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Creep Constitutive Model and Numerical Realization of Coal-Rock Combination Deteriorated by Immersion

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Abstract: Coal-rock combination refers to the coal and rock as a whole, and the failure of the whole structure of the combination is the main cause for the instability of the deep underground engineering. In deep underground engineering, the coal-rock combination is usually under certain hydrogeological conditions, and it is prone to seepage and rheological failure instability accidents due to the long-term action of water and stress. In this study, the creep constitutive model of coal-rock combination considering the influence of moisture content was established based on the Burgers creep model. According to the experimental results of triaxial creep of rock, the relationship between the moisture content and the parameter of the Burgers creep model was derived, and the correctness of the constitutive model in this study was verified. Then, through the C++ language, the core equation of the model was modified, and the numerical calculation of the model was realized by introducing the coal-rock combination creep model considering the influence of moisture content into FLAC3D numerical simulation software. Finally, the model was used to simulate and study the creep characteristics of coal-rock combination with different moisture contents under triaxial loading. The results showed that the stress environment and moisture content have significant effects on the creep characteristics of the coal-rock combination. Under the same stress state, with the increased of moisture content, the strain rate of the coal-rock combination exhibited a non-linear rapid increase in the constant-velocity creep stage, the limit creep deformation and the instantaneous elastic deformation increased, and the viscosity coefficient was significantly decreased. For example, when the axial stress was 5 MPa and the moisture content increased from 0% to 1.5%, the strain rate increased by 44.06%, the limit creep deformation increased by 20%, the instantaneous elastic deformation increased 10.53%, and the viscosity coefficient decreased by about 50%. When the moisture content is 0%, the axial stress increased from 5 to 14 MPa, and the limit creep deformation increased nearly four times. With the increase of moisture content, this value will further expand. The research conclusions can provide a certain reference basis for the long-term stability control of surrounding rock in underground engineering affected by the water.

Keywords: coal-rock combination; creep; constitutive model; moisture content; numerical simulation

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1. Introduction

Creep behavior and the long-term strength of coal and rock is an important factor that influences the instability and destruction of the deep underground engineering, which is closely related to the long-term action of deep high stress. In addition, the creep characteristic of coal and rock in deep underground engineering such as deep-buried diversion tunnels and high dam foundations is also affected by the hydrological environment [1,2]. With the immersion time increasing, the internal damage of coal-rock intensifies. As a result, the mechanical properties changed greatly, and the creep deformation and deformation rate increased significantly [3], which will inevitably have a serious impact on the long-term stability of the deep underground engineering. The coal-rock combination is a multi-layer combination structure that is usually seen as a whole composed of the coal seam and its roof and floor strata. In the deep underground space, deformation and failure of the coal-rock combination are often the main causes of coal mining disasters [4–7]. Therefore, the investigation and better understanding of the creep characteristics of coal-rock combination immersed in water under deep high stress conditions is of key importance in the scientific design and safe operation of deep underground engineering, especially for deep large deformation and long-term deformation.

In recent years, many studies on the mechanical properties of coal and rock with different moisture content have been carried out, which provides a theoretical basis for the study of the long-term stability of underground engineering under the water environment. For the rock under the influence of different moisture content, Li et al. [8,9] investigated the wetting-induced deformation behavior of rock mass in fault fracture zones, and established a new time-varying effect model to describe the wetting deformation of the rock mass. Yao et al. [10] obtained the evolution law of long-term strength and internal crack propagation of rock under different moisture contents by triaxial creep test. Hashiba et al. [11] and Mirosława [12] studied the mechanical properties of rock under different moisture contents through the uniaxial compression test; Li et al. [13] conducted experiments on the rheological properties of the rock in the saturated state and found that with the increase of moisture content, the strength of the rock specimen gradually decreased, and the strain rate and deformation increased significantly. Shtumpf [14] proposed a method to measure the moisture content of rock mass and revealed that the increase of moisture content makes the strength and deformation characteristics of rock mass change significantly; Ojo et al. [15], Vásárhelyi [16] and Ván [17] conducted relevant mechanical tests on rocks under saturated conditions, and obtained the stress–strain law of rocks under saturated conditions. In addition, they proposed the wet strength and ideal water sensitivity of rock must be established to assess the potential changes of strength and deformation for practical engineering design. Okubo et al. [18] showed that moisture content and time were the main reasons for the change of rock mechanical properties. In addition, many scholars have carried out a lot of correlation studies on the influence of rock creep failure under different moisture contents through laboratory tests and numerical simulation [19–28]. For the coal under the influence of different moisture content, Poulsen et al. [29] obtained that the strength of coal and coal-bearing rock decreases with the increase of moisture content by the physical experiment; Wang et al. [30] found that with the increase of moisture content, the strength, elastic modulus, and cohesion of soft coal increased first and then decreased, and the Poisson's ratio showed an increasing trend by the uniaxial and triaxial compression tests; Talapatra and Karim [31] studied the influence of moisture content on the deformation and permeability of coal, and found that the deformation and permeability of coal increased with the increase of moisture content. In addition, some scholars have studied the creep failure characteristics of coal with different moisture content by the acoustic emission test [32–34].

In terms of the creep model, the characteristics of various rock materials in the attenuation and steady creep stages can be accurately described by the traditional Burgers model, which is widely used in rock engineering. Therefore, many scholars often use the burgers model as the basis for establishing the creep model and improving it. For example, based on the classical Burgers model, Tang et al. [35] introduced the creep empirical element of moisture content to improve the study of rock creep properties under the influence of moisture content. Yang et al. [36] improved the Burgers creep model considering the influence of parameter degradation in the rock mass. Based on the Burgers model, Xue et al. [37] established the creep damage model considering the temperature and volume stress in the deep salt rock formation. In addition, Zhao [38] established a rock creep mechanical model considering moisture content based on the unified theological mechanical model theory. Sun et al. [39] proposed an improved Nishihara model considering moisture content by using the damage theory, and many scholars studied the creep constitutive models of rocks with different moisture contents after freezing and thawing [40–42].

In the aspect of secondary development of creep model, Li [43] and Chen [44] carried out secondary development of a coal-rock creep model, and introduced an example to verify, provide solutions and ideas for the customization of the creep model and the research of coal-rock with different moisture content. Kong et al. [45] developed the modified Naylor constitutive model with VC++(7.0) environment, and a series of simulations of triaxial tests are performed to verify the correctness of the compiled model; He and Chen [46] developed a simplified concrete damage constitutive model in FLAC3D environment, and the model has a certain accuracy. In addition, many scholars carried out the secondary development through numerical simulation software such as ABAQUS and PFC to realize the numerical calculation of the self-defined creep constitutive model of coal and rock [47–50].

In summary, a lot of research work has been carried out on the creep characteristics of coal and rock under different moisture contents, and a lot of progress has been made. However, since the coal in the deep underground space does not exist alone, most of them appear in the combinatorial structure of "coal-rock". If the coal or rock mass is taken as the research object alone, the result is one-sided and the solution to the deep underground engineering is lacking. In the meanwhile, considering the long-term effect of deep high stress of coal-rock combination in the deep underground space, it is of practical engineering significance to study the creep characteristics of the coal-rock combination with different moisture contents under triaxial loading.

Therefore, the creep constitutive model of the coal-rock combination considering the influence of moisture content was established in this paper based on the Burgers creep model. The relationship between moisture content and the correlation coefficients of the model was obtained combined with the experimental results of triaxial creep of rock. Then the experimental data were inverted, and the fitting test was carried out with the original experimental data. The creep constitutive model of coal-rock combination considering the influence of moisture content was introduced into FLAC3D software through the Visual Studio 2010 software, and the creep characteristics of coal-rock combination with different moisture content under triaxial loading conditions were obtained by using this model, and the correctness of the constitutive model was verified.

2. Creep Constitutive Model and Numerical Realization

2.1. Creep Constitutive Model of Coal-Rock Combination Considering the Influence of Moisture Content

Creep characteristics of the coal-rock combination are quite different compared with coal or rock, especially when they are immersed in water for a long time, their creep characteristics are more complicated. The influence of moisture content on the coal-rock combination cannot be described in the existing creep constitutive model. One of the reasons is that the key mechanical parameters in the constitutive model are generally constant, and the rock parameters do not change with the moisture content, which is linear creep. However, in fact, such a constitutive model does not reflect the true change law of coal-rock creep. Among the traditional creep models, the Burgers model has creep characteristics such as instantaneous elasticity, creep, and stress relaxation, which can better reflect the creep characteristics of the coal-rock combination. By adjusting the four parameters of the shear modulus and viscosity coefficient of Kelvin body and the shear modulus and viscosity coefficient of Maxwell body through the model, the creep characteristics of all rock materials can be obtained. Based on this, if the change in the above-mentioned four parameters with moisture content can be obtained, the relationship equation can be established, and the Burgers model can be improved to study the creep characteristics of coal-rock under different moisture contents. That is the creep constitutive model of coal-rock combination considering the influence of moisture content. The creep model is shown in Figure 1. In Figure 1, σ is the stress, $E_1(\omega)$ and $E_2(\omega)$ are the elastic moduli of Kelvin's body and Maxwell's body affected by moisture content, $\eta_1(\omega)$ and $\eta_2(\omega)$

are the viscosity coefficient of Kelvin's body and Maxwell's body affected by moisture content, and ω is the moisture content.

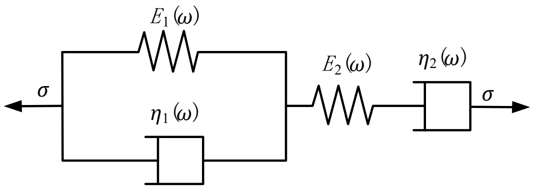

Figure 1. The creep constitutive model of coal-rock combination considering the influence of moisture content.

Burgers creep equation is known as:

$$\varepsilon = \left[1 - \exp\left(-\frac{E_1}{\eta_1}t\right)\right] + \frac{\sigma}{E_2} + \frac{\sigma}{\eta_2}t \tag{1}$$

Then, through the experimental data of triaxial compression creep tests of oil shale under different moisture content (obtained from Wang et al. [51]), and the creep experiment data of the oil shale in different moisture content (the axial stress is 3 MPa and the confining pressure is 0.5 MPa) are substituted into Equation (1). The inline () and beta () functions in MATLAB software are used to invert and fit the model parameters. MATLAB software has powerful functions of numerical calculation and nonlinear fitting, and the built-in multiple optimization algorithms make it more adaptable. The values of E_1, E_2, η_1, η_2 at each moisture content are obtained by calculation, and the corresponding relationship between moisture content and model parameters is shown in Table 1.

Table 1. Correspondence between moisture content and model parameters.

Moisture Content ω (%)	E_1 (GPa)	E_2 (GPa)	η_1 (GPa·h)	η_2 (GPa·h)	R^2
0	1.170	0.417	5.824	268.99	0.999
0.67	1.225	0.327	6.684	103.24	0.998
1.33	1.410	0.313	3.83	51.64	0.998
1.75	1.426	0.312	0.909	29.20	0.993

To verify the correctness of the constitutive model, when the moisture content is 0.67%, the model parameters are used to invert the test data. The inversion test data are compared with the original test data, as shown in Figure 2. The comparison results showed that the experimental data after inversion using the above model parameters were not much different from the original experimental data, and the correlation coefficient R^2 is 0.998, which can verify the correctness of the constitutive model.

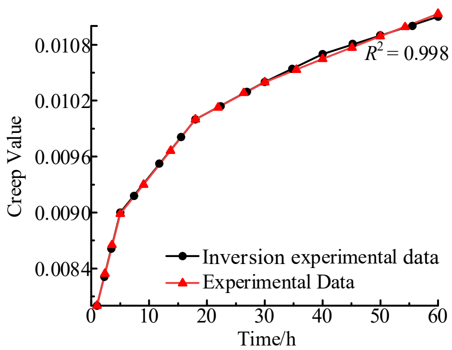

Figure 2. The fitting curve of experimental data and inversion experimental data.

The data in Table 1 were imported into Origin software for fitting analysis, the moisture content was taken as the X-axis, and each parameter in the model was the Y-axis. The parameters were fitted by the Exp3P2 model. The fitting results were shown in Figure 3.

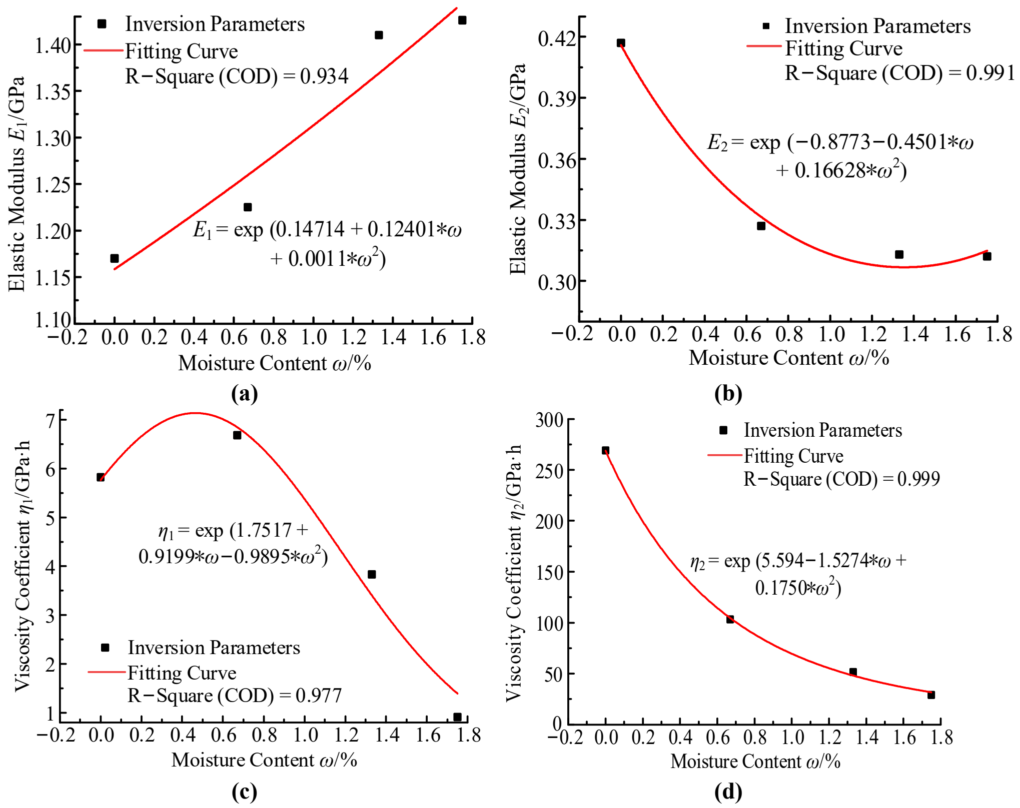

Figure 3. The fitting relationship curve of each parameter in the model and moisture content: (**a**) Fitting curve between elastic modulus E_1 and moisture content; (**b**) fitting curve between elastic modulus E_2 and moisture content; (**c**) fitting curve between viscosity coefficient η_1 and moisture content; (**d**) fitting curve between viscosity coefficient η_2 and moisture content.

It could be seen that the relationship between the moisture content and the parameters in the model was:

$$\begin{aligned} E_1 &= \exp\,(0.14714) * \exp\,(\,0.12401 * w) * \exp\,(\,0.0011 * w^2\Big) \\ E_2 &= \exp\,(-0.8773 - 0.4501 * w * \exp\,(0.16628 * w^2\Big) \\ \eta_1 &= \exp\,(1.7517) * \exp\,(0.9199 * w - 0.9895 * w^2) \\ \eta_2 &= \exp\,(5.594 - 1.5274 * w) * \exp\,(\,0.1750 * w^2\Big) \end{aligned} \quad (2)$$

2.2. Numerical Calculation Realization of the Creep Model

To facilitate the programming of the constitutive model, and through the interface between Visual Studio 2010 and FLAC3D simulation software, the core equation was modified by C++ language, and creep constitutive model of coal-rock combination considering the influence of moisture content was introduced into FLAC3D software.

In order to realize the numerical calculation of the model, it was necessary to write a one-dimensional constitutive equation into a three-dimensional differential form. By using the deviator strain rate relationship between Kelvin body and Maxwell body in Burgers model [43] in a three-dimensional state,

$$\Delta e_{ij} = \left(\frac{b}{a} - 1\right) e_{ij}{}^{K,O} + XS_{ij}{}^{N} + YS_{ij}{}^{O} \quad (3)$$

$$S_{ij}^{N} = \frac{1}{X}\left[\Delta e_{ij} - \left(\frac{b}{a} - 1\right)e_{ij}^{K,O} - YS_{ij}^{O}\right] \quad (4)$$

where Δe_{ij} is the total deviator strain rate of the model, S_{ij}^N and S_{ij}^O are the first and second deviator stress tensor in a time step, respectively, and $e_{ij}^{K,O}$ is the second deviator strain tensor in a time step [44].

In Equations (4) and (5), a, b, X, and Y have the following relationships:

$$\begin{aligned} a &= 1+\frac{G_1\Delta t}{2\eta_1} \\ b &= 1-\frac{G_1\Delta t}{2\eta_1} \\ X &= \frac{1}{2G_2}+\frac{\Delta t}{4\eta_2}+\frac{\Delta t}{4a\eta_1} \\ Y &= \frac{\Delta t}{4\eta_2}+\frac{\Delta t}{4a\eta_1}-\frac{1}{2G_2} \end{aligned} \quad (5)$$

where G_1 is the shear modulus of Kelvin body, GPa; G_2 is the shear modulus of Maxwell body, GPa.

In the aspect of secondary development of creep model, the total stress should be decomposed into spherical stress tensor σ_m and deviator stress tensor S_{ij}:

$$\sigma_{ij} = \sigma_m\delta_{ij} + S_{ij} \quad (6)$$

The increment relation of the spherical stress tensor is:

$$\sigma_m^{N} = \sigma_m^{O} + K\Delta\varepsilon_{kk} \quad (7)$$

where, σ_m^N, σ_m^O are the spherical stress tensor in a time step, K is the bulk modulus, $\sigma_m^O = (\sigma_{11}+\sigma_{22}+\sigma_{33})/3$, $\Delta\varepsilon_{kk} = \Delta\varepsilon_{11}+\Delta\varepsilon_{22}+\Delta\varepsilon_{33}$

Substituting Equations (4) and (7) into Equation (6), the total stress tensor of the model was

$$\sigma_{ij}^{N} = \sigma_m^{N}\delta_{ij} + S_{ij}^{N} \quad (8)$$

The numerical calculation of the model was realized based on the visual studio 2010 software, and the core equation of the model was realized by the programming language. The key work included the definition of model variables, the modification of the functions such as Properties(), Initialize(), Run(), etc. The code editing window is shown in Figure 4.

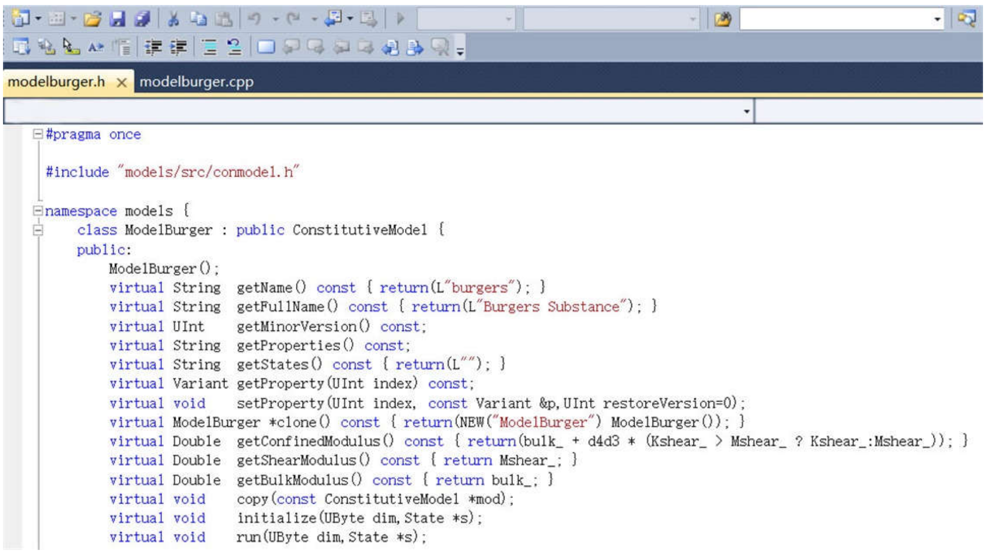

Figure 4. Code editing window.

3. Numerical Simulation Research

3.1. Simulation Scheme

In this study, the numerical simulation model established in this paper was cylindrical to facilitate the simulation calculation. The upper part of the model is coal and the lower part is siltstone. The size of the numerical model was Φ 50 mm $\times$ L 100 mm, and the displacement constraint is applied at the bottom. The confining pressure was set to 3 MPa, and the axial stress was loaded in order of 5, 8, 11, 14 MPa. Based on the above experimental results, we set up four groups of moisture contents to study the creep characteristics of coal-rock combination, and the creep time was 12 h. The specific simulation scheme is shown in Table 2. Three monitoring points were set at the top of the model to record the creep value of the model. The creep constitutive model of coal-rock combination considering the influence of moisture content established in this paper was used for simulation. The model parameters were obtained from the conversion Equation (2) of moisture content in a C++ environment. The physical and mechanical parameters of coal and siltstone were shown in Table 3, and the numerical model was shown in Figure 5.

Table 2. Simulation scheme.

Moisture Content ω (%)	Confining Pressure (MPa)	Axial Stress (MPa)	Creep Time (h)
0	3	5	12
0.5	3	8	12
1.0	3	11	12
1.5	3	14	12

Table 3. Physical and mechanical parameters.

Lithology	Density (kg/m^3)	Cohesion (MPa)	Friction Angle (°)	Poisson's Ratio	Tensile Strength (MPa)
Coal	1628	3.05×10^6	32	0.32	1.05×10^6
Siltstone	2637	6.51×10^6	38	0.2	5.29×10^6

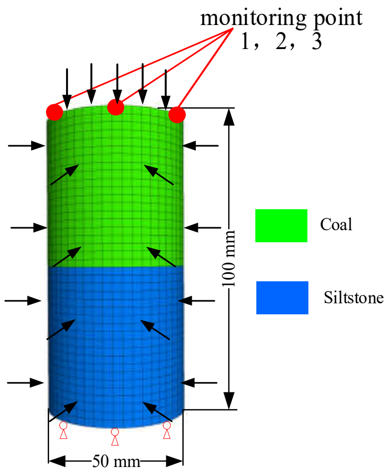

Figure 5. Numerical calculation model.

3.2. Simulation Result Analysis

3.2.1. Deformation Characteristics

According to the data collected from the simulation records, the strain–time curves under different axial stress were obtained by using Origin function drawing software, as shown in Figure 6. It could be seen from the figure that the strain-time curve of coal-rock combination under triaxial stress accorded with the first and second stages of rock typical creep curve, which is the initial creep and constant creep stage. It failed to reflect its plastic characteristics in the simulation due to the Burgers model belonging to the viscoelastic model, so the accelerated creep stage could not be reflected. With the application of loading, the coal-rock combination first underwent instantaneous elastic deformation in the initial creep stage, which was caused by the closure of microcracks in the rock. At the same time, it could be seen from Figure 6 that the mechanical properties of the coal-rock combination changed due to the influence of the moisture content (ω) and stress under the same confining pressure. After entering the creeping stage, the creep deformation was more obvious, which was reflected in the limit creep deformation of the combination increases with the increase of moisture content and the stress. For example, when the axial stress was 5 MPa, the moisture content increased from 0% to 1.5%, and the limit creep deformation increased by about 20%. When the moisture content is 0%, the axial stress increased from 5 to 14 MPa, and the limit creep deformation increased nearly four times. The limit creep deformation was controlled by the limit creep deformation modulus, so the limit creep deformation modulus decreased with the increase of moisture content, which was also in line with the characteristics of the influence of water on the timeliness of rock. According to the strain–time curve under the influence of different stress states and different moisture content, the magnitude of the strain was positively correlated with the moisture content and axial stress.

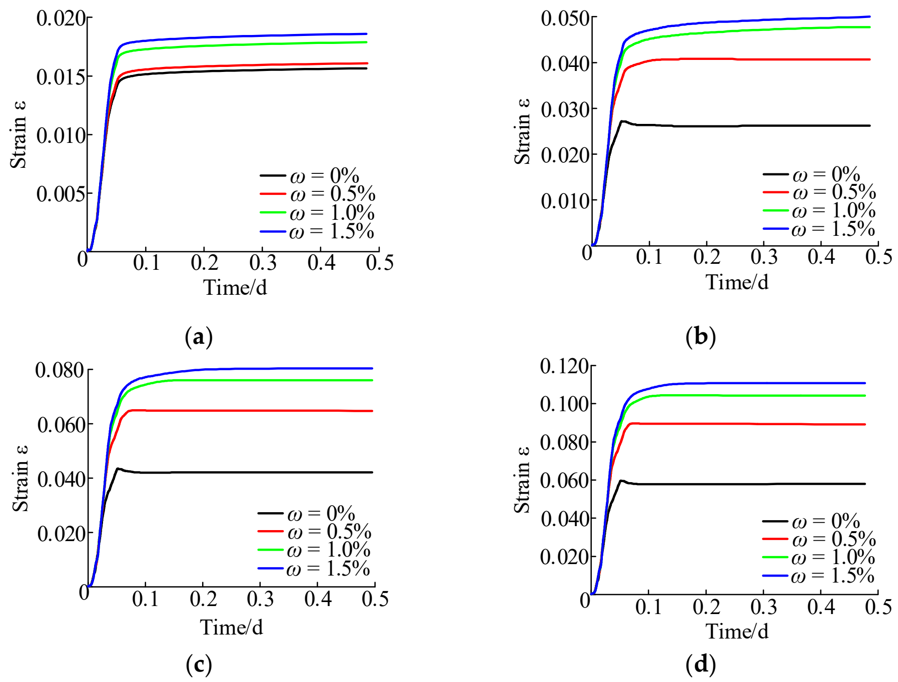

Figure 6. Strain-time curves of coal-rock combination under different moisture content: (**a**) Axial stress 5 MPa; (**b**) Axial stress 8 MPa; (**c**) Axial stress 11 MPa; (**d**) Axial stress 14 MPa.

Instantaneous elastic deformation is also a very important stage in the creep process of coal-rock combination. Take the axial stress of 5 MPa as an example, as shown in Figure 7. It could be seen from the figure that the greater the moisture content, the greater the instantaneous elastic deformation under the same stress state. When the moisture content increased from 0% to 1.5%, the instantaneous elastic deformation increased by approximately 10.53%. The magnitude of the instantaneous elastic deformation was controlled by the instantaneous elastic deformation modulus. Therefore, it could be known from Hooke's law that the instantaneous elastic deformation modulus decreased as the moisture content increased.

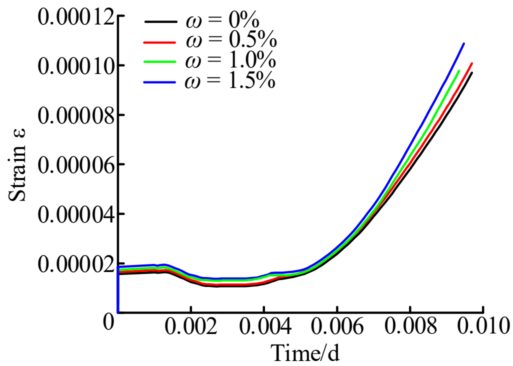

Figure 7. Instantaneous elastic deformation stage when the axial stress is 5 MPa.

3.2.2. Strain Rate Characteristics

The important indicator to show the creep speed of the coal-rock combination was strain rate. The different moisture contents had an important influence on the strain rate. The greater the moisture content of the coal-rock combination was, the greater the strain rate was. It would eventually become stable, which is entering the constant creep stage. At this time the strain rate was approximately a constant value. Strictly speaking, the constant creep stage did not exist, but the stage was divided according to the experimental phenomenon [52]. Then, the strain rate–moisture content curves under different axial stress were as shown in Figure 8. It could be seen from the figure that under the same stress state, the strain rate increased with the increase of moisture content. For example, when the axial stress was 5 MPa, the moisture content increased from 0% to 1.5%, and the strain rate increased by 44.06%. At the same time, when the moisture content was the same, the strain rate increased with the increase of axial stress. For example, when the moisture content was 0.5%, the axial stress increased from 5 to 14 MPa, and the strain rate increased by 40.38%.

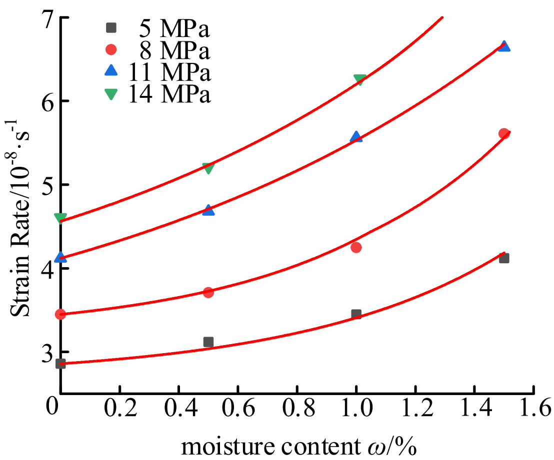

Figure 8. Strain rate–moisture content curve of coal-rock combination.

3.2.3. Viscosity Coefficient Characteristics

A characteristic index reflecting rock creep and flow was the viscosity coefficient, which reflected the rheological properties of materials, and could be expressed by the slope of the straight line segment of the stress–strain rate curve. As can be seen from Figure 9, when the moisture content was 0%, 0.5%, 1.0%, and 1.5%, the corresponding viscosity coefficients were 4.76×10^{14}, 3.85×10^{14}, 3.61×10^{14}, and 2.38×10^{14} Pa·s, respectively. It could be seen that with the increase of moisture content, the viscosity coefficient of the coal-rock combination gradually decreased. The reason may be that water changes the internal structure and properties of the combination, resulting in a decrease in the viscosity coefficient, so the strain rate increased. This further explained the rise of the above strain rate.

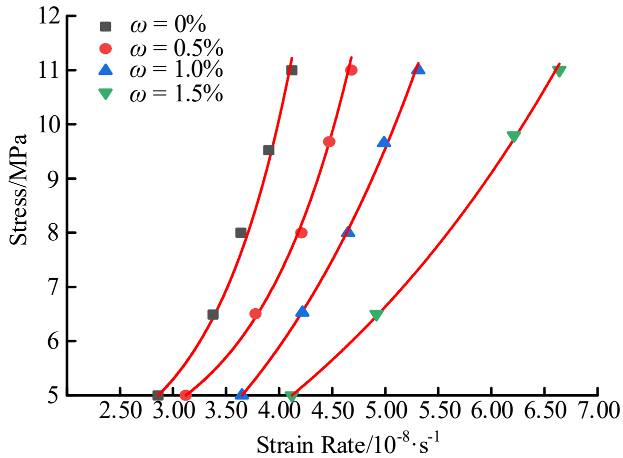

Figure 9. Stress–strain rate curve of coal and rock mass.

4. Discussion

Creep instability failure is a common failure form in underground engineering, which is closely related to stress and the geological environment, so the groundwater will inevitably affect the creep performance of coal and rock. In order to reveal the influence of water on the creep characteristics of underground engineering, scholars and engineers have done a lot of research work on pure coal or pure rock samples and obtained the influence of water on the creep characteristics of the samples. However, in underground engineering, coal and rock do not exist in the form of a monomer, but in a multi-layer structure in which the coal and rock coexist, that is, in the form of combination. Therefore, it is of practical engineering significance to study the creep characteristics of the coal-rock combination after water immersion deterioration.

Compared with previous studies, this study improved the traditional Burgers model, established the relationship between model parameters and moisture content, and then put forward a creep constitutive model of coal-rock combination considering the influence of moisture content. The model can well describe the creep characteristics of combination samples after immersion, and the advantages of high fitting accuracy and simple parameter acquisition are obvious. At the same time, the numerical calculation of the user-defined constitutive model is realized by using the secondary development of FLAC3D simulation software.

In the existing studies, Okubo et al. [16] showed that moisture content and time are the main reasons for the change of rock mechanical properties; in this study, through the establishment of creep constitutive model of coal-rock combination considering the influence of moisture content, and by the parameter inversion and fitting verification, the correlation between moisture content and various mechanical parameters in the model was finally obtained. The deformation characteristics, strain rate characteristics, and viscosity coefficient characteristics of coal-rock combination are analyzed qualitatively and quantitatively through numerical simulation. Vásárhelyi [14], through the comparative test of limestone in the dry and saturated state, shows that: the physical and mechanical parameters of rock in the saturated state are about 66% of that in the dry state. In this study, the numerical simulation showed that when the moisture content increased from 0% to 1.5%, the strain rate increased by 44.06%, the limit creep deformation increased by 20%, and the instantaneous elastic deformation increased by about 10.53%, and the viscosity coefficient decreased about 50%. The difference between the two test results is due to the differences in the test pieces used, the former uses limestone, and the latter uses coal-rock combinations. Another reason may be the difference in loading method, the former uses the uniaxial loading, and this paper is the triaxial loading. Compared with previous studies, the creep characteristics of coal-rock combination under different water content can provide a more accurate reference for the design and construction of underground engineering under water immersion conditions.

As for the creep mechanical properties of coal-rock combination, this paper only analyzed the initial and constant creep stages due to the limitations of Burgers model itself, and the accelerated creep stage of coal-rock combination is not involved. In the future, it will be necessary to carry out in-depth research on triaxial compression creep experiments and nonlinear creep constitutive models of coal-rock combination.

5. Conclusions

On the basis of the present analysis, the following conclusions are drawn:

The Burgers model was modified by creep experimental data, and the creep constitutive model of coal-rock combination considering the influence of moisture content was established, and the parameters of the model were obtained. The experimental data are inversed by using the model parameters, and the inversed experimental data are compared with the original experimental data. The correlation coefficient R^2 is 0.998, which showed that the model had the advantages of high fitting precision and simple parameter acquisition. Then, in order to use the model to study the creep characteristics of coal-rock combination under different moisture content, the numerical calculation of the model is realized by the VS platform;

Creep deformation characteristics of coal-rock combination are closely related to moisture content and stress environment. Under the same stress state, with the increase of moisture content, the limit creep deformation modulus and instantaneous elastic deformation modulus of coal-rock combination decreased, and the corresponding deformation also increased significantly. When the axial stress is 5 MPa, the moisture content increased from 0% to 1.5%, the limit creep deformation increased by about 20%, and the instantaneous elastic deformation increased by about 10.53%. Under the same moisture content, with the increase of axial stress, the limit creep deformation modulus decreased, and the corresponding deformation modulus increased significantly. When the moisture content is 0%, the axial stress increased from 5 to 14 MPa, the limit creep deformation increased nearly four times.

The characteristics of strain rate and viscosity coefficient of coal-rock combination are closely related to moisture content and stress environment. Under the same stress state, the strain rate of the coal-rock combination increased nonlinearly and rapidly with the increase of moisture content, while the viscosity coefficient decreased significantly. When the axial stress was 5 MPa and the moisture content increased from 0% to 1.5%, the strain rate increased by about 44.06% and the viscosity coefficient decreased by about 50%. When the moisture content was the same, the axial stress increased from 5 to 14 MPa, the strain rate increased by 67.74%.

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