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# Experimental Study on Creep Characteristics and Damage Model of Carbonaceous Slate After Freeze-Thaw

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**Abstract**: Taking the carbonaceous slate of Zhuokeji tunnel on the Wenchuan-Ma,erkang expressway as the research subject, triaxial compression creep tests were conducted under various freeze-thaw cycles to analyze the creep strain characteristics and long-term strength of the carbonaceous slate. Assuming that the aging damage of rock under load follows the Weibull probability density distribution, the loaded damage variable is defined. The freeze-thaw damage variable is defined according to the phenomenological theory of damage mechanics. Considering the coupling effect of freeze-thaw and stress, a total damage variable for freeze-thaw and load is constructed. Based on the creep behavior of carbonaceous slate, the structure of the H-H|N-N|S creep model is determined. Based on this, the damage evolution is carried out, and a new creep damage model that can reflect the coupling of freeze-thaw and stress is obtained, which is extended to a three-dimensional stress state. The solution method for model parameters is provided, and the damage evolution law is analyzed. The creep characteristics of carbonaceous slate are identified using the established model. A traditional model is introduced for comparison, and the simulation comparison curve is analyzed to verify the feasibility and rationality of the new model.

**Key words**: tunnel engineering; carbonaceous slate; creep; freezing-thaw; loading; damage model

## 1 Introduction

The creep theory of rock is significant for in-depth explanation and analysis of rheological phenomena of engineering rock masses, particularly in tunnel and high slope engineering. With the acceleration of infrastructure construction in China, the research scope of creep theory has becn greatly broadened and deepened[1-2]. The long-term stability of rock mass decreases as creep behavior becomes more significant, influenced by the factors such as water, freeze-thaw cycles, and high temperatures, and weathering.

Currently, a lot of researches on creep characteristics of rocks under various influencing factors has been made. WANG[5] take deep shale in Tangkou coal mine as research object, the triaxial compressive creep tests under the thermal-mechanical-chemical coupling effect were carried out, different factors effect of deep shale creep properties is analyzed, the creep model of considering temperature and chemical pH value influencing factor deep rock were established. QIANG, et al.[6] carried out the uniaxial compression creep experiment under the coupling effect of chemical solution with constant-speed flow and constant stress. The deformation characteristics of silty sandstone in the multi-field environment is analyzed. CHEN, et al.[7] design and heating-cooling carried out drainage creep tests on claystone under different confining pressures and deviatoric stresses, the coupled thermo-hydro-mechanical creep model for claystone was established on the basis of Perzyna overstress theory. ZHANG, et al.[8] conducted triaxial creep tests on sandstone under different temperatures, A one-dimensional constitutive model under rock temperature and confining pressure was established. FENG, et al.[9] conducted research on sandstone under combined action of chemical-freeze-thaw cycles, explored the creep rate and long-term strength law of rock under different thawing condition and pH value. It can be seen that much research has been done on creep model under coupling influenced of different external factors, but there are fewer existing research

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on creep characteristics and damage model influenced by the coupling of freeze-thaw and stress carried out under construction.

In this paper, the carbonaceous slate of Zhuokeji tunnel of Wenchuan-Ma'erkang expressway was taken as the research object, the triaxial compression creep tests under different freeze-thaw cycles are carried out to analyze the creep strain characteristics and long-term strength of carbonaceous slate. Based on experimental results, considering the coupling effect of freeze-thaw and stress, the total damage variable of freeze-thaw and load is constructed. A new creep damage model that can reflect the coupling of freeze-thaw and stress is obtained, which is extended to three-dimensional stress state. Meanwhile, damage evolution law is analyzed. The creep data of carbonaceous slate are identified by the established model is introduced for comparison, and the simulation comparison curve is analyzed to verify the feasibility and rationality of the new model.

## 2 Creep test

### 2.1 Researching background

The researching background of this study is Zhuokeji tunnel of Wenchuan-Ma'erkang expressway, which is located in Ma'erkang county with 1 917 m length and 4 564 m high altitude; The buried depth of tunnel is about 172 m. The bedrock strata exposed in the Upper Triassic Xinduqiao strata ($T_3x$) and the lithology of tunnel is dominated by carbonaceous slate, which Surrounding Rocks Grade from Ⅳ to Ⅴ. A significant creep phenomenon is observed in Surrounding Rocks, the deformation and failured of tunnel initial support due to creep as shown in Figure 1.

**Fig. 1 The initial support of the tunnel is deformed and damaged due to the creep of surrounding rock**

### 2.2 Experimental materials and test principle

The carbonaceous slates selected in this test were taken from Zhuokeji tunnel in Sichuan, China. Triaxial creep tests was conducted using the compression creep test system RLW-2000 (Figure 2). Variable freeze-thaw cycles and progressive loading can be set up in test system. In order to revive actual stress state of surrounding rock, the confining pressure was applied to a predetermined value according to stress values of sample depth, and the confining pressure is selected to be 20 MPa. Carbonaceous slates is machined into cylindrical standard specimens with a diameter of 50 mm and a height of 100 mm. The average values of the initial basic physical parameters for the rock samples are shown in Table 1. According to the previous research studies[10], The rock sample is frozen for 12 h at −20 ℃ and thawed for 12 h at 20 ℃. A freeze-thaw cycle takes place every 24 h. The freeze-thaw cycle test was performed 0, 5, 15, and 30 times, respectively.

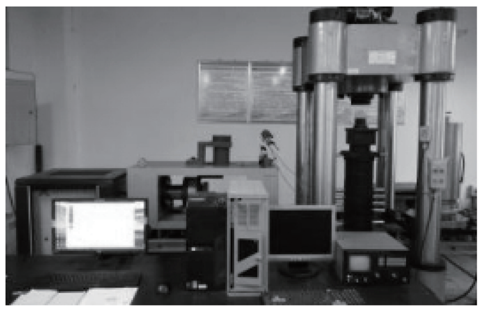

**Fig. 2 Creep test instrument**

**Table 1 Mechanical parameters of rock**

| Natural gravity ($kN/m^3$) | Void ratio (%) | Natural water content (%) | Natural density ($g/cm^3$) | Dry density ($g/cm^3$) |
|---|---|---|---|---|
| 23.47 | 0.58 | 1.78 | 2.54 | 2.52 |

### 2.3 Experimental design

Maximal deviatoric stress of carbonaceous slate was gained by conventional triaxial test before creep test. In the experiment, taking 0 times freezing-thawing cycles as basic working condition with the confining pressure remained at 20 MPa, two parallel samples were measured, the Conventional triaxial test results of rock as shown in Figure 3.

Maximal deviatoric stress $q_f$ equal to mean values among three groups of rock samples, thus, $q_f$ is equal to 142.49 MPa. It is assumed that $\Delta q$ (load increment) is

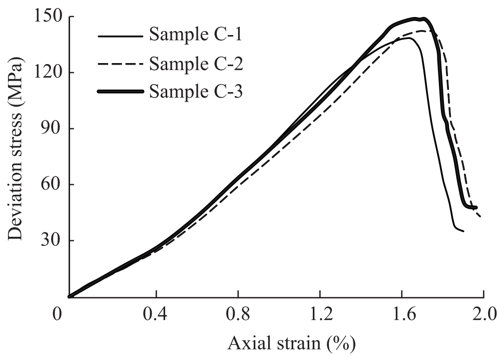


**Fig. 3 Conventional triaxial test results of rock**

equal to $Kq_f/c$($K$ is refer to strength reduction coefficient and $c$ is refer to the grade of creep load)[11] in the experiment. According to the previous research studies[12], $c$ is equal to 6, $K$ is equal to 0.7,The deviatoric stress level were 16.62, 33.24, 49.86, 66.48, 83.1, and 99.72 MPa respectively. After the confining pressure was stabilized, the axial pressure (deviatoric stress) is applied. And the rock sample was loaded for 100 h every level.

## 2.4 Experimentation Results

It can be seen from Figure 4 that the creep deformation curves of carbonaceous slate under different freezing-thaw, every level of loading has labelled under the curves. The creep curves under separately loading can be drawn as Figure 5 using the Boltzman accumulate principle[12]. Take the 5 times freezing-thaw cycles for example, within 0 h to 90 h creep data be selected to drawing the Isochronous deviatoric stress-axial strain curves as shown in following Figure 6. The characteristics of accelerated creep disappear when the deviatoric stress is 83.10 MPa. So that we can put the data of 78.33 h is approximately equal to the data of 90 h for the integrity of curves.

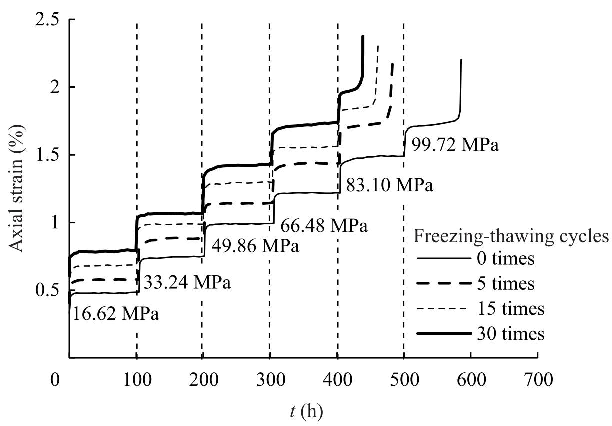


**Fig. 4 Creep test results**

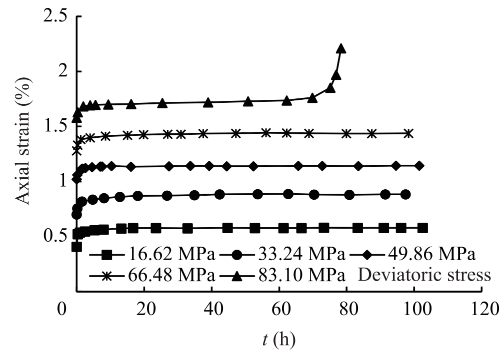


**Fig. 5 Separate loading creep curves**

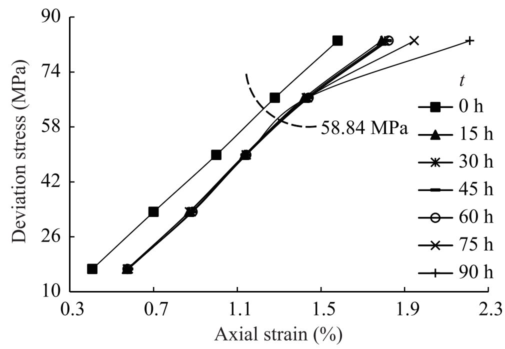


**Fig. 6 Isochronous deviatoric stress axial strain curves**

As shown in Figure 4, creep curves of carbonaceous slate present a ladder-shaped increasing rule, the axial strain increasing with the increase of time. The creep failure was occurred after load step-6 under 0 times freeze-thaw cycles. But the creep failure was occurred after load step-5 under 5, 15 and 30 freeze-thaw cycles, which indicates that the freeze-thaw cycles had a significant effect on the creep deformation of the rock samples, and the freeze-thaw cycle effect was more significant when the stress level of the creep load was higher.

It can be seen from Figure 5 that creep strain the creep deformation increasing with the increase of time, and the growth rate gradually decays and tends to stabilize. Meanwhile, decay creep transit to steady creep had completed . It can be seen from Figures 5 that the process of steady creep is majority of whole creep process. When the stress in rock exceeds its long-term strength, rock creep presents the characteristics go to nonlinear accelerated creep till failure.

It can be seen from Figures 5 that the isochronous deviatoric stress-strain curve is composed of 0 h linear segment and nonlinear curve cluster, and the 15 h to 90 h nonlinear curve cluster gradually deviates to the strain axis. Hence, selecting the value of inflection point as long-term strength[13], the long-term strength of carbonaceous slate can be determined as 58.84 MPa under 5 freeze-thaw cycles. Using the same method, the long-term strength of carbonaceous slate can be determined as 76.02, 55.63, and 51.49 MPa respectively under 0, 15 and 30 freeze-thaw cycles. Obviously, the long-term strength is decreased with the increase of freeze-thaw action.

## 3 Damage model of rock creep

### 3.1 Definition of damage variable

As a kind of complex inhomogeneous geological material, rock is influenced by the factors of water, freeze-thaw, weathering in natural environment so as to the deterioration performance of rock caused by stress. In this paper, damage is defined as the deterioration performance of rock caused by changes in micro-structure[14]. The creep deformation of rock after freeze-thaw action caused by the corresponding accumulation of internal cracks under external forces. In the creep model of rock, the damage variables are defined considering rock internal damage which can reflected the internal structure degradation of rock. In this study, combining with the existing environment of carbonaceous slate and experimental condition, we considering that the process of rock damage controlled by the coupling of freeze-thaw and stress. Therefore, the coupling effect of freeze-thaw and stress should be considered when we defining the damage model of rock. And the evolution equation of rock damage under freeze-thaw and load should be established.

It is assumed that $N$ is the total microelement number of rock and that $N$ is the microelement number of damaged rock under a certain load, and then $D$ is defined as the loaded damage variable, i. e. .

Assuming that rocks are composed of $M$ micro-units, where $M_1$ is represented nondestructive micro-unit, $M_2$ is represented destructive micro-units caused by the coupling of freeze-thaw and stress, $M_2$ is consist of $M_d$ (damage micro-units caused by freeze-thaw) and $M_s$ (damage micro-units caused by stress). The total damage variable D that can reflect the coupling of freeze-thaw and stress can be expressed as follows:

$$D = \frac{M_2}{M} = \frac{M_d + M_s}{M}, 0 \leqslant D \leqslant 1. \tag{1}$$

Base on the percentages of destructive micro-units, $D_d$ was defined by the ratio of $M_d$ and $M$, $D_s$ is defined by the ratio of $M_s$ and $M- M_d$, thus

$$\begin{cases} D_d = \dfrac{M_d}{M}, \\ D_s = \dfrac{M_s}{M - M_d}. \end{cases} \tag{2}$$

From Equations (1) and (2), the following equation can be derived:

$$D = D_d + D_s - D_d D_s. \tag{3}$$

where, $D$ is the damage variable $D$ that can reflect the coupling of freeze-thaw and stress, It can be seen from Equation (3) that $D$ is unequal to $D_d$ plus $D_s$. It indicates that there exists the complicated interaction between the freeze-thaw and stress, so that the values of $D$ calculated by Equation (3) less than the values calculated by Equation (1).

Because of the different mechanism of interaction between the freeze-thaw and stress, the different performance of rock can be found under freeze-thaw or stress. Due to the coupling of freeze-thaw and stress, it would have mutual feedback between the failure region caused by stress and the failure region caused by freeze-thaw. Thus, the mechanical performance of rock material will be reduced.

According to phenomenological damage mechanics theory[15], following formula was defined the rock freeze-thaw damage variable $D_d$ in this paper:

$$D_d = 1 - \frac{E_d}{E_0}, \tag{4}$$

Where, $E_0$ is the initial elastic modulus of the rock; $E_d$ is the elastic modulus of the rock after different freeze-thaw cycles.

In this paper, the initial elastic modulus and the elastic modulus of the rock after freeze-thaw cycles is measured by conventional triaxial compression test.

When the freeze-thaw damage variable $D_d$ has the effect on rock, the change of the elastic modulus are an attenuation process, the damage variable would gradually accumulated and finally tends to be stable with the increase of number of cycles. Then $E_d$ would eventually reach a stable value, Equation (4) can be updated by the exponential function, we have

$$D_d = \frac{E_0 - E_d}{E_0}(1 - e^{-\alpha t}), \quad (5)$$

where, $t$ is the failure time; $\alpha$ is the parameter that characterizes the internal damage of the rock.

Let $E_0$ equal to 5 GPa, $E_d$ equal to 1 GPa, The relationship between $D_d$ and time of rock under different $\alpha$ is obtained by experiments. The creep curves are shown in Figure 7.

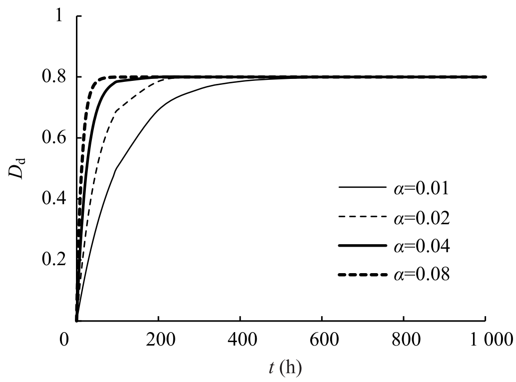


**Fig. 7 Variation curves of $D_d$ with time $t$**

Figure 7 shows the relationship curve between the damage variable $D_d$ and the time when the $\alpha$ take different values. It can be seen from the figure that regardless of the value of $\alpha$, the damage variable has basically the same trend over time, increasing with the increase of time, and the growth rate gradually decays and tends to stabilize. The $\alpha$ value controls accumulation rates of damage under freeze-thaw . The larger the $\alpha$ value, the more faster the values of $D_d$ increase to constant value. Hence, Formula (5) structure would becomes more flexible, the method of updating Equation (4) by exponential function is feasible, Equation (5) is the evolution equation of total $D_d$ under freeze-thaw.

In order to describe this nonlinear creep deformation characteristic, the creep parameter can no longer be used as a fixed value. It is a function of time variation. It is assumed that the variation law of damage variable and time product satisfies the following Equation (6).

The characteristics of heterogeneous and nonlinear are considered in rock, Internal particles of rock moved and microdefect development even to interpenetrated when rock were subjected to long-term loads. The changing of internal microstructure has the random characteristic. The randomness was interpreted as ageing probability in this study, the development of failure region caused by stress presented random distribution with time. Assuming that aging damage under stress obey probability density function $\varphi(t)$, the stress damage variable ($D_s$) can be written as

$$D_s = \frac{M_s}{M - M_d} = \frac{\int_0^t (M - M_d)\varphi(t)\,dt}{M - M_d} = \int_0^t \varphi(t)\,dt. \quad (6)$$

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. Assuming that the time-dependent damage of rock under loading follows Weibull distribution, then, $\varphi(t)$ can be expressed by:

$$\varphi(t) = \frac{m}{\beta}\left(\frac{t}{\beta}\right)^{m-1}\exp\left[-\left(\frac{t}{\beta}\right)^m\right], \quad (7)$$

Where, $\beta$ and m are parameters related to mechanical properties.

Substituting Equation (7) into Equation (6), we obtain

$$D_s = 1 - \exp\left[-\left(\frac{t}{\beta}\right)^m\right], \quad (8)$$

Equation (8) is damage evolution equation of $D_s$.

Substituting Equation (5) and Equation (11) into Equation (3), Equation (3) can be written as

$$D = 1 - \left(2 - e^{-\alpha t} - \frac{E_d + E_d e^{-\alpha t}}{E_0}\right)\exp\left[-\left(\frac{t}{\beta}\right)^m\right], \quad (9)$$

Equation (9) is damage evolution equation of $D$.

### 3.2 Creep model

When the stress in rock is lower than its long-term strength, the rock generally experiences the two stages of elasticity and viscoelastic strain. In general, the model consists of two parts connected in series, one part is a spring (H1), the other part is a spring (H2), and a sticky pot (N) in parallel (H | N) which can describe the creep characteristics of rock at this time. When the stress in rock exceeds its long-term strength, the rock will enter the accelerated creep stage after experiencing the first two creep stages. rock creep presents the characteristics of the accelerated creep stage, so we can consider that the viscoplastic element is used to describe the accelerated creep stage of rock. So that the structure of H-H | N-N | S creep model is determined.

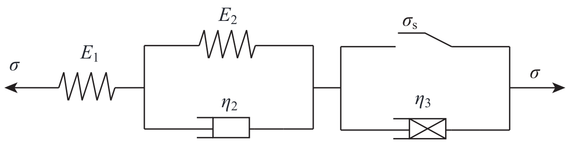


**Fig. 8 Schematic diagram of the rock nonlinear creep model**

The Equation of state corresponding to model structure was shown in Figure 5 can be expressed by:

$$\begin{cases}\boldsymbol{\sigma}=\sigma_{(1)}=\sigma_{(2)}=\sigma_{(3)}, \\ \boldsymbol{\varepsilon}=\varepsilon_{(1)}+\varepsilon_{(2)}+\varepsilon_{(3)}, \\ \dot{\varepsilon}_{(1)}=\dot{\sigma}_{(1)}/E_1. \\ \sigma_{(2)}=E_2\varepsilon_{(2)}+\eta_2\dot{\varepsilon}_{(2)}, \\ \sigma_{(3)}=\sigma_s+\eta_3\dot{\varepsilon}_{(3)},\end{cases} \tag{10}$$

where, $\boldsymbol{\sigma}$ is stress; $\boldsymbol{\varepsilon}$ is strain; $\eta$ is coefficient of viscosity; $\sigma_s$ is long-term strength, the superscript of $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are represented the stress rates and strain rates. The fifth formula of Equation (10) is validate when the stress in rock exceeds its long-term strength.

Solving Equation (10), we obtain

$$\varepsilon=\frac{\sigma}{E_1}+\frac{\sigma}{E_2}[1-\exp(-\frac{E_2}{\eta_2}t)]+\frac{\sigma-\sigma_s}{\eta_3}t, \tag{11}$$

Formula (11) is the creep equation of the rock 1D creep constitutive model (as shown in the Figure 8). The friction block begins to work and the nonlinear pot is deformed when $\sigma \geqslant \sigma_s$.

Base on existing theory of damage mechanics[15], assuming that the deterioration law of $P$ (mechanical parameter of rocks) following isotropy, the parameters of time-dependent damage $P(t, \alpha, \beta, m)$ can be expressed by

$$P(t,\alpha,\beta,m)=P(1-D)=P\exp[-(\frac{t}{\beta})^m]\cdot (2-e^{-\alpha t}-\frac{E_d+E_d e^{-\alpha t}}{E_0}). \tag{12}$$

Substituting Equation (12) into Equation (11), we obtain

$$\varepsilon=\frac{\sigma}{E_1(t,\alpha,\beta,m)}+\frac{\sigma-\sigma_s}{\eta_3(t,\alpha,\beta,m)}t+\frac{\sigma}{E_2(t,\alpha,\beta,m)}[1-\exp(-\frac{E_2}{\eta_2}t)], \tag{13}$$

Formula (13) is the creep equation of the rock 1D creep model that can reflect the coupling of freeze-thaw and stress.

The surrounding rock is generally under three-way stress, with few cases of one-way stress. Applying the 1D constitutive model to practical engineering scenarios is difficult. Therefore, the 1D creep model needs to be converted into a 3D model. Based on isotropy hypothesis, according to generalized Hooke's law, the constitutive relation of 3D stress state is

$$\begin{cases}\boldsymbol{\sigma}_m=3K\boldsymbol{\varepsilon}_m, \\ \boldsymbol{S}_{ij}=2G\boldsymbol{e}_{ij},\end{cases} \tag{14}$$

Where, $\boldsymbol{\sigma}_m$ is the spherical stress tensor; $\boldsymbol{\varepsilon}_m$ is the volumetric strain tensor; $\boldsymbol{S}_{ij}$ is the deviator stress; $\boldsymbol{e}_{ij}$ is the deviator strain; $K$ is the bulk modulus; $G$ is the shear modulus. inner stress tensor decomposition of rock is applied, we have:

$$\boldsymbol{\sigma}_{ij}=\boldsymbol{S}_{ij}+\boldsymbol{\delta}_{ij}\boldsymbol{\sigma}_m, \tag{15}$$

Where, $\boldsymbol{\sigma}_{ij}$ is stress tensor; $\boldsymbol{\delta}_{ij}$ is unit tensor .

Volume creep of rock material was not considered in this paper, If only consider instantaneous volumetric deformation of loading, yield functions $F$ was introduced in this paper, so that Equation (13) is extended to three-dimensional stress state.

$$\begin{cases}\varepsilon_{ij}=\dfrac{(\boldsymbol{S}_{ij})_0}{2G_1(t,\alpha,\beta,m)}+\dfrac{\boldsymbol{\sigma}_m}{3K(t,\alpha,\beta,m)}\delta_{ij}+\dfrac{(\boldsymbol{S}_{ij})_0}{2G_2(t,\alpha,\beta,m)}[1-\exp(-\dfrac{G_2}{\eta_2}t)] \\ \quad F<0,(\boldsymbol{S}_{ij})_0<(\boldsymbol{S}_{ij})_S, \\ \varepsilon_{ij}=\dfrac{(\boldsymbol{S}_{ij})_0}{2G_1(t,\alpha,\beta,m)}+\dfrac{\boldsymbol{\sigma}_m}{3K(t,\alpha,\beta,m)}\delta_{ij}+\dfrac{(\boldsymbol{S}_{ij})_0}{2G_2(t,\alpha,\beta,m)}[1-\exp(-\dfrac{G_2}{\eta_2}t)]+\dfrac{t}{2\eta_3(t,\alpha,\beta,m)}\dfrac{F}{F_0}\dfrac{\partial Q}{\partial\sigma_{ij}}, \\ \quad F\geqslant 0,(\boldsymbol{S}_{ij})_0\geqslant(\boldsymbol{S}_{ij})_s,\end{cases} \tag{16}$$

where, $(S_{ij})_0$ is initial deviator stress tensor; $(S_{ij})_s$ is deviator stress tensor corresponding to long-term strength; $F_0$ is initial value of $F$; $Q$ is plastic potential function. thus, $F$ can be written as

$$F=\sqrt{J_2}-\sigma_s/\sqrt{3}, \tag{17}$$

Where $J_2$ is invariant of the stress deviator, subscript 2 is second invariant of the stress deviator.

In this study, the value of intermediate principal stress is equal to confining pressure, thus

$$\begin{cases} \boldsymbol{\sigma}_m = (\sigma_1 + 2\sigma_3)/3, \\ S_{11} = 2(\sigma_1 - \sigma_3)/3, \\ \sqrt{J_2} = (\sigma_1 - \sigma_3)/\sqrt{3}. \end{cases} \tag{18}$$

Let $F_0$ equal to 1, assuming that the plastic potential function as yield function ($Q=F$)[16-18], Substituting Equation (18) into Equation (16), and the 3D damage creep model can be converted to the following equations:

$$\begin{cases} \varepsilon_{11}(t) = \dfrac{\sigma_1 - \sigma_3}{3G_1(t,\alpha,\beta,m)} + \dfrac{\sigma_1 + 2\sigma_3}{9K(t,\alpha,\beta,m)} + \\ \quad \dfrac{\sigma_1 - \sigma_3}{3G_2(t,\alpha,\beta,m)}[1 - \exp(-\dfrac{G_2}{\eta_2}t)], \\ \quad (\sigma_1 - \sigma_3) < (\sigma_1 - \sigma_3)_s, \\ \varepsilon_{11}(t) = \dfrac{\sigma_1 - \sigma_3}{3G_1(t,\alpha,\beta,m)} + \dfrac{\sigma_1 + 2\sigma_3}{9K(t,\alpha,\beta,m)} + \\ \quad \dfrac{\sigma_1 - \sigma_3}{3G_2(t,\alpha,\beta,m)}[1 - \exp(-\dfrac{G_2}{\eta_2}t)] + \\ \quad \dfrac{(\sigma_1 - \sigma_3) - (\sigma_1 - \sigma_3)_s}{3\eta_3(t,\alpha,\beta,m)}t, \\ (\sigma_1 - \sigma_3) \geqslant (\sigma_1 - \sigma_3)_s, \end{cases} \tag{19}$$

Where, $(\sigma_1-\sigma_3)$ is deviator stress; $(\sigma_1-\sigma_3)_s$ is long-term strength.

Formula (19) is the axial creep equation of the rock 3D creep damage model that can reflect the coupling of freeze-thaw and stress.

## 4 Parameter solution and model verification

### 4.1 Solving method of Parameters

Formula (19) can be applied to creep behavior verification. By fitting the creep curves, there are nine parameters, $G_1$, $G_2$, $K$, $\eta_2$, $\eta_3$, $\alpha$, $\beta$, $m$ and $(\sigma_1-\sigma_3)_s$ to be determined; where $(\sigma_1-\sigma_3)_s$ is the long-term strength of rock which can be measured by the method shown in Figure 6, $G_1$ and $K$ are obtained by generalized Hooke's law. Considering that it must be a huge quantity of computation, the residual 6 parameters are calculated by mathematic software 1st Opt with BFGS algorithm.

In this paper, $E_0$ and $E_d$ were defined as the initial elastic modulus and the elastic modulus of the rock after different freeze-thaw cycles respectively. The rock damage amount is a cumulative effect, the damage increases with the increase of loading. Based on Figure 5 (Separate loading creep curves), the parameters $\alpha$, $\beta$, $m$ are calculated by the established model. the parameters $\alpha$, $\beta$, $m$ have different values in every stage of loading. Hence, the damage parameters is determined by the averaging values of $\alpha$, $\beta$, $m$ under freeze-thaw cycles. The accumulation process of $D$ under freeze-thaw cycles takes on an increasing trend from low to high levels. Thus, the solution method of model parameters is given.

### 4.2 Verification of the creep model

New established model was used to simulate the creep curves obtained by separate loading method. It can obtain the comparison curves between simulation results and test values as shown in Figure 9. In order to verify the proposed model. The accuracy and applicability of the new model were verified by comparing the calculation results in exist model (Figure 8). It should be pointed that damage was not considered in exist model. The creep model parameters are obtained by fitting, as shown in Table 2. It should be pointed out that, when the times of freeze-thaw are equal to 0, $E_0=E_d$, thus $D_d=0$, $\alpha$ has non unique solution exist, but it was not affected the process of calculate $D_s$ and $D$.

As shown in Figure 9 and Table 2. It can be seen that the coefficient of determination $R^2>0.9878$, indicating that the new model proposed herein is in good agreement with creep behavior of carbonaceous slate. In contrast, The simulate performance of exist model (Figure 8) is acceptable with an $R^2>0.9425$. But has poor performance in simulating the creep curves under the last stage of loading. Large bias is found in the changing of accelerated creep behavior.

which can better reflect the mechanical behavior of rock under various freeze-thaw cycles, thus verifying the rationality of the constitutive model.

### 4.3 Damage Analysis

Substituting the parameters of Table (2) into Equation (9), we obtain the evolution curves of total damage variable $D$ under freeze-thaw and load as shown in Figure 10.

As shown in Figure10 and Table 2. The accumulative rate of total damage variable D under freeze-thaw and load is relatively slow before freeze-thaw cycles, $D$ causing damage by loading that the unique factor at present.

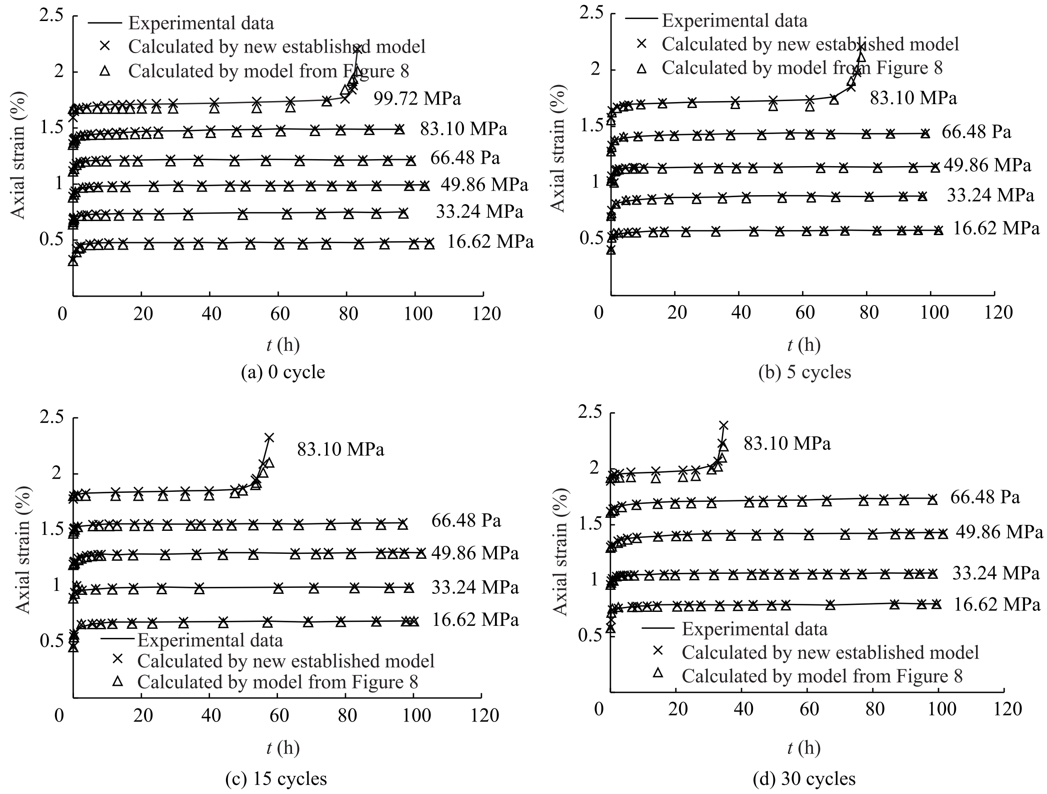


**Fig. 9 Comparison curves between simulation results and test values**

**Table 2 Creep damage model parameters**

| Freeze-thaw cycles (time) | Deviatoric stress (MPa) | $G_1$(GPa) | $G_2$(GPa) | $K$(GPa) | $\eta_2$ (GPa·h) | $\eta_3$ (GPa·h) | $\alpha$ | $\beta$ | $m$ | $(\sigma_1-\sigma_3)_s$ (MPa) | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 16.62 | 1.936 | 6.754 | 4.196 | 59.223 | — | — | 110.26 | 1.52 | 76.02 | 0.983 9 |
| | 33.24 | 7.764 | 30.787 | 16.822 | 199.081 | — | | | | | 0.984 6 |
| | 49.86 | 13.837 | 54.869 | 29.981 | 295.659 | — | | | | | 0.985 5 |
| | 66.48 | 20.358 | 65.863 | 44.108 | 381.295 | — | | | | | 0.992 5 |
| | 83.10 | 22.508 | 89.253 | 48.768 | 277.936 | 185.734 | | | | | 0.989 6 |
| | 99.72 | 34.867 | 138.261 | 75.545 | 335.770 | 12.375 | | | | | 0.991 2 |
| 5 | 16.62 | 1.568 | 6.219 | 3.398 | 42.320 | — | 0.07 | 84.59 | 1.26 | 58.84 | 0.984 4 |
| | 33.24 | 10.479 | 41.554 | 22.705 | 230.982 | — | | | | | 0.992 3 |
| | 49.86 | 13.945 | 55.296 | 30.214 | 247.758 | — | | | | | 0.989 9 |
| | 66.48 | 18.932 | 71.071 | 41.019 | 286.438 | 136.031 | | | | | 0.984 2 |
| | 83.10 | 22.482 | 89.149 | 48.711 | 196.716 | 7.358 | | | | | 0.989 7 |
| 15 | 16.62 | 1.390 | 5.510 | 3.011 | 32.494 | — | 0.16 | 57.53 | 0.85 | 55.63 | 0.979 6 |
| | 33.24 | 6.160 | 22.427 | 13.347 | 113.603 | — | | | | | 0.991 4 |
| | 49.86 | 9.473 | 37.566 | 20.526 | 134.210 | — | | | | | 0.984 5 |
| | 66.48 | 13.959 | 55.351 | 30.244 | 160.942 | 83.439 | | | | | 0.990 5 |
| | 83.10 | 15.116 | 59.939 | 32.751 | 72.545 | 4.216 | | | | | 0.988 4 |
| 30 | 16.62 | 1.102 | 4.370 | 2.388 | 21.969 | — | 0.37 | 31.04 | 0.41 | 51.49 | 0.984 6 |
| | 33.24 | 7.256 | 28.773 | 15.721 | 108.782 | — | | | | | 0.989 7 |
| | 49.86 | 8.284 | 32.849 | 17.948 | 88.778 | — | | | | | 0.985 9 |
| | 66.48 | 13.509 | 53.568 | 29.269 | 109.152 | 51.368 | | | | | 0.990 8 |
| | 83.10 | 18.561 | 73.673 | 40.215 | 27.841 | 2.504 | | | | | 0.991 5 |

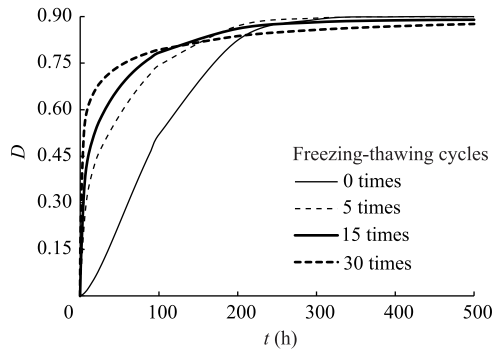


**Fig. 10 Evolution curves of total damage variable $D$ under freeze-thaw and load**

The accumulative rate of $D$ was accelerated after before freeze-thaw cycles. The more freeze-thaw cycles the larger the $\alpha$ value, the faster $D_d$ value accumulates. $D_d$ is contribute most to the accumulative evolution of $D$, the $D$ values will increase faster to constant. Overall, internal structure degradation of carbonaceous slate increase much more quickly with the increase of freeze-thaw cycles which have the definite promotion effect on creep failure.

The new established model has similar trends and show a great coincidence with creep behavior through the analysis and validation, demonstrated the feasibility of new established model. However, it is necessary to further verify its application in different types of rocks.

## 5 Conclusions

(1) The creep curves of carbonaceous slate exhibit a ladder-shaped increasing pattern, with axial strain increasing over time. As the number of freeze-thaw cycles increased, the long-term strength of the rock decreased, indicating that freeze-thaw cycles make rocks more susceptible to failure.

(2) The loaded damage variable is defined by a probability density distribution. The freeze-thaw damage variable is defined according to the phenomenological damage mechanics theory. Considering the coupling effect of freeze-thaw and stress, a total damage variable for freeze-thaw and load is constructed.

(3) Based on the creep behavior of carbonaceous slate, the structure of the H-H|N-N|S creep model is determined. Based on this, the damage evolution is carried out, and a new creep damage model that can reflect the coupling of freeze-thaw and stress is obtained, which is extended to a three-dimensional stress state.

(4) The structure of the H-H|N-N|S creep model is determined. The solution method for model parameters is provided. The creep data of carbonaceous slate is identified using the established model. A traditional model is introduced for comparison, and the simulation comparison curve is analyzed to verify the feasibility and rationality of the new model.

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## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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