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Long-term creep law and constitutive model of extremely soft coal rock subjected to single-stage load

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Abstract: In order to study the long-term creep law of extremely soft coal rock, the uniaxial and triaxial creep tests of extremely soft coal rock subjected to single-stage loads were carried out by using the self-developed triaxial creep test system. The following results and conclusions are obtained. 1) In the uniaxial long-term creep test, transient creep stage, steady-state creep stage, and accelerated creep stage occur successively during 232 hours, and the cumulative creep strain is as high as 3.45%, which is 10.5 times of the instantaneous deformation. The strain rate for the total steady-state creep stage is as high as $8\times10^{-5}-10\times10^{-5}$/h, the maximum accelerated creep rate reaches up to 0.043/h, and the strain rate of total creep process is distributed in a U shape. 2) In the triaxial long-term creep tests subjected to the same axial pressure(0.96 MPa), the ability of resisting long-term deformation of extremely soft coal rock increases continuously with the increase of confining pressure from 0 to 0.6 MPa, which is shown as follows: the creep strain decreases significantly; the strain rate of steady-state creep stage decreases by order of magnitudes; the duration before creep failure increases obviously; the ratio of creep to instantaneous strain decreases dramatically; the intensity of accelerated creep failure decreases markedly. The creep strain and deformation rate are especially sensitive to the confining pressure change in the range of 0–0.2 MPa. 3) The accelerated creep stage of extremely soft coal rock is characterized by "gradual" time dependent instability, which is significantly different from the "abrupt" accelerated fracture instability of ordinary rock. 4) The nonlinear viscoelastic plastic creep model is established by connecting a new nonlinear viscoelastic model considering the concept of accelerated creep start-up time with Burgers model in series to describe the three creep stages of extremely soft coal rock subjected to single-stage load. Then, the creep parameters were identified by employing the Levenberg-Marquardt optimization algorithm. The fitting curves are highly consistent with the experimental curves, verifying the validity of the proposed model. These findings can provide reference for theoretical analysis of nonlinear large creep deformation and support design of extremely soft rock.

Keywords: extremely soft coal rock; single-stage load; long-term creep test; large deformation; nonlinear creep model

1 Introduction

With the in-depth implementation of China's major engineering constructions and the increasing mining scope of resources, there are emerged more and more soft or extremely soft rock geological engineering problems. Especially in the extremely soft broken surrounding rock (according to the rock strength grading standards[1], extremely soft rock refers to a rock type whose uniaxial (saturated) compressive strength is within the range of 0–5 MPa), where the rheological behaviour of surrounding rock is extremely strong. It often leads to frequent disasters such as strong nonlinear deformation instability of surrounding rock of tunnel (roadway), breaking of support structures and overall failure of support system[2–6]. Rheological mechanics behaviour of extremely soft rock has become a bottleneck restricting long-term safe operation of underground engineering. It is imperative to study the long-term creep law of extremely soft rock and establish a reasonable constitutive relation, and to provide a more reliable creep analysis model and reference for long-term stability analysis, support design and construction operation of extremely soft rock engineering.

The creep mechanical behavior of different types of rocks has been extensively studied. Griggs [7], Sun[8], Yang et al.[9], Fujii et al.[10], Maranini et al.[11], Zhang et al.[4] and Liu et al.[12] have obtained many research results in uniaxial and triaxial compression creep of soft rocks such as limestone, shale, siltstone, salt rock, weathered sandstone and coal. Xu et al.[13], Jiang et al.[14], Hu et al[15], Yang et al.[16] and Zhao et al.[17] carried out systematic researches on creep mechanical behaviours of hard rocks such as greenschist, marble, red sandstone and peridotite under step loading or cyclic loading and unloading. In addition, the creep model theory of rock has always been the focus and difficulty of research. There are two main methods to express the rheological model: the first method is using the empirical model to fit the creep test data, and the commonly used ones are power function, exponential function and logarithmic function. This method generally has a good fitting effect,

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while the physical meaning is unclear. The other method is the component model[18–19]. The classical component combination models include Maxwell model, Kelvin model, Bingham model, Burgers model and Nishihara model. However, the classical rheological model is composed of linear components, it can hardly describe the nonlinear accelerated rheological law[20]. Therefore, more and more nonlinear rheological models have been established to accurately describe the total creep process. There are two main modeling methods: the first method is proposing new nonlinear rheological components and then add them to the original linear model to build a nonlinear creep model that can describes the three creep stages[14,21]; the other method is establishing the nonlinear rheological damage model based on the endochronic theory, fracture mechanics or damage mechanics theory to reasonably reflect the three-stage damage evolution process of rock creep[15, 22].

According to the above research, it can be found that: (1) Restricted by creep test equipment, the triaxial creep test results are still limited. (2) Previous studies have focused more on creep behaviours of hard rock and soft rock, while few result of extremely soft coal rock. (3) Due to the anisotropy of rock specimens, most of the existing creep tests were carried out under multi-stage loading for a single sample (In fact, it is difficult to exclude the influence of cumulative damage when analyzing the multi-stage loading test data), and there were few creep tests under the single-stage long-term loading condition. Especially for extremely soft rock, which is more sensitive to stress and confining pressure, and the deformation time is even longer. A single-stage long-term creep test can more accurately reflect the creep nature of extremely soft rock[23]. (4) In previous studies, the test data of accelerated creep was much less than that of decaying creep and steady-state creep. Understanding the mechanical behaviors of different rock types during accelerated creep is limited and there are few test results that can reflect the nonlinear creep behaviors of rocks.

Therefore, the present results has a significance for understanding the rock creep mechanical properties under high confining pressure and high deviator stress. However, it has been proved that the creep rate under low stress test is much higher than that the calculated results of high stress creep test[5]. Extremely soft coal has the characteristics of low strength, breakable, difficult specimen preparation, and creep tests heavily rely on test equipment, resulting in few long-term creep mechanical properties of extremely soft coal rock, even less to establish a mechanical model that can describe the nonlinear creep behavior of extremely soft rock. It is difficult to accurately elucidate the creep law of surrounding rock of extremely soft tunnel by using the existing creep test results. In this study, based on the test results of similar samples of extremely soft coal rock, and under the help of self-developed triaxial creep test system which have the ability of long time stress stabilization, a long-term creep test of extremely soft coal rock under the same axial pressure and different confining pressure is carried out by using the single-stage loading method. The results reveal the long-term creep law and creep failure characteristics of extremely soft coal rock, and then discussing the differences with other rock types. The nonlinear creep model of extremely soft coal rock is established by analyzing the creep behavior and the relationship between creep rate and confining pressure. The results obtained from this paper can provide an experimental explanation for long-term nonlinear large deformation geological disaster event of extremely soft rock tunnel.

2 Long-term creep tests under single-stage loading

Due to the complex sedimentary environment of coal seams in China, and the influence of multi-stage geological structural extrusion, rolling and sliding, extremely soft and broken coal seams are extensively distributed in the Northwest and North China geological plates[24]. This study takes the typical No.2–1 coal seam in Zhengzhou mining area, which is affected by multi-stage geological tectonism, as the research object. The coal rock specimen is a powder coal with strong broken structure and low strength. Under these mining conditions, the surrounding rock of extremely soft coal roadway generally has poor self-stability, strong deformation and long duration[25–26]. Thus it is urgent to research its creep mechanical properties to further guide engineering design.

2.1 Experimental setup

The self-developed servo-controlled rock rheological test system under the combined of axial pressure and confining pressure was used to carry out the creep test, as plotted in Fig. 1. It consisted of several components, namely: axial loading system, confining pressure loading system, deformation measurement system and servo-controlled system. Axial pressure and confining pressure are loaded by static oil pressure and hydrostatic pressure. The deformation is measured by high-precision grating ruler. The axial pressure and confining pressure loading range are 0–200 kN and 0–10 MPa. The extreme value of deformation measurement is 25 mm and the measurement accuracy is ± 0.2 μm. The advantages of this test system as follows: (1) High accuracy and long duration of pressure stabilization (Fig. 2 shows the pressure holding capability of the laboratory apparatus during long-term creep testing). (2) Tests of multiple specimens under different loading conditions can be carried out simultaneously.

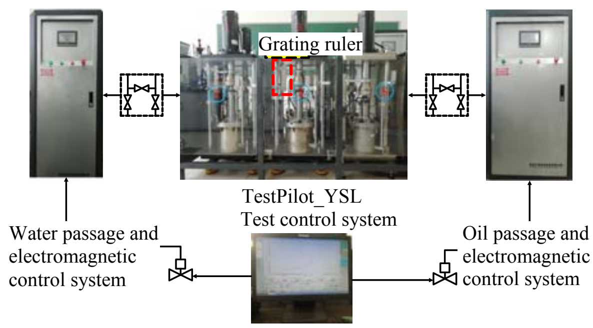


Fig. 1 Servo-controlled rheological test system for rock under combined axial and hydraulic pressure

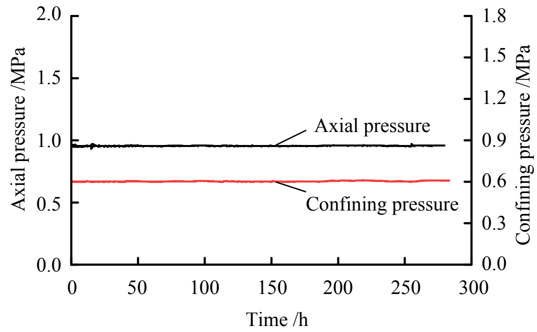


Fig. 2 Pressure holding capability of the laboratory apparatus during long-term creep testing

2.2 Specimen preparation

It is difficult to prepare the standard specimens for extremely soft and broken coal rock, many researchers have used coal briquette specimens instead of raw coal to carry out laboratory studies, and these results indicate that the strength and deformation laws of coal briquette specimens have a good consistency with raw coal[27–33]. Therefore, based on the physical and mechanical information such as strength, deformation and structural characteristics of raw coal, developing an extremely soft coal rock specimen that is highly similar to raw coal in terms of physical and mechanical parameters, deformation and failure characteristics and micro-structure. Table 1 illustrates the physical and mechanical parameters of the raw coal and coal-like material. During the specimen preparation process, the production equipment and technology of coal-like specimens were optimized, different particle sizes of coal aggregate and compound cementing agent were selected scientifically. 25 groups orthogonal ratio tests of 4 factors and 5 levels were carried out and among these tests the physical and mechanical parameters of 200 extremely soft coal rock specimens were tested (including density, uniaxial compressive strength (UCS), Young's modulus, internal friction angle, shear strength). Then, the sensitivity of each parameter was analyzed, a multiple linear prediction model for mechanical parameters was established and scanning the microstructure of extremely soft coal rock specimen. The specimen preparation information as follows: the mass proportion of coarse aggregate (raw coals with particle size of 1–2 mm) was 26.6%, fine aggregate (raw coals with particle size of 0–0.5 mm) was 62.2%, gypsum (particle size is 0.048 mm, fast final set model for 15–45 min) was 8.5%, mineral butter was 1.7% and light calcium carbonate was 1%. The mass ratio of raw materials to water was 10:1. With the computer–controlled material testing machine, the vertical formation pressure of 7.2 MPa was pressed for 10 min. The detail of coal-like specimen preparation is referred to the literature[34]. Due to the homogeneity and repeatability of the prepared coal rock specimens, the influence of specimen discreteness on single-stage loads test results was effectively eliminated.

Table 1 Physical and mechanical parameters of the raw coal and coal-like material

Materials	Density /(g · cm^{-3})	Uniaxial compressive strength /MPa	Young's modulus /MPa	Cohesion /MPa	Internal friction angle /(°)
Coal-like sample	1.286	1.78	131.85	0.18	25.80
Raw coal	1.280	1.72	126.35	0.17	27.00
Difference/%	0.470	3.49	4.35	−5.90	−4.44

2.3 Test scheme

Due to the low strength of coal-like specimens, axial pressure applied by standard specimen of ϕ50 mm× 100 mm is relatively low, which may affect the loading accuracy of the testing machine. Therefore, the axial load can increase to 4 times with the specimen diameter increased to 100 mm. However, it is limited by the internal height of the bearing barrel and specimen sealing requirement, the maximum allowable height of the specimen is not more than 120 mm. Therefore, the coal-like specimen size was determined to be ϕ100 mm× 100 mm. Figure. 3 shows the creep specimens after sealing is completed. The size of the creep specimen used in this study is consist with the recommendation of International Rock Mechanics Tests for non-standard creep specimen[35]. It is limited by test equipment or loading capacity, the creep specimen size may be changed. But attention should be paid to ensure that the maximum particle size in creep specimen is less than 0.1 times of the specimen height. The maximum particle size of the coal-like specimen in this study is 2 mm, which is less than 0.1 times of the specimen height.

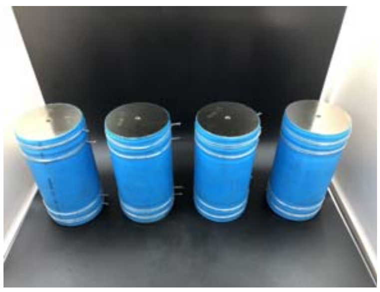


Fig. 3 Creep specimens after completion of sealing

In addition, according to the modified formula[36] recommended by International Society for Rock Mechanics (ISRM) (Equation. (1)), the uniaxial compressive strength (R) of non-standard size specimen can be converted to 1.92 MPa.

$$R_c = 0.889R\left(0.778 + 0.22\frac{H}{D}\right) \tag{1}$$

where R_c is the uniaxial compressive strength of standard specimen; R is the uniaxial compressive strength of arbitrary height to diameter ratio specimen (MPa); H and D are the specimen height and diameter (mm).

According to the statistical results[37], the yield creep stress threshold of rock is generally (40%–60%)

R. The test axial pressure was set at 50% *R*, which can be converted into an axial pressure is 7.5 kN. The confining pressure was set at 0–0.6 MPa. Table 2 shows the corresponding creep test schemes.

Table 2 Creep test schemes

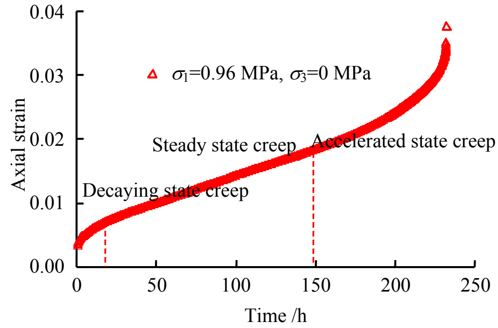
Test number	Confining pressure /MPa	Axial pressure /kN	Load method
1	0.0	7.5	Single-stage load
2	0.2	7.5	
3	0.6	7.5	

3 Results and discussion

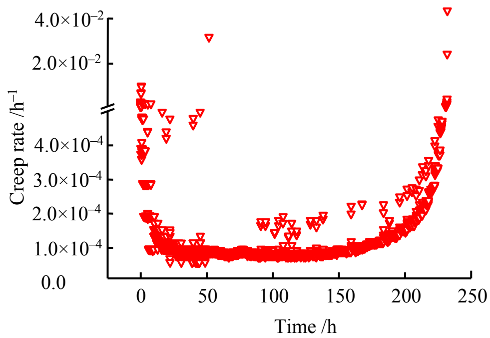
3.1 Long-term creep characteristics of extremely soft coal rock

3.1.1 Uniaxial long-term creep law of extremely soft coal rock

The uniaxial long-term creep law of extremely soft coal rock under single-stage load as shown in Fig. 4. The extremely soft coal rock are failure after 232 h of long-term creep deformation. The smooth deformation curve of the total creep process indicates that the significant timeliness and persistence of deformation. By analyzing the creep deformation and creep rate curves, it can be found that: (1) Extremely soft coal rock undergoes typical decaying creep stage, steady-state creep stage and accelerated creep stage under constant load with deviatoric stress of 50%*R*. The cumulative creep strain is as high as 3.45%, accounting for 91.3% of the total strain. Compared with previous research[14, 17, 37], the creep strain of extremely soft coal rock is much higher than that of hard rock or medium-soft rock by about 0.5%–1%. In addition, the cumulative creep deformation of hard rock or medium–soft rock is generally less than the instantaneous deformation, while the cumulative creep deformation of extremely soft coal rock is up to 10.5 times of the instantaneous deformation (0.33%), and this conclusion indicates that the strong timeliness of deformation of the extremely soft coal rock. Therefore, more attention should be paid to the strong influence of long-term deformation of surrounding rock on engineering structure in extremely soft rock engineering. (2) Extremely soft coal rock experiences a rapid decelerated creep for 10–15 h and then enters the steady-state creep stage. The time of steady-state creep stage accounts for more than 50%. The creep rate for the total steady-state creep stage is basically unchanged and the creep rate is as high as 8×10^{-5}– 10×10^{-5}/h. This is a distinct characteristic of extremely soft coal rock which is significantly different from hard rock or medium–soft rock. The steady state creep rate of the hard rock or medium–soft rock is almost zero, suggesting the steady-stage creep increases slowly or slightly with time[14, 17]. (3) The creep rate of extremely soft coal rock increases remarkably in accelerated creep stage and the maximum accelerated creep rate reaches up to 0.043/h. The strain creep rate of total creep process is distributed in a U-shape.



(a) Creep deformation curve



(b) Creep rate curve

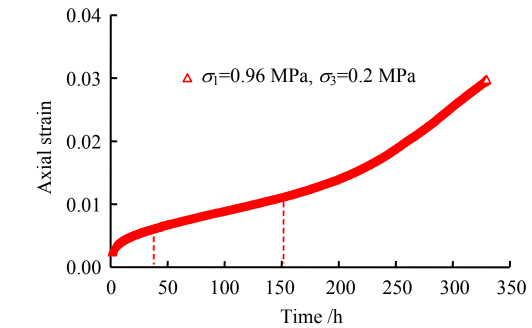
Fig. 4 Uniaxial long-term creep curve in test 1

3.1.2 Triaxial long-term creep law of extremely soft coal rock

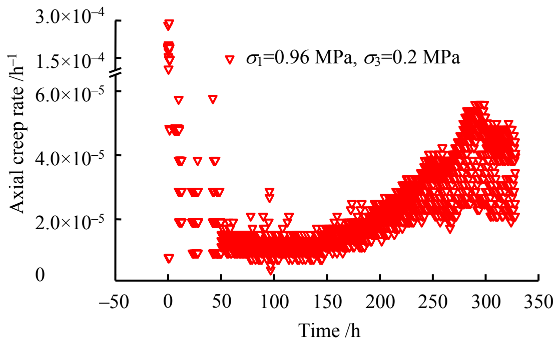
When the confining pressure increases from 0 to 0.2 MPa, the triaxial long-term creep law of extremely soft coal rock under single-stage load as plotted in Fig. 5. Under these loading condition, decaying creep stage, steady-state creep stage and accelerated creep stage was occurred successively, while the creep strain (axial strain) decreases from 3.45% to 2.74%. The steady-state creep rate decreases significantly, and the maximum creep rate of accelerated creep stage decreases by several orders of magnitudes (from the order of 10^{-2}/h decrease to 10^{-5}/h). Moreover, the creep rate curve changes from U shape to V shape, which indicates that under these test loading conditions, the creep intensity of extremely soft coal rock is obviously weakened.

The creep law of extremely soft coal rock after loading 280 h is shown in Fig. 6. The results indicate that only decaying creep stage and steady-state creep occur, and the creep strain reaches 0.11% (according to the subsequent multi-stage loading test, there is no accelerated creep occurred under the loading time lasting for 2 000 h). It should be noted that the steady-state creep rate decreases by one order of magnitude compared with test 2. However, even under these test loading conditions (deviatoric stress is 0.36 MPa, approximately 18.4%*R*), the creep of extremely soft coal rock (0–232 h) is still higher than the instantaneous deformation and with more evident timeliness than that of ordinary rock.

By comparing the accelerated creep curves of extremely soft rock and hard rock or medium–soft rock in test 1 and test 2, it can be found that the increase of creep rate is relatively moderate during extremely

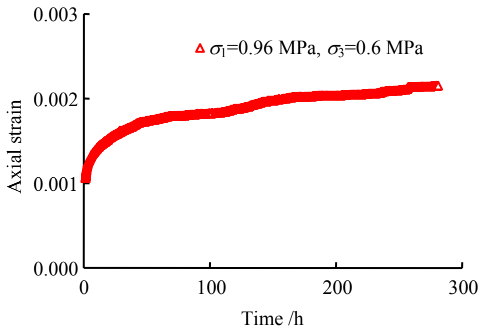


(a) Creep deformation curve

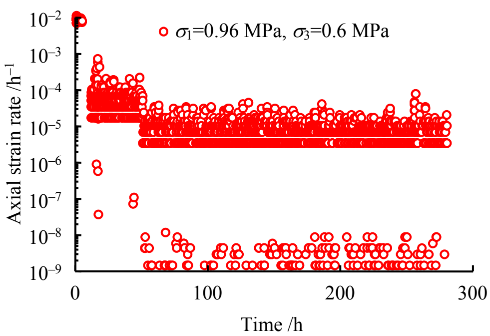


(b) Creep rate curve

Fig. 5 Triaxial creep curves in test 2



(a) Creep deformation curve



(b) Creep rate curve

Fig. 6 Triaxial creep curves in test 3

soft coal rock accelerated creep stage, which is characterized by "gradual" accelerated deformation and instability. This characteristic is significantly different from the curve morphology of "abrupt" accelerated fracture instability in accelerated creep stage of ordinary rock[14, 17]. Moreover, the duration of accelerated creep stage accounts for more than 35% and 50% in tests 1 and 2, which indicates that the accelerated deformation and failure stage of extremely soft coal rock has a significant time process. The start-up of accelerated deformation can be timely captured through field deformation monitoring during the engineering practice, and then followed by appropriate prevention and control measures.

Table 3 Comparison for creep indexes of extremely soft coal rock subjected to same axial pressure and different confining pressure

Confining pressure /MPa	Axial stress /MPa	Creep time /h	Instantaneous strain /10^{-2}	Creep value in 0–232 h /10^{-2}	Ratio of creep to instantaneous strain	Accelerated creep start-up time /h
0.0		232	0.33	3.45	10.4	144
0.2	0.96	328	0.25	1.46	5.9	154
0.6		>2 000	0.11	0.11	1.0	>2 000

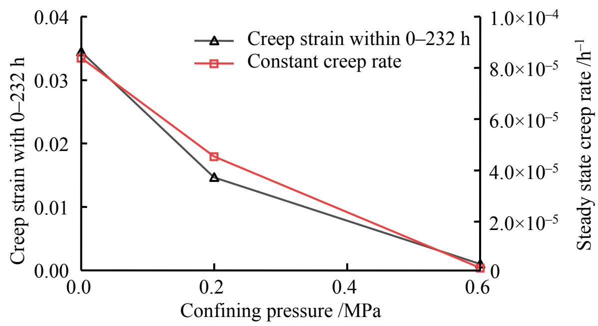


Fig. 7 Effect of confining pressure on creep strain and steady-state creep rate under the same axial pressure

3.1.3 Effect of confining pressure on the creep characteristics of extremely soft coal rock

Combined with statistical results of creep indexes as shown in Table 3 and Fig. 7, the influence of confining pressure on creep characteristics of extremely soft coal rock is analyzed in detail. Under the same axial loading conditions and with the confining pressure increasing from 0 to 0.6 MPa, it can be found that: (1) The duration before creep failure increases significantly and the accelerated creep failure is difficult to occur under higher confining pressure loading conditions. (2) The cumulative creep strain (0–232 h) decreases significantly. (3) The ratio of creep to instantaneous strain is significantly reduced. (4) The steady-state creep rate decreases sharply with the increase of confining pressure. The above results confirm that extremely soft coal rock is high sensitive to confining pressure. With the increase of confining pressure, the specimen's ability to resist long-term deformation is constantly enhanced and the creep rate and accelerated creep damage intensity in steady-state creep stage are significantly reduced. Figure. 7 shows the effect of confining pressure on creep strain and steady-state creep rate under the same axial pressure. From Fig. 7, it can be found that the creep rate and creep strain of extremely soft coal rock responds more strongly to the confining pressure variation in the range of 0–0.2 MPa (close to the support strength of bolting net). This conclusion has an important inspiration for guiding the field support of extremely soft rock roadway (tunnel).

3.1.4 Creep failure characteristics of extremely soft coal rock

The failure characteristics of extremely soft coal rock under different test conditions as shown in Fig. 8. Comparative analysis shows that under uniaxial compression, the failure mode is mainly manifested as a little number of penetrating fractures that distributed and developed along the axis of the specimen, and the fracture surface is clearly visible at an angle of 0° – 30° with the axis. However, for uniaxial long-term creep tests, internal rupture of specimen is fully developed, the specimen is completely broken and falls on the test bench. It would be difficult to take the specimens out without outer waterproof films. There were not obvious fractures on the specimen surface for long-term creep tests under the confining pressure of 0.2 MPa and the specimens mainly develops some lateral bulging deformation.

(a) Conventional uniaxial (b) Uniaxial creep (c) Triaxial creep

Fig. 8 Failure characteristics of extremely soft coal rock samples under different test conditions

3.2 Nonlinear creep model and parameter identification of extremely soft coal rock

3.2.1 Nonlinear creep model of extremely soft coal rock

According to the long-term creep test results of extremely soft coal rock under different confining pressures conditions, its main deformation behaviors as follows: (1) The instantaneous deformation occurs in extremely soft coal rock during the application of load. Hence, the creep model needs to have the component which can reflect its instantaneous deformation, such as elastic component and ideal plastic component. (2) Due to extremely soft coal rock is characterized by a typical decaying creep. Hence, the Kelvin body should be included in the creep model; (3) The creep rate of extremely soft coal rock in steady-state creep stage is large and creep strain do not converge in a long loading period. Consequently, the creep curve of extremely soft coal rock belongs to an unstable creep. Therefore, the creep model needs to contain a separate dashpot component. Burgers model can be adopted to comprehensively describe the instantaneous deformation (elastic), decaying creep deformation (viscoelastic) and non-convergent steady-state creep (viscous) deformation characteristics of the surrounding rock in extremely soft coal roadway. The component diagram of Burgers as illustrated in Fig. 9.

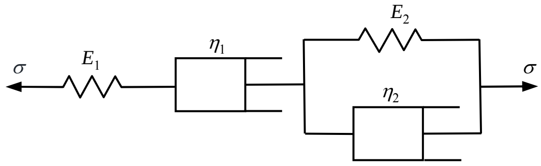


Fig. 9 Component diagram of Burgers model

The creep equation of Burgers model under one-dimensional is

$$\varepsilon=\frac{\sigma}{E_1}+\frac{\sigma}{\eta_1}t+\frac{\sigma}{E_2}\left[1-\exp\left(-\frac{E_2}{\eta_2}t\right)\right] \quad (2)$$

where σ and ε are the stress and strain of Burgers model; E_i and η_i ($i=1$ and 2) are the elastic and viscous parameters of rock; and t is the creep time.

However, the Burgers creep model cannot describe the typical accelerated creep characteristics of extremely soft coal rock in test 1 and test 2. The conventional linear creep models cannot describe the nonlinear accelerated creep process through series or parallel. Hence, it is warranted to propose new nonlinear viscoplastic component to accurately describe the nonlinear accelerated creep characteristics of extremely soft coal rock. Based on creep test results, the new creep model can be reasonably determined from the following two aspects.

Firstly, it can be seen from the accelerated creep curve as shown in Figs. 4 and 5 that the creep increases with the increase of time in a form of power function, and thus the relationship between nonlinear viscous components and time can be preliminarily considered as a power function.

$$\varepsilon=\frac{\sigma}{\eta(t)}=\frac{\sigma t^n}{\eta} \quad (3)$$

where η is the material viscosity coefficient; and n is the creep index.

Secondly, the extremely soft coal rock does not enter the accelerated creep stage directly, but first undergoes the decaying creep stage and the steady-state creep stage. The duration of each creep stage in creep test 1 and test 2 under different confining pressures is obviously different. In particular, the start-up time of accelerated creep is different for test 1 and test 2 (as shown in Table 3). This conclusion indicates that the accelerated creep will be triggered only when creep damage accumulates to a certain level. Therefore, in order to reflect the accelerated creep characteristics under different conditions and expand the creep model generality, a plastic component based on the concept of accelerated creep start-up time is introduced[38]. The mechanical characteristics of this plastic component is as follow. Under a given stress state, the deformation of the introduced plastic component is zero when the creep time of the specimen does not reach the accelerated creep start-up time; the plastic flow will occur when the creep time reaches the creep start-up time. The constitutive equation of this plastic component can be given as

$$\varepsilon=\begin{cases}0, & t\leqslant t_{\mathrm{a}}\\ \infty, & t>t_{\mathrm{a}}\end{cases} \tag{4}$$

where t_{a} is the accelerated creep start-up time. It should be noted that the non-convergent creep deformation occurs in extremely soft coal rock under different stress states in tests 1–3. Accelerated creep may occur when the creep accumulates to a certain extent (Accelerated creep will also occur if the creep time is accumulated long enough in test 3). However, the accelerated creep start-up time under different test conditions will inevitably be different due to different confining pressures and deviatoric stresses. The accelerated creep start-up time will be long when the confining pressure is large enough or the deviatoric stress is little enough, whereas the opposite trend is observed when the confining pressure is little enough or the deviatoric stress is large enough. Therefore, the accelerated creep start-up time should be defined as a function of stress state:

$$t_{\mathrm{a}}=f_1(\sigma_3)f_2(\sigma_1-\sigma_3) \tag{5}$$

The expression of this function is easily acquired under a sufficient number of test results and then it can be applied to solve the accelerated creep start-up time t_{a} under different stress states.

Then, a new nonlinear viscoplastic component is developed by linking the plastic component and nonlinear viscous component in parallel. These new nonlinear viscoplastic components can be used to describe the accelerated creep characteristics of extremely soft coal rock under different stress and time states, as shown in Fig. 10. The new nonlinear viscoplastic component can be given as

$$\varepsilon=\begin{cases}0, & t<t_{\mathrm{a}}\\ \dfrac{\sigma(t-t_{\mathrm{a}})^n}{\eta}, & t\geqslant t_{\mathrm{a}}\end{cases} \tag{6}$$

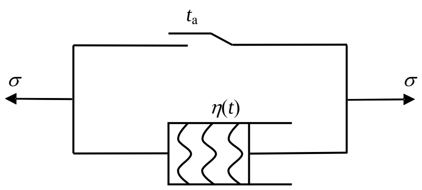


Fig. 10 New nonlinear viscoplastic component

Accelerated creep stage is a time-dependent nonlinear deformation process. The introduction of accelerated creep start-up time, on the one hand, it can clearly illustrate the physical significance of the proposed creep model, which is conducive to popularize and apply these creep model. On the other hand, it can simplify the model parameter identification process. If the total creep process is fitted by nonlinear equations, it will be unattainable to achieve model parameter identification and acquisition.

Finally, the nonlinear viscoelastic–plastic mechanical creep model that can reasonably captures the total process of extremely soft coal rock is obtained by connecting the above new nonlinear viscoplastic component in series with Burgers body, as shown in Fig. 11. The constitutive equation of this viscoelastic–plastic component can be given as

$$\varepsilon=\begin{cases}\dfrac{\sigma}{E_1}+\dfrac{\sigma}{\eta_1}t+\dfrac{\sigma}{E_2}\left[1-\exp\left(-\dfrac{E_2}{\eta_2}t\right)\right], & (t<t_{\mathrm{a}})\\ \dfrac{\sigma}{E_1}+\dfrac{\sigma}{\eta_1}t+\dfrac{\sigma}{E_2}\left[1-\exp\left(-\dfrac{E_2}{\eta_2}t\right)\right]+\dfrac{\sigma(t-t_{\mathrm{a}})^n}{\eta_3}, \\ (t\geqslant t_{\mathrm{a}})\end{cases} \tag{7}$$

The creep model degrades into Burgers model when the creep time $t<t_{\mathrm{a}}$ and it can be used to describe the decaying creep and steady-state creep characteristics. The creep model can be used to describe the characterization of decaying creep, steady-state creep and nonlinear accelerated creep of extremely soft coal rock when $t\geqslant t_{\mathrm{a}}$.

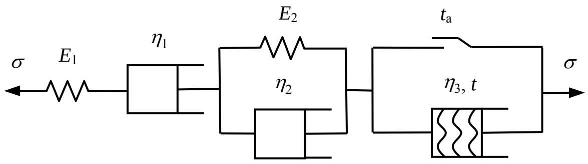


Fig. 11 Nonlinear viscoelastic plastic creep model of extremely soft coal rock under single-stage loading

The creep equation of Burgers model under three–dimensional stress state can be derived as follow. For triaxial creep test under constant confining pressure conditions, the stress tensors are decomposed into spherical stress tensor $\boldsymbol{\sigma}_{\mathrm{m}}$ and deviator stress tensor $\boldsymbol{S}_{ij}$, which are defined as

$$\left.\begin{aligned}\boldsymbol{\sigma}_{\mathrm{m}}&=\frac{1}{3}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2+\boldsymbol{\sigma}_3)=\frac{1}{3}\boldsymbol{\sigma}_{kk}\\ \boldsymbol{S}_{ij}&=\boldsymbol{\sigma}_{ij}-\delta_{ij}\boldsymbol{\sigma}_{\mathrm{m}}=\boldsymbol{\sigma}_{ij}-\frac{1}{3}\delta_{ij}\boldsymbol{\sigma}_{kk}\end{aligned}\right\} \tag{8}$$

Then,

$$\boldsymbol{\sigma}_{ij}=\boldsymbol{S}_{ij}+\delta_{ij}\boldsymbol{\sigma}_{\mathrm{m}} \tag{9}$$

where $\boldsymbol{\sigma}_{\mathrm{m}}$ is average principal stress; δ_{ij} is Kronecker function and the subscripts i, j, k is equal to 1, 2 and 3. Under the assumption that the material is isotropic, the spherical stress can only change the volume of the material without changing its shape, whereas the deviatoric stress causes only a change in its shape. Therefore, the strain tensors can be decomposed into a spherical strain tensor $\boldsymbol{\varepsilon}_{\mathrm{m}}$ and a deviatoric strain tensor $\boldsymbol{e}_{ij}$,

$$\left.\begin{aligned}\boldsymbol{\varepsilon}_{\mathrm{m}}&=\frac{1}{3}(\boldsymbol{\varepsilon}_1+\boldsymbol{\varepsilon}_2+\boldsymbol{\varepsilon}_3)=\frac{1}{3}\boldsymbol{\varepsilon}_{kk}\\ \boldsymbol{e}_{ij}&=\boldsymbol{\varepsilon}_{ij}-\delta_{ij}\boldsymbol{\varepsilon}_{\mathrm{m}}=\boldsymbol{\varepsilon}_{ij}-\frac{1}{3}\delta_{ij}\boldsymbol{\varepsilon}_{kk}\end{aligned}\right\} \tag{10}$$

And then,

$$\boldsymbol{\varepsilon}_{ij} = \boldsymbol{e}_{ij} + \delta_{ij}\boldsymbol{\varepsilon}_{\mathrm{m}} \quad (11)$$

In three–dimension conditions, Hookean body of the materials can be given as

$$\left.\begin{aligned} \boldsymbol{\sigma}_{\mathrm{m}} &= 3K\boldsymbol{\varepsilon}_{\mathrm{m}} \\ \boldsymbol{S}_{ij} &= 2G\boldsymbol{e}_{ij} \end{aligned}\right\} \quad (12)$$

where K is the volume modulus and G is the shear modulus.

$$\left.\begin{aligned} K &= \frac{E}{3(1-2\mu)} \\ G &= \frac{E}{2(1+\mu)} \end{aligned}\right\} \quad (13)$$

where μ is the Poisson's ratio.

It can be assumed that the elastic strain is caused by spherical stress tensor and creep is caused by deviatoric stress tensor, which is embodied in the shear deformation and complies with the constitutive equation of creep model. Therefore, the creep equation under three–dimensional stress condition can be given as

$$\left.\begin{aligned} \boldsymbol{\varepsilon}_{\mathrm{m}} &= \frac{\boldsymbol{\sigma}_{\mathrm{m}}}{3K} \\ \boldsymbol{e}_{ij} &= \frac{\boldsymbol{S}_{ij}}{2G_1} + \frac{\boldsymbol{S}_{ij}}{2\eta_{\mathrm{modified}}}t + \frac{\boldsymbol{S}_{ij}}{2G_2}\left[1-\exp\left(-\frac{G_2}{\eta_2}t\right)\right] \end{aligned}\right\} \quad (14)$$

Then add the spherical strain tensor to both sides of Eq. (14) to derive the three–dimensional creep equation of Burgers model:

$$\varepsilon(t) = \frac{\sigma_1+2\sigma_3}{9K} + \frac{\sigma_1-\sigma_3}{3G_1} + \frac{\sigma_1-\sigma_3}{3\eta_1}t + \frac{\sigma_1-\sigma_3}{3G_2}\left[1-\exp\left(-\frac{G_2}{\eta_2}t\right)\right] \quad (15)$$

Based on Eq. (15), three–dimensional nonlinear creep model of extremely soft coal rock is finally given as

$$\varepsilon(t) = \begin{cases} \dfrac{\sigma_1+2\sigma_3}{9K} + \dfrac{\sigma_1-\sigma_3}{3G_1} + \dfrac{\sigma_1-\sigma_3}{3\eta_1}t + \dfrac{\sigma_1-\sigma_3}{3G_2}\cdot \\ \left[1-\exp\left(-\dfrac{G_2}{\eta_2}t\right)\right],\ (t < t_{\mathrm{a}}) \\ \dfrac{\sigma_1+2\sigma_3}{9K} + \dfrac{\sigma_1-\sigma_3}{3G_1} + \dfrac{\sigma_1-\sigma_3}{3\eta_1}t + \dfrac{\sigma_1-\sigma_3}{3G_2}\cdot \\ \left[1-\exp\left(-\dfrac{G_2}{\eta_2}t\right)\right] + \dfrac{(\sigma_1-\sigma_3)(t-t_{\mathrm{a}})^n}{3\eta_3},\ (t \geqslant t_{\mathrm{a}}) \end{cases} \quad (16)$$

3.2.2 Parameter identification of the nonlinear creep model

In order to evaluate the proposed creep model rationality, the parameters of the constitutive equation should be determined according to the creep test data. There are two main methods to identify the model parameters: numerical iterative method and creep curve analytic method. In this paper, a direct and effective curve analytic method is used to identify the instantaneous parameters. And then the numerical iteration method is used to determine creep parameters.

(1) Instantaneous parameters

According to Eq. (17), the Young's modulus E_1 can be obtained from the relationship between stress and strain in instantaneous loading stage:

$$E_1 = \frac{\sigma_1-\sigma_3}{\varepsilon_1} \quad (17)$$

where ε_1 is the instantaneous strain in initial loading stage.

Then the bulk modulus K and shear modulus G_1 can be calculated by combining with Eq. (13). Poisson's ratio is less affected by confining pressure[39], which can be measured by conventional uniaxial compression test.

(2) Creep parameters

To simplify the parameter iteration equation, Eq. (16) can be replaced as follows:

$$\left.\begin{aligned} & A = \frac{\sigma_1+2\sigma_3}{9K} + \frac{\sigma_1-\sigma_3}{3G_1},\ B = \frac{\sigma_1-\sigma_3}{3\eta_1} \\ & C = \frac{\sigma_1-\sigma_3}{3G_2},\ D = \frac{G_2}{\eta_2} \end{aligned}\right\} \quad (18)$$

$$\Delta\varepsilon(t) = \frac{(\sigma_1-\sigma_3)(t-t_{\mathrm{a}})^n}{3\eta_3} \quad (19)$$

When the creep process only has the test curve in $t < t_{\mathrm{a}}$, the above equations can be simplified into

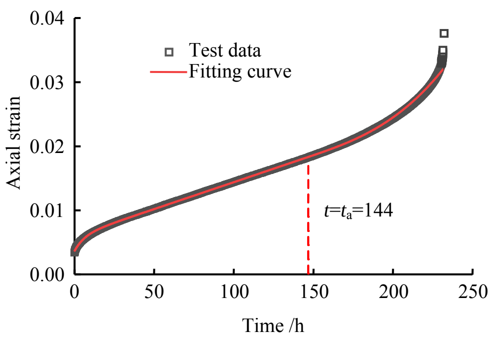
$$\varepsilon(t) = A + Bt + C\left[1-\exp(-Dt)\right],\ (t < t_{\mathrm{a}}) \quad (20)$$

Origin data processing software that based on Levenberg–Marquardt optimization algorithm can be directly used for nonlinear fitting of the test curves. After obtaining the values of parameters A, B, C and D in Eq. (20), and then parameters η_1, η_2 and G_2 are accessible. However, when the creep process contains the nonlinear accelerated creep stage ($t \geqslant t_{\mathrm{a}}$), Eq. (16) can be transformed as

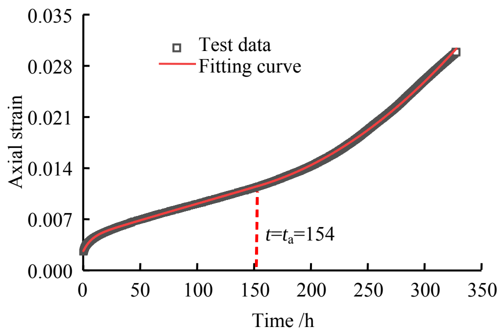
$$\varepsilon(t) = A + Bt + C\left[1-\exp(-Dt)\right] + \Delta\varepsilon(t),\ (t \geqslant t_{\mathrm{a}}) \quad (21)$$

In this condition, taking the creep start-up time (t_a) as the cut-off point, the creep process can be divided into an early accelerated creep stage and an accelerated creep stage. The fitting parameter steps of early accelerated creep stage are the same as the procedure used in Eq. (20). For the parameters fitting of accelerated creep stage, the parameters η_1, η_2 and G_2 obtained above need to be substituted into the first three terms of Eq. (21) to calculate creep theoretical value for the total time. Then, the actual strain value containing in the accelerated creep curve is subtracted from the above creep theoretical value to obtain the corresponding relationship between a set of strain differences and time during the accelerated creep. Eq. (19) is used for nonlinear fitting to obtain the creep parameters η_3 and n .

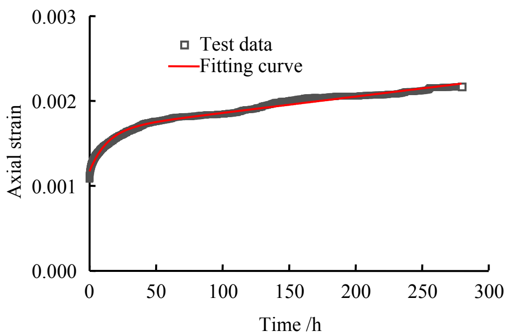
Figure 12 plots the fitting curves of creep tests 1–3, and the creep model parameters as shown in Table 4. It can be found that the creep test curve is good consistent with the fitting curve and all the correlation coefficient is above 0.984. This conclusion indicates that the proposed nonlinear creep model can accurately describe the long-term creep characteristics of extremely soft coal rock under single-stage loading.



(a) Uniaxial long-term creep test (axial pressure 0.96 MPa)



(b) Triaxial long-term creep test (confining pressure 0.2 MPa, axial pressure 0.96 MPa)



(c) Triaxial long-term creep test (confining pressure 0.6 MPa, axial pressure 0.96 MPa)

Fig. 12 Creep test curves and fitting curves of extremely soft coal rock under single-stage loading

Table 4 Nonlinear creep model parameters of extremely soft coal rock

Test number	σ_3 /MPa	σ_1 /MPa	K /GPa	G_1 /GPa	η_1 /(GPa·h)	G_2 /GPa	η_2 /(GPa·h)	η_3 /(GPa·h)	n	t_a /h	R^2
1	0.0	0.96	0.37	0.11	3.81	0.14	0.85	29 289.00	2.98	144	0.984
2	0.2	0.96	0.39	0.11	5.58	0.13	0.90	797.42	2.02	154	0.998
3	0.6	0.96	0.42	0.12	62.32	0.24	3.23	—	—	—	0.994

4 Conclusions

(1) The results of uniaxial constant load creep tests (axial stress of 50%R) indicate that the extremely soft coal rock has experienced three typical stages of decaying creep, steady-state creep and accelerated creep. The cumulative creep strain is as high as 3.45%, which is 10.5 times of the instantaneous deformation. The steady creep rate is as high as 8×10^{-5}–10×10^{-5}/h and the creep rate remains constant for a long time. The maximum accelerated creep rate reaches up to 0.043/h. The strain rate of total creep process is distributed in a typical U shaped. The deformation of extremely soft coal rock is more timeliness than that of ordinary rocks, especially for hard rock. Therefore, timely support of the extremely soft rock should be paid more attention in engineering practice.

(2) The steady-state creep characteristics of extremely soft coal rock is significantly different from the ordinary rocks, especially for hard rocks. The duration of steady-state creep accounts for more than 50% and the characteristics of high creep rate and long-term non-zero have a serious threat to the long-term stability of engineering structures.

(3) Under the same axial pressure conditions, the confining pressure have a significant impact on creep behavior of extremely soft coal rock. The ability of resisting long-term deformation of extremely soft coal rock increases continuously with the increase of confining pressure from 0 to 0.6 MPa. The creep strain decreases significantly; the strain rate of steady-stage decreases by order of magnitudes; the duration before creep failure increases significantly; the ratio of creep to instantaneous strain decreases dramatically; the intensity of accelerated creep failure decrease markedly. The creep strain and deformation rate are especially sensitive to confining pressure change in the range of 0–0.2 MPa, which inspires the support design of extremely soft rock in the field.

(4) The accelerated creep stage of extremely soft coal

rock is characterized by "gradual" time dependent instability, which is significantly different from the "abrupt" accelerated fracture instability of hard rocks. Moreover, the intensity of accelerated creep is extremely sensitive to confining pressure. The start-up of accelerated deformation can be timely captured through dynamic deformation monitoring during the engineering practice, and the supporting strength or supporting time can be adjusted to reduce the intensity of accelerated creep or delay the occurrence of accelerated creep.

(5) The failure mode of extremely soft coal rock under long-term creep test is significantly different from the brittle plastic failure under conventional uniaxial compression. Under uniaxial compression condition, the failure mode of extremely soft coal rock is mainly manifested by a small number of penetrating fractures at an angle of 0°–30° with the axis. For uniaxial long-term creep tests, the extremely soft coal specimen are fully broken and crushed. The specimens mainly develops lateral bulging deformation under the confining pressure is 0.2 MPa.

(6) According to the accelerated creep characteristics of extremely soft coal rock, The nonlinear viscoelastic plastic creep model is established by connecting a new nonlinear viscoelastic model considering the concept of accelerated creep start-up time with Burgers model in series to describe the total process of decaying creep stage, steady-state creep stage and accelerated creep stage of extremely soft coal rock under single-stage load. The creep parameters are determined by employing the Levenberg–Marquardt optimization algorithm to nonlinear fit of the test curve. The test curves are highly consistent with the creep theoretical curves, which proves that the proposed model is reasonable. Moreover, the proposed model in this study can be extended to the long-term nonlinear creep mechanical properties of other similar extremely soft rocks.

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