepsilon + \eta_1 \frac{d\varepsilon}{dt} + \eta_2 \frac{d\varepsilon}{dt}.
\]
If the stress is a constant, Equation (4) can be figured out:

\[
\begin{align*}
\varepsilon_e &= \frac{\sigma}{E_0} \\
\varepsilon_{ve} &= \frac{\sigma}{E_1} (1 - e^{-\frac{\sigma}{\eta_1}t}) \\
\varepsilon_{vp} &= \frac{\sigma - \sigma_s}{\eta_2} t.
\end{align*}
\]  

(5)

Similarly, substituting Equation (5) into Equation (4), the creep equation can be written as

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} (1 - e^{-\frac{\sigma}{\eta_1}t}) + \frac{\sigma - \sigma_s}{\eta_2} t.
\]

(6)

By calculating the derivative of Equation (6) concerning time, the creep deformation rate can be derived as

\[
\frac{d\varepsilon(t)}{dt} = \frac{\sigma}{\eta_1} e^{-\frac{\sigma}{\eta_1}t} + \frac{\sigma - \sigma_s}{\eta_2}.
\]

(7)

when \(t \to \infty\), the limit of creep deformation rate can be obtained:

\[
\lim_{t \to \infty} \frac{d\varepsilon(t)}{dt} = \frac{\sigma - \sigma_s}{\eta_2}.
\]

(8)

According to Equation (8), the creep rate tends to keep constant as time tends to infinity. It is suggested that the traditional Nishihara model can describe the primary and steady-state creep stages of coal or rock fairly well, but not for the accelerating creep stage.

For this reason, to describe the accelerating creep properties of coal, a nonlinear dashpot is proposed. If the applied stress exceeds the plastic yield stress, the nonlinear dashpot will be triggered and become functioning. Thus, the nonlinear dashpot may be sensitive to the creep time, and it can accurately reflect the deformation behavior in the tertiary creep stage. As illustrated in Figure 5, the nonlinear creep model has been built up by replacing the Newtonian dashpot in the classical Nishihara model with the nonlinear dashpot.

Assuming that the strain vs time of nonlinear visco-plastic body under the constant stress condition conforms to the following formula:

\[
\varepsilon_{vp}(t) = \frac{\sigma - \sigma_e}{\eta_2} t^n,
\]

(9)

where \(n\) refers to the tertiary creep factor (\(n \geq 1\)). Based on the experimental data, the factor \(n\) can be determined using the least-square method through manual or mathematic software.
Consequently, the constitutive equation of nonlinear creep model under one-dimensional constant stress can be written as

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{\sigma}{E_1} t} \right), \quad (\sigma < \sigma_s), \\
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{\sigma}{E_1} t} \right) + \frac{\sigma - \sigma_s}{\eta_1} t, \quad (\sigma \geq \sigma_s),
\]

when \( n = 1 \), Equation (10) can be transformed into

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{\sigma}{E_1} t} \right), \quad (\sigma < \sigma_s), \\
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{\sigma}{E_1} t} \right) + \frac{\sigma - \sigma_s}{\eta_1} t, \quad (\sigma \geq \sigma_s).
\]

Comparison of Equation (10) with Equation (11) indicates that the Nishihara model is a special case of nonlinear creep model, when the tertiary creep factor \( n = 1 \).

### 4.2 Effective stress for coal containing gas

Based on the rock mechanics theory, in Section 4.1, a nonlinear creep model was presented to describe the creep properties of rock or coal under uniaxial compression. In fact, in this paper, the creep deformation of coal is not only affected by triaxial stress but also by gas pressure during the creep process. There are two main effects of gas pressure on coal. On the one hand, the coal absorbs gas molecules resulting in expansive deformation. On the other hand, the gas pressure will compress the coal particles. Because of the above two factors, the effective stress of coal containing gas is different from that of rock and soil. Unfortunately, many researchers ignored it and treated gas containing coal as rock or soil, when studying the effective stress of coal under uniaxial (or triaxial) stress and gas pressure.

In 1925, Terzaghi presented effective stress principle in studying soil mechanics, namely

\[
\sigma'_{ij} = \sigma_{ij} - p \delta_{ij},
\]

where \( \sigma'_{ij} \) is the effective stress, \( \sigma_{ij} \) is the total stress, \( p \) is the pore pressure, and \( \delta_{ij} \) is the Kronecker symbol. However, the theory of Terzaghi effective stress cannot describe the porous coal adsorbed gas correctly. The reasons are as follows. Firstly, the pore structure of coal is different from that of soil, and the porosity and pore diameter of coal are much smaller than those of soil. In general, the porosity of coal is less than 10 percent. Secondly, the water in the soil is mainly free water, which is subjected to gravity and can transmit hydrostatic pressure, but the adsorbed gas does not transmit gas pressure.

Supposing the briquette is isotropic and obeys the Langmuir equation

\[
V = \frac{abp}{1 + bp},
\]

where \( V \) is gas adsorption capacity, and \( a \) and \( b \) are adsorption constants.

The expansive deformation caused by coal adsorbed gas is

\[
\varepsilon_a = \frac{akRT}{V_0} \ln (1 + bp),
\]

in which \( \varepsilon_a \) is swelling strain, \( V_0 \) is gas molar constant, 22.4 L/M in the standard state, and \( R, T, k \) is the universal gas constant, absolute temperature, and proportional coefficient, respectively.

Under uniaxial (or triaxial) compression, the swelling stress of coal will occur resulting from the expansive deformation. Assuming that the expansive stress of briquette is the same in all directions, and the relationship between expansive stress and swelling strain obeys the Hooke’s law, thus the expansive stress is as follows:

\[
\sigma_a = E \varepsilon_a = \frac{akERT}{V_0} \ln (1 + bp).
\]
in which \( \sigma_n \) and \( E \) are swelling stress and elastic modulus, respectively.

The section “A-A” having the area \( S \) is arbitrarily selected in briquette, as shown in Figure 6. Based on the principle of force balance, we can get the following equation:

\[
\sigma S = (\sigma_n + \sigma_\epsilon)(1 - \varphi)S + p\varphi S,
\]  
\hspace{1cm} \text{(16)}

where \( \varphi \) and \( \sigma_\epsilon \) are the porosity and bearing stress of coal skeleton, respectively.

Effective stress can be defined as the bearing stress leading to the deformation of the coal skeleton by an external force. Therefore, the effective stress of gas-filled coal can be obtained:

\[
\sigma_\epsilon = \frac{\sigma_\epsilon(1 - \varphi)S}{S} = \sigma_\epsilon(1 - \varphi),
\]  
\hspace{1cm} \text{(17)}

Substituting Equation (17) into Equation (16):

\[
\sigma_\epsilon = \sigma - \varphi p - \sigma_n(1 - \varphi) = \sigma - \varphi p - \frac{akERT(1 - \varphi)}{V_0} \ln(1 + bp).
\]  
\hspace{1cm} \text{(18)}

Let \( \alpha = \frac{akERT}{V_0} \), then Equation (18) can be written as:

\[
\sigma_\epsilon = \sigma - \varphi p - \alpha(1 - \varphi) \ln (1 + bp).
\]  
\hspace{1cm} \text{(19)}

Therefore, the creep equation for gas-containing coal under uniaxial compression can be obtained by replacing \( \sigma \) in Equation (10) with \( \sigma_\epsilon \) in Equation (19):

\[
\begin{align*}
\varepsilon(t) &= \frac{\sigma_n}{E_0} + \frac{\sigma_\epsilon}{E_1}(1 - e^{-\frac{\sigma_n}{E_1} t}) , \quad (\sigma_\epsilon < \sigma_n) \\
\varepsilon(t) &= \frac{\sigma_n}{E_0} + \frac{\sigma_\epsilon}{E_1}(1 - e^{-\frac{\sigma_n}{E_1} t}) + \frac{\sigma_m}{n_2} t^n , \quad (\sigma_\epsilon \geq \sigma_n)
\end{align*}
\]  
\hspace{1cm} \text{(20)}

There are generation and expansion of microcracks and microcracks within the coal body during creep. The expansive stress resulting from coal adsorbed gas can offset part of the external force. The expansive stress and uniaxial (or triaxial) stress will cause irreversible damage within the coal and the propagation of cracks. Moreover, the gas molecules will also wedge the microcracks by the gas pressure. Consequently, uniaxial (or triaxial) compressive stress and gas pressure play an important role in the time-dependent creep deformation of gas-filled coal. It is essential to consider the swelling deformation and the effective stress of coal when studying the mechanical behavior of gas-filled coal.

4.3 Three-dimensional creep equations for coal containing gas

The one-dimensional creep equations can be generalized to construct three-dimensional (3-D) creep equations using an analogy method.\(^{27,29,36,37,45}\) For 3-D problems, the total strain can be given by:

\[
\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^{ve} + \varepsilon_{ij}^{vp},
\]  
\hspace{1cm} \text{(21)}

According to the generalized Hook law, 3-D constitutive equations for the elastic body can be expressed as.

\[
\varepsilon_{ij}^e = \frac{s_{ij}}{2G_0} + \varepsilon_{ij}^{ve} = \frac{\sigma_{kk}}{3K},
\]  
\hspace{1cm} \text{(22)}

where \( s_{ij} \) and \( e_{ij}^{ve} \) are the deviatoric stress tensor and deviatoric strain tensor, respectively, \( \sigma_{kk} \) and \( e_{kk} \) denote the first invariants of stress tensor and strain tensor, respectively, and \( G_0 \) and \( K \) stand for the shear modulus and bulk modulus, respectively.

Thus, the strain of the elastic body can be written as

\[
\varepsilon_{ij}^e = \frac{s_{ij}}{2G_1} + \frac{\sigma_{kk}}{3K} + \frac{\sigma_m}{n_2} t^n , \quad (F < 0)
\]  
\hspace{1cm} \text{(23)}

where \( \sigma_m \) are Kronecker function and spherical stress tensor, respectively.

According to elastic-plastic theory, the spherical stress tensor produces elastic volumetric strain only, whereas the rheological part results from deviatoric stress tensor.\(^{4,45}\) The 3-D constitutive equation for the viscoelastic body is expressed as follows

\[
\varepsilon_{ij}^{ve} = \frac{s_{ij}}{2G_1} (1 - e^{-\frac{\sigma_n}{E_1} t}),
\]  
\hspace{1cm} \text{(24)}

where \( G_1 \) is the shear viscoelastic modulus.

The 3-D constitutive relation of the visco-plastic body of the nonlinear creep model can be described as.

\[
\begin{align*}
\varepsilon_{ij}^{vp} &= 0 , \quad (F < 0) \\
\varepsilon_{ij}^{vp} &= F \frac{\partial Q}{\partial \sigma_{ij}} t^n , \quad (F \geq 0)
\end{align*}
\]  
\hspace{1cm} \text{(25)}

where \( \sigma_{kk} \) is the Cauchy stress tensor, \( F \) is the yield function, and \( Q \) is the plastic potential function.\(^{36}\) The tested material is assumed to be associated with flow rule with \( F = Q \).

The deviator stress plays a primary role in the creep period, so that

\[
F = \sqrt{J_2} - \frac{\sigma_n}{\sqrt{3}} ,
\]  
\hspace{1cm} \text{(26)}

where \( J_2 \) is the second invariant of the deviatoric stress.

Substituting Equation (23), (24), and (25) into Equation (21), the 3-D constitutive equations of the nonlinear creep model can be figured out:

\[
\begin{align*}
\varepsilon_{ij}^e(t) &= \left( \frac{s_{ij}}{2G_0} + \frac{\sigma_{kk}}{3K} \right) + \frac{s_{ij}}{2G_1} (1 - e^{-\frac{\sigma_n}{E_1} t}) , \quad (F < 0) \\
\varepsilon_{ij}^e(t) &= \left( \frac{s_{ij}}{2G_0} + \frac{\sigma_{kk}}{3K} \right) + \frac{s_{ij}}{2G_1} (1 - e^{-\frac{\sigma_n}{E_1} t}) + \frac{F}{n_2} \frac{\partial Q}{\partial \sigma_{ij}} t^n , \quad (F \geq 0)
\end{align*}
\]  
\hspace{1cm} \text{(27)}
The axial deviatoric stress\(^6\)\(^,\)\(^7\) can be written as.

\[
s_{11} = \sigma_1' - \sigma_m' = \frac{1}{3} \left( \sigma_1' + \sigma_2' + \sigma_3' \right) = \frac{2}{3} (\sigma_1' - \sigma_3'). \quad (28)
\]

where \(\sigma_1'\) is effective stress.

According to the effective stress formula for coal containing gas (Equation 19), we obtain the following equation:

\[
\sigma_1' = \sigma_1 - \varphi p - a(1 - \varphi) \ln (1 + bp) . \quad (29)
\]

Substituting Equation (29) into Equation (28), then

\[
s_{11} = \frac{2}{3} (\sigma_1 - \sigma_3). \quad (30)
\]

Similarly, it can be obtained that

\[
\sigma_m = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3), \quad \sqrt{J_2} = \frac{\sigma_1 - \sigma_3}{\sqrt{3}} . \quad (31)
\]

Substituting Equations (30) and (31) into Equation (27), the creep strain in the axial direction is given by.

\[
\begin{align*}
\varepsilon_{11}(t) &= \frac{\sigma_1' - \sigma_3'}{9k} + \frac{\sigma_1' - \sigma_3'}{3G_0} + \frac{\sigma_1' - \sigma_3'}{3G_1}\left(1 - e^{-\frac{\sigma_1'}{\sigma_1}}\right), \quad (\sigma_1 - \sigma_3 < \sigma_t) \\
\varepsilon_{11}(t) &= \frac{\sigma_1' - \sigma_3'}{9k} + \frac{\sigma_1' - \sigma_3'}{3G_0} + \frac{\sigma_1' - \sigma_3'}{3G_1}\left(1 - e^{-\frac{\sigma_1'}{\sigma_1}}\right) + \frac{\sigma_1' - \sigma_3'}{3G_2}\rho, \quad (\sigma_1 - \sigma_3 \geq \sigma_t)
\end{align*}
\]

(32)

It is suggested that a nonlinear hardening phenomenon exists in the stage of rock decay and steady-state creep with little or no damage inside the rock, which can be neglected. The damages and internal fracture of coal samples will evolve with the continual increase of axial stress before the acceleration creep stage.\(^5\)\(^,\)\(^8\)\(^-\)\(^10\)\(^,\)\(^15\)\(^-\)\(^26\)\(^,\)\(^31\)\(^-\)\(^33\)\(^,\)\(^35\)\(^-\)\(^37\) We have seldom come across the creep characteristics and constitutive model for rock, soil, and concrete.\(^2\)\(^-\)\(^10\)\(^,\)\(^15\)\(^-\)\(^26\)\(^,\)\(^31\)\(^-\)\(^33\)\(^,\)\(^35\)\(^-\)\(^37\) The damage in the coal sample leads to the initiation and propagation of the pore and crack structure. Then, the permeability of methane increases and the adsorption of methane also rises. Gas adsorption leads to the deformation of the coal mesostructure including expansion and extrusion deformation.\(^6\)\(^1\) The adsorption swelling stress and extrusion stress of the gas increase with the change in the coal sample damage. From Equation (32), it can be found that axial strain is the function of stress and time, and the effect of adsorption stress on the effective stress of coal can be offset under the triaxial compression.

### 4.4 Model validation

Before the validation of the nonlinear Nishihara creep model, we write Equation (32) as the following equation for the nonlinear regression of experimental data:

\[
\begin{align*}
\varepsilon(t) &= A + B (1 - e^{-Ct}), \quad (\sigma_1 - \sigma_3 < \sigma_t) \\
\varepsilon(t) &= A + B (1 - e^{-Ct}) + D e^\rho, \quad (\sigma_1 - \sigma_3 \geq \sigma_t)
\end{align*}
\]

(33)

where \(A, B, C, D,\) and \(n\) are the fitting parameters. It can be found that both the uniaxial creep curve and the triaxial creep curve could be fitted by Equation (33). Because of the virtue of simplicity and applicability, Equation (33) hence can be widely used in numerical calculations and engineering projects. For axial creep equations under the condition of triaxial compression tests, the parametric relations are as follows:

\[
\begin{align*}
A &= \frac{\sigma_1 + 2\sigma_3}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} \\
B &= \frac{\sigma_1 - \sigma_3}{3G_1} \\
C &= \frac{G_1}{\eta_1} \\
D &= \frac{\sigma_3 - \sigma_3 - \sigma_1}{3\eta_2}
\end{align*}
\]

(34)

In the current study, the creep parameters were determined through a nonlinear least squares regression analysis using MATLAB (MathWorks).\(^6\)\(^2\)\(^,\)\(^6\)\(^3\) The calculations and fitting results are as shown in Figure 7 and Table 2.

From Figure 7, the curves of the nonlinear creep model agree well with the experimental data. The fitting results of the classical Nishihara creep model are the same as that of the nonlinear Nishihara creep model in the primary creep stage and steady creep stage. The nonlinear creep model can accurately reproduce the tertiary creep phase, whereas the Nishihara model is unable to describe the accelerating creep process, as shown in Figure 7B,D,F,H.

The tertiary creep factor \(n\) is introduced in the nonlinear model to control the creep deformation evolution with time so that the nonlinear model can accurately describe the full creep stage of coal. In contrast, due to the lack of such a controlling parameter, the Nishihara model fails to describe the accelerating creep stage. Besides, the fitting coefficient \((R^2)\) represents how successful the fit is. As shown in Table 2, the fitting coefficient is larger than 0.99 at the last creep stage of each briquette sample.

### 5 DISCUSSION

Previous researches focused on the creep characteristics and constitutive model for rock, soil, and concrete.\(^2\)\(^-\)\(^10\)\(^,\)\(^15\)\(^-\)\(^26\)\(^,\)\(^31\)\(^-\)\(^33\)\(^,\)\(^35\)\(^-\)\(^37\) We have seldom come across the paper that deals with the coupling effect of triaxial compression and gas pressure on the creep deformation of coal. Investigation on the creep behavior of coal under triaxial compression and gas pressure has a significance in the prevention of coal and gas outburst as well as enhanced coalbed methane recovery. Hence, in the present study, we
FIGURE 7  Fitting results: (A), (C), (E), and (G) are the fitting results for coal specimens S1, S2, S3, and S4, respectively, with the nonlinear Nishihara creep model, and (B), (D), (F), and (H) are the comparisons between classical Nishihara model and nonlinear Nishihara model at the last creep stage of specimens S1, S2, S3, and S4, respectively.
investigated the effects of triaxial stress and gas pressure on the creep behavior of coal.

As shown in Figure 3D and Figure 7H, when the deviatoric stress was beyond the yield stress, the accelerating creep of sample S4 occurred. The strain increased quickly after about 0.2 hours, but before that time, the strain increased slowly. It indicates that there is at least an inflection point on the curve of accelerating creep. In this case, the creep curve could be divided into two segments, and the segment breakpoint was determined by the inflection point, that is, $t = 0.2$ hours. Therefore, if we can accurately determine the creep model and its parameters to find out the creep inflection point, then we can provide theoretical guidance for the prevention of coal and gas outburst.

There are differences between gas-filled coal and rock as well as soil in terms of effective stress calculation. Unfortunately, many researchers seemed to neglect the swelling stress caused by the adsorption of gas when studying the effective stress of coal and also ignore the effective stress when investigating the creep model of coal or rock. In this article, we demonstrated that the coupling effect of gas pressure and uniaxial (or triaxial) compression, the swelling stress will occur. On the contrary, if the gas pressure is high and the energy of the gas is larger than the bond energy of molecules (or atoms), the gas molecules may wedge and enter the coal material macromolecules (or aromatic layers). Then, the microscopic fractures occur resulting in the swelling deformation of the coal body and the diffusion and seepage of gas.

The previous investigation has shown that the gas permeability is a function of the mean free path of the gas molecules, and thus, it depends on factors that influence the mean free path, such as the pressure, temperature, and the nature of the gas. Physically, Klinkenberg effect is significant in any situation where the mean free path of gas molecules in porous media approaches the pore dimension, that is, when significant molecular collisions are with the pore wall rather than with other gas molecules. Gas permeability is then enhanced by “slip flow”. The effective gas permeability at a finite pressure given by Klinkenberg (1941) is

$$k_e = k_\infty \left(1 + \frac{b}{p}\right),$$

where $k_\infty$ is the absolute, gas-phase permeability under very large gas-phase pressure at which condition the Klinkenberg effect.

| Specimen | $p$ (MPa) | $\sigma_1$ (MPa) | $A$ | $B$ | $C$ | $D$ | $n$ | $R^2$ |
|----------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| S1       | 0.13      | 6               | 1.004           | 0.429           | 0.659           | /               | /               | 0.921           |
|          |           | 9               | 2.120           | 0.545           | 0.312           | /               | /               | 0.959           |
|          |           | 12              | 3.413           | 0.987           | 0.363           | /               | /               | 0.962           |
|          |           | 15              | 5.468           | 2.300           | 4.885           | 1.293e3         | 3.193           | 0.999           |
| S2       | 0.20      | 6               | 1.694           | 0.403           | 0.362           | /               | /               | 0.921           |
|          |           | 9               | 2.791           | 0.542           | 0.336           | /               | /               | 0.957           |
|          |           | 12              | 4.088           | 1.205           | 0.408           | /               | /               | 0.970           |
|          |           | 15              | 5.509           | 0.352           | 39.930          | 0.368e3         | 2.191           | 0.999           |
| S3       | 0.30      | 3               | 1.001           | 0.239           | 0.309           | /               | /               | 0.890           |
|          |           | 6               | 2.122           | 0.367           | 0.424           | /               | /               | 0.946           |
|          |           | 9               | 3.103           | 0.449           | 0.231           | /               | /               | 0.922           |
|          |           | 12              | 4.032           | 0.540           | 0.366           | /               | /               | 0.955           |
|          |           | 15              | 5.040           | 1.376           | 0.321           | /               | /               | 0.988           |
|          |           | 18              | 6.757           | 0.285           | 4.671           | 0.332e3         | 3.004           | 0.992           |
| S4       | 0.40      | 3               | 0.920           | 0.221           | 0.336           | /               | /               | 0.853           |
|          |           | 6               | 2.145           | 0.467           | 0.381           | /               | /               | 0.950           |
|          |           | 9               | 3.320           | 0.611           | 0.277           | /               | /               | 0.956           |
|          |           | 12              | 4.508           | 1.075           | 0.369           | /               | /               | 0.983           |
|          |           | 15              | 5.723           | 1.671           | 3.946           | 48.650e3        | 7.680           | 0.997           |
effects are negligible; and \( b \) is the Klinkenberg factor, dependent on the pore structure of the medium and temperature for a given gas. Also, the Klinkenberg coefficient is not constant and it varies even the influence of effective stress is eliminated.\(^6\) Jones found that \( b \) generally decreases with increasing permeability according to\(^6\) 

\[
b \propto k^{-0.36}.
\] (36)

Based on a study using 100 cores ranging in permeability from 0.01 to 1000 MD.

It can be seen that the permeability with the Klinkenberg effect is larger than that without the Klinkenberg effect. And the Klinkenberg effect can affect the gas seepage,\(^6\) while it cannot affect the creep behavior of the coal body. In the present study, the aim is to research the creep law of the coal sample under triaxial stress and gas pressure, not the seepage law of gas. The adsorption stress of gas is mainly determined by gas pressure, temperature, and the nature of gas (adsorption capacity from strong to weak order for \( \mathrm{CO}_2 > \mathrm{CH}_4 > \mathrm{N}_2 > \mathrm{He} \)).\(^6\) In this paper, the creep deformation of the coal sample was tested and the creep model of the coal was also established and validated. Therefore, in this study, the Klinkenberg effect does not affect the experimental results (time-dependent deformation of coal body under triaxial stress). And this effect also does not affect the calculation of effective stress and adsorption stress.

In 1996, the formula of swelling strain (Equation 14) caused by coal adsorbed gas was first proposed by He et al.\(^5\) Subsequently, in 2005, Wu and Zhao\(^5\) investigated the swelling strain and effective stress of coal. The swelling strain formula, in paper,\(^5\) is as follows:

\[
\varepsilon_s = \frac{2a\rho R T}{9\nu K} \ln (1 + bp),
\] (37)

which is consistent with Equation (14). Based on the principle of force balance, the effective stress formula of gas-filled coal was deduced (Equation 19). The effective stress was normally ignored in previous researches when studying the creep model of rock or coal. Therefore, in this paper, we considered the effective stress in the nonlinear Nishihara model to enrich the previous works. Comparing with the existing experimental data, it can be found that the nonlinear creep model can accurately reproduce the full creep stage, especially the accelerating creep stage.

However, because of the limitation of laboratory conditions, the gas pressure investigated in this study is relatively low. In future work, experiments under high gas pressure should be carried out.

## 6 CONCLUSIONS

To research the coupling effect of triaxial stress and gas pressure on the creep evolution of coal, we performed a series of creep experiments of briquettes under triaxial compression and gas pressure. The main conclusions reached in the present study are as follows.

1. The experimental results showed that when the deviatoric stress was lower than the yield stress, no accelerating creep occurred, resulting in the micropores and microcracks within the coal body were mostly compressed and compacted. In contrast, when the applied stress exceeded the yield stress, the accelerating creep deformation occurred until the coal failure took place, indicating that the microcracks propagated at this stage.
2. Moreover, the gas pressure played a positive role in the creep process of coal. As the gas pressure increased, the axial strain of coal also increased under the same triaxial compression regime.
3. The swelling strain and swelling stress of coal occurred because of the adsorption of gas. Based on the principle of force balance, the effective stress formula of coal was intensively studied. The adsorption swelling strain, swelling stress, and the change of effective stress should be taken into account when investigating the mechanical properties of coal under the uniaxial (or triaxial) compression and gas pressure.
4. The effective stress was taken into consideration in the nonlinear Nishihara model. And the fitting results indicated that the nonlinear Nishihara model could accurately reproduce the full creep stage, especially the accelerating creep stage, which the Nishihara model failed to predict.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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