Integrated identification method of rheological model of sandstone in Sanmenxia bauxite

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Abstract: Based on the uniaxial compression creep experiments conducted on bauxite sandstone obtained from Sanmenxia, typical creep experiment curves were obtained. From the characteristics of strain component of creep curves, the creep strain is composed of instantaneous elastic strain, ε_{me}, instantaneous plastic strain, ε_{mp}, viscoelastic strain, ε_{ce}, and viscoplastic strain, ε_{cp}. Based on the characteristics of instantaneous plastic strain, a new element of instantaneous plastic rheology was introduced, instantaneous plastic modulus was defined, and the modified Burgers model was established. Then identification of direct screening method in this model was completed. According to the mechanical properties of rheological elements, one- and three-dimensional creep equations in different stress levels were obtained. One-dimensional model parameters were identified by the method of least squares, and in the process of computation, Gauss−Newton iteration method was applied. Finally, by fitting the experimental curves, the correctness of direct method model was verified, then the examination of posterior exclusive method of the model was accomplished. The results showed that in the improved Burgers models, the rheological characteristics of sandstone are embodied properly, microscopic analysis of creep curves is also achieved, and the correctness of comprehensive identification method of rheological model is verified.

Key words: uniaxial compression creep experiments; instantaneous plastic rheological model element; improved Burgers model; direct screening method; posterior exclusive method

1 Introduction

So far, most bauxite resources have been mined out by open-pit mining, but with the depletion of the bauxite resources in shallow earth in recent years, it becomes a trend that underground mining researches will be conducted for the development of bauxite resources [1,2]. Due to the natural existence condition and the properties of surrounding rocks, the major problem faced in underground mining is how to ensure the roadway stability. An important influence on the long-term stability of roadway will be exerted by the rheological properties of surrounding rocks, so extensive researches have been conducted previously. Based on the Burgers model, BAI et al [3] performed study on the roadway stability to provide guidance to the design of roadway support in Malin Coalmine. WANG et al [4] conducted

researches on the effects of the rheological factors on the economical and effective support methods. LU et al [5] proposed that the highly resistant and yielding support system was beneficial to the long term stability of the broken soft rock in depth. The study carried out by ZHAO et al [6] on the roadway support in soft rocks showed that rheological behavior was the main factor involved in roadway deformation in depth. LI et al [7] believed that mastering the fractures development is very important to maintain the stability of soft rock roadway.

Many scholars have conducted relevant researches about rheological model. For example, a nonlinear rheological model [8] was introduced to study long-term stability of backfill material in roadway, and the engineering practice comparative analysis indicated its correctness. GRGIC et al [9] used two constitutive laws to analyze the phenomena involved in the mining collapses. YANG and CHENG [10] put forward a new

non-stationary and nonlinear visco-elastic shear creep model, and the experimental data verified its reasonability. HOXHA et al [11] established a creep model describing primary and inverse creep of gypsum rock. In their research, the new model fitted better laboratory results and allowed describing of the accelerated creep.

In the identification process of rheological model, based on the practical rheological curves, the analysis and generalization are required to choose or establish the rheological model. The combination of direct screening method and posterior exclusive method was applied [12].

With respect to instantaneous plastic strain, OIKAWA1 and SUGAWARA [13] indicated that transient plastic strain generated as temperature increased. YUAN et al [14] mentioned instantaneous plastic strain in their article too. However, the definition of the instantaneous plastic strain and the derivation of the constitutive equation were not made in these work. LI et al [15] proposed instantaneous plastic strain constitutive equation, but the applicability was limited due to the requirement of great number of parameters.

There are many identification methods for model parameters, and some scholars have also identified rheological model parameters which contribute to the feasibility of model examination [16−18].

2 Experimental data analysis and rheological model establishment

Loading and unloading creep experiments of sandstone in natural condition were carried out on the computer controlled rock shear rheometer (RYL-600). In the experiment process, the mode of graded incremental cycle was applied and the unloading processes were force controlled. Samples were strictly processed in accordance with the requirements of international rock mechanics test, and the dimensions were d 50 mm × 100 mm. Three typical loading and unloading curves of sandstone samples are shown in Fig. 1.

Data analysis indicates that creep curves exhibit both the instantaneous elastic deformation and the instantaneous plastic deformation. If ε represents the total strain of a sample, ε_{me} represents instantaneous elastic strain, ε_{mp} represents instantaneous plastic strain, ε_{ce} represents viscoelastic strain, ε_{cp} represents viscoplastic strain, then $\varepsilon = \varepsilon_{me} + \varepsilon_{mp} + \varepsilon_{ce} + \varepsilon_{cp}$. The division of strain components is shown in Fig. 2.

Based on the characteristics of experimental curves, preliminary identification of rheological model is conducted. In this model, the elastic strain, ε_{me}, can be represented by the elastic element (H), the viscoelastic strain, ε_{ce}, is represented by ($H|N$) element, and then the strain, ε_{cp}, can be represented by viscous element (N).
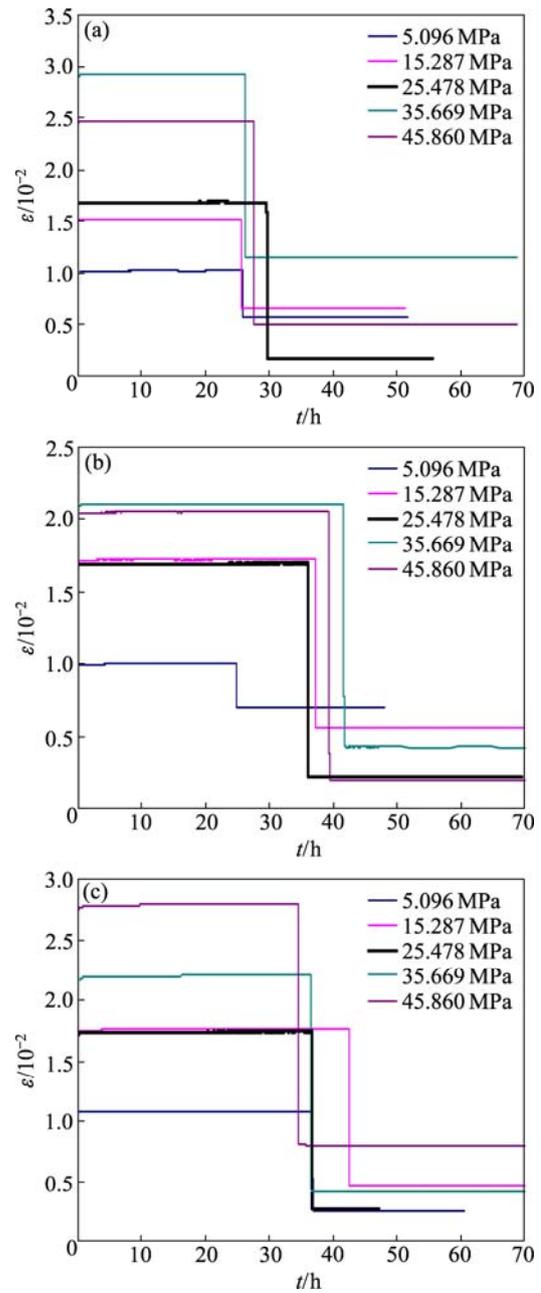

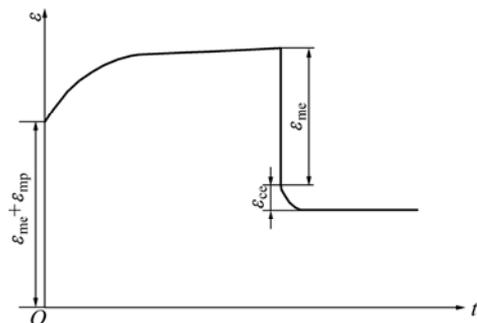**Fig. 1** Typical creep loading and unloading curves: (a) Sample a; (b) Sample b; (c) Sample c

Fig. 2 Strain components diagram

Because of the lack of the specific rheological element which represents the instantaneous plastic strain ε_{mp}, in

this work, a new instantaneous plastic model element, in which P_0 is defined as the instantaneous plastic modulus, and σ_{s1} is defined as initial stress of instantaneous plastic deformation, is proposed, and the new model is shown in Fig. 3. Therefore, instantaneous plastic deformation ε_{mp} can be represented by new instantaneous plastic model element, and a modified Burgers model is established initially.
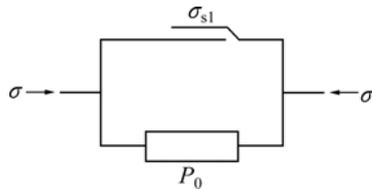

Fig. 3 Instantaneous plastic model element

In instantaneous plastic model, definition of P_0 is the key of model establishment. Referring to the instantaneous elastic deformation, the ratio, σ/ε_{me}, in which σ is the loading stress and ε_{me} is the instantaneous elastic strain, is defined as the instantaneous elastic modulus E. Just as the instantaneous elastic deformation, instantaneous plastic deformation is caused in a very short time, therefore, the relationship among σ, ε_{mp} and t, can be simplified as the relationship between σ and ε_{mp}. Combined with the component of instantaneous plastic strain after separating, the accumulated instantaneous plastic strain under different stress levels is obtained. Because of the unrecoverable characteristic of instantaneous plastic deformation during unloading, the iterative equation of accumulated instantaneous plastic strain when stress ranges from 5.096 MPa to 45.860 MPa is shown in Eq. (1), and the accumulated values of instantaneous plastic strain under different stress levels are shown in Table 1.

$$
\begin{cases}
\varepsilon_{mp2} = \varepsilon_{mp1} + \varepsilon'_{mp2} \\
\varepsilon_{mp3} = \varepsilon_{mp1} + \varepsilon'_{mp2} + \varepsilon'_{mp3} = \varepsilon_{mp2} + \varepsilon'_{mp3} \\
\varepsilon_{mpn} = \varepsilon_{mp1} + \varepsilon'_{mp2} + \cdots + \varepsilon'_{mpn} = \varepsilon_{mp(n-1)} + \varepsilon'_{mpn}
\end{cases}
\tag{1}
$$

where ε_{mp1}, ε_{mp2}, ε_{mp3}, $\cdots$, ε_{mpn} are the accumulated values of instantaneous plastic deformation under different stress levels, respectively.

Table 1 Accumulated values of instantaneous plastic strain

Stress/MPa	Strain/10^{-2}		
	Sample (a)	Sample (b)	Sample (c)
5.096	0.57262	0.68705	0.253753
15.287	1.225706	1.236995	0.681919
25.478	1.390751	1.448764	0.92096
35.669	2.524103	1.865926	1.302357
45.86	3.002567	2.048626	2.079262

Linear fittings of the accumulated instantaneous plastic strain are shown in Fig. 4, in which the correlation coefficients, R^2, of the samples approximately ranges from 0.95 to 0.97. It can be concluded that the relationship between σ and ε_{mp} is linear when the sample is loaded, so the instantaneous plastic modulus P_0 can be defined as

$$
P_0 = \frac{\sigma_0}{\varepsilon_{mp}} = \frac{\sigma - \sigma_{S1}}{\varepsilon_{mp}}
\tag{2}
$$

where σ_0 ($\sigma_0 = \sigma - \sigma_{s1}$) is the stress of instantaneous plastic element. Under the action of stress σ, the strain of the model is defined as

$$
\begin{cases}
\varepsilon = 0 \quad (\sigma < \sigma_{s1}) \\
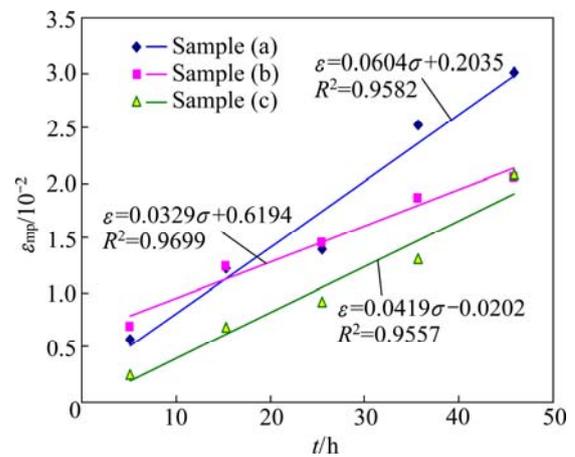\varepsilon = \varepsilon_{mp} \quad (\sigma > \sigma_{s1})
\end{cases}
\tag{3}
$$

Fig. 4 Relationship between ε_{mp} and σ

It can be concluded from above analysis that the creep constitutive model shown in Fig. 5 is composed of instantaneous elastic element (H), instantaneous plastic element, viscoelastic element ($H|N$) and viscous deformation element (N) under uniaxial compression. This model is built on the basis of both loading and unloading conditions, so it is suitable for analysis of decay or steady-state creep in the loading and unloading processes.
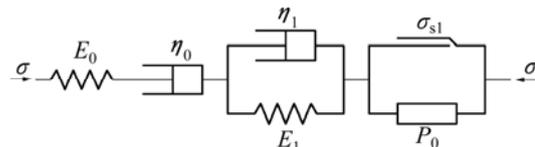

Fig. 5 Modified Burgers model

3 Formulae derivation of one-dimensional creep model

1) When $\sigma < \sigma_{s1}$, the model regresses to Burgers model. The derivation process of creep formulae is

shown as

$$\begin{cases} \varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \\ \sigma_1 = E_0 \varepsilon_1 \\ \sigma_2 = \eta_0 \dot{\varepsilon}_2 \\ \sigma_3 = E_1 \varepsilon_3 + \eta_1 \dot{\varepsilon}_3 \\ \sigma = \sigma_1 = \sigma_2 = \sigma_3 \end{cases} \tag{4}$$

The constitutive equation which is obtained by eliminating ε_1, ε_2 and ε_3 is shown as

$$\frac{\eta_0 \eta_1}{E_0 E_1} \ddot{\sigma} + \left(\frac{\eta_0}{E_0} + \frac{\eta_0 + \eta_1}{E_1} \right) \dot{\sigma} + \sigma = \eta_0 \dot{\varepsilon} + \frac{\eta_0 \eta_1}{E_1} \ddot{\varepsilon} \tag{5}$$

The creep equation of Burgers model can be obtained by applying Laplace transform or superposition principle in Eq. (5) as

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma}{\eta_0} t + \frac{\sigma}{E_1} \left(1 - e^{-\frac{E_1}{\eta_1} t} \right) \tag{6}$$

2) When $\sigma > \sigma_{s1}$,

$$\begin{cases} \varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 \\ \sigma_1 = E_0 \varepsilon_1 \\ \sigma_2 = \eta_0 \dot{\varepsilon}_2 \\ \sigma_3 = E_1 \varepsilon_3 + \eta_1 \dot{\varepsilon}_3 \\ P_0 \varepsilon_4 + \sigma_s = \sigma_4 \\ \sigma = \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 \end{cases} \tag{7}$$

The constitutive equation is shown as follows:

$$\frac{\eta_1 (E_0 + P_0)}{E_0 P_0} \ddot{\sigma} + \left(1 + \frac{E_1}{E_0} + \frac{E_1}{P_0} + \frac{\eta_1}{\eta_0} \right) \dot{\sigma} + \frac{E_1}{\eta_0} \sigma = \eta_1 \ddot{\varepsilon} + E_1 \dot{\varepsilon} \tag{8}$$

And the creep equation can be written as

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma - \sigma_s}{P_0} + \frac{\sigma}{\eta_0} t + \frac{\sigma}{E_1} \left(1 - e^{-\frac{E_1}{\eta_1} t} \right) \tag{9}$$

According to one-dimensional creep equation, model characteristic curves can be obtained. When $\sigma < \sigma_{s1}$, the characteristic curves are the same as Burgers model. When $\sigma > \sigma_{s1}$, the characteristic curves are shown in Fig. 6, in which σ is a constant equal to σ_0.

4 Formulae derivation of three-dimensional creep model

Based on the tensor theory, under three-dimensional conditions, tensors can be decomposed into the spherical stress tensor σ_m and the deviatoric stress tensor S_{ij}. In general, the change in material volume is caused by the spherical tensor σ_m, and the change in shape is caused by
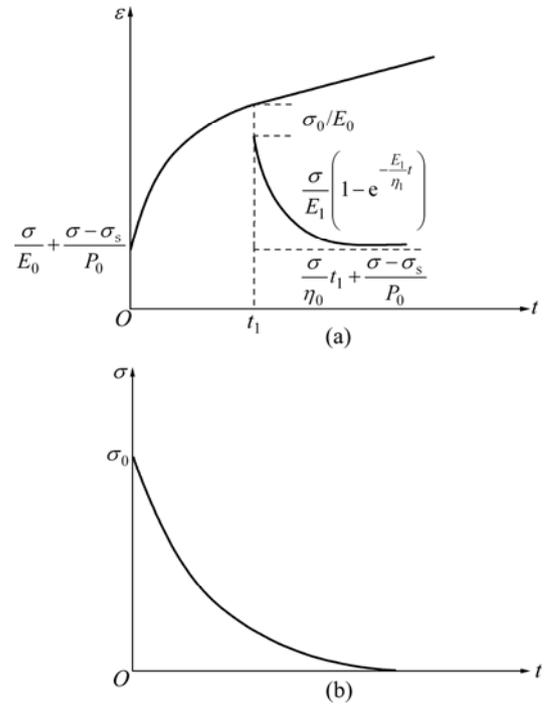

Fig. 6 Characteristic curves of modified Burgers model: (a) Creep characteristic curves under loading and unloading conditions; (b) Characteristic curve of stress relaxation

deviatoric tensor S_{ij}. Stress σ_{ij} presented in the form of tensor is shown as

$$\sigma_{ij} = S_{ij} + \sigma_m \delta_{ij} \tag{10}$$

$$\delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases} \tag{11}$$

where δ_{ij} is a spherical unit tensor.

As shown in Eq. (12), strain tensor can also be decomposed into the spherical strain tensor ε_m and the deviatoric strain tensor ε_{ij}:

$$\varepsilon_{ij} = e_{ij} + \delta_{ij} \varepsilon_m \tag{12}$$

Under different axial stress, three-dimensional creep formulae of new model are shown as follows.

1) When $\sigma < \sigma_{s1}$,

$$\begin{cases} e_{ij} = \dfrac{S_{ij}}{2G_0} + \dfrac{S_{ij}}{2\eta_0} t + \dfrac{S_{ij}}{2G_1} \left(1 - e^{-\frac{G_1}{\eta_1} t} \right) \\ \varepsilon_m = \dfrac{\sigma_m}{3K} \end{cases} \tag{13}$$

2) When $\sigma > \sigma_{s1}$,

$$\begin{cases} e_{ij} = \dfrac{S_{ij}}{2G_0} + \dfrac{S_{ij} - \sigma_s}{2G_0'} + \dfrac{S_{ij}}{2\eta_0} t + \dfrac{S_{ij}}{2G_1} \left(1 - e^{-\frac{G_1}{\eta_1} t} \right) \\ \varepsilon_m = \dfrac{\sigma_m}{3K} \end{cases} \tag{14}$$

where G_0 and G_1 are the shear modulus. The conversions among elastic constants are shown in Eq. (15). Combining with the rule on instantaneous plastic modulus P_0, G_0' which can be written as $G_0' = P_0/[2(1+v_0')]$ is obtained on the assumption that G_0' has a similar definition as G_0.

$$\begin{cases} E = \dfrac{9KG}{3K+G} \\ v = \dfrac{3K-2G}{2(3K+G)} \\ K = \dfrac{E}{3(1-2v)} \\ G = \dfrac{E}{2(1+v)} \end{cases} \quad (15)$$

Based on the creep formulae of new model under three-dimensional condition, the creep equations under triaxial stress can be derived. In creep experiments, σ_m ($\sigma_m = (\sigma_1+\sigma_2+\sigma_3)/3 = \sigma_1/3$) can be obtained on the assumption that no confining stress is applied ($\sigma_1 \neq 0$, $\sigma_2=\sigma_3=0$). Therefore, the creep stress can be expressed in the form of tensors as

$$\begin{Bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{Bmatrix} = \begin{Bmatrix} \sigma_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{Bmatrix} =$$

$$\begin{Bmatrix} \dfrac{\sigma_1}{3} & 0 & 0 \\ 0 & \dfrac{\sigma_1}{3} & 0 \\ 0 & 0 & \dfrac{\sigma_1}{3} \end{Bmatrix} + \begin{Bmatrix} \dfrac{2\sigma_1}{3} & 0 & 0 \\ 0 & -\dfrac{\sigma_1}{3} & 0 \\ 0 & 0 & -\dfrac{\sigma_1}{3} \end{Bmatrix} \quad (16)$$

The triaxial creep equations of the modified Burgers model (the confining pressure is zero) are shown as follows.

1) When $\sigma < \sigma_{s1}$,

$$\begin{cases} \varepsilon_1 = \dfrac{\sigma_1}{9K} + \dfrac{\sigma_1}{3G_0} + \dfrac{\sigma_1}{3\eta_0}t + \dfrac{\sigma_1}{3G_1}\left(1-e^{-\frac{G_1}{\eta_1}t}\right) \\ \varepsilon_2 = \varepsilon_3 = \dfrac{\sigma_1}{9K} - \dfrac{\sigma_1}{6G_0} - \dfrac{\sigma_1}{6\eta_0}t - \dfrac{\sigma_1}{6G_1}\left(1-e^{-\frac{G_1}{\eta_1}t}\right) \end{cases} \quad (17)$$

2) When $\sigma > \sigma_{s1}$,

$$\begin{cases} \varepsilon_1 = \dfrac{\sigma_1}{9K} + \dfrac{\sigma_1}{3G_0} + \dfrac{2\sigma_1-3\sigma_s}{6G_0'} + \dfrac{\sigma_1}{3\eta_0}t + \dfrac{\sigma_1}{3G_1}\left(1-e^{-\frac{G_1}{\eta_1}t}\right) \\ \varepsilon_2 = \varepsilon_3 = \dfrac{\sigma_1}{9K} - \dfrac{\sigma_1}{6G_0} - \dfrac{\sigma_1+3\sigma_s}{6G_0'} - \dfrac{\sigma_1}{6\eta_0}t - \dfrac{\sigma_1}{6G_1}\left(1-e^{-\frac{G_1}{\eta_1}t}\right) \end{cases} \quad (18)$$

where K is the volume deformation modulus; ε_1 is the axial creep equation without confining stress; ε_2 and ε_3 are the lateral creep equations without confining stress. The lateral creep data can also be fitted by the lateral creep equation.

5 Model parameter identification

In the one-dimensional model, least squares method is applied to the indentation process of parameters and Gauss−Newton method is adopted in the calculation process. Parameters, such as E_1, η_0, η_1, can be obtained by substituting the separated instantaneous elastic and plastic strain into creep formula. Because of the linear relationship between instantaneous elastic, plastic strain and load stress, E_0 and P_0 can be obtained as

$$\begin{cases} P_0 = \dfrac{\sigma - \sigma_{s1}}{\varepsilon_{mp}} \\ E_0 = \dfrac{\sigma}{\varepsilon_{me}} \end{cases} \quad (19)$$

After the identification of parameters in the modified Burgers model, the creep experimental data of sandstone are fitted using the calculated data. The identification results of parts rock sample (b) are shown in Table 2, and the fitting results are shown in Fig. 7.

As shown in Fig. 7, the fitting correlation coefficient, R^2, of the modified Burgers model is high. The results again prove the correctness of the new model. According to the parameter indentation and the analysis of fitting results, the model examination by using posterior exclusive method is completed. Based on the program interface provided by FLAC[3D], secondary

Table 2 Modified Burgers model identification parameters of rock sample (b)

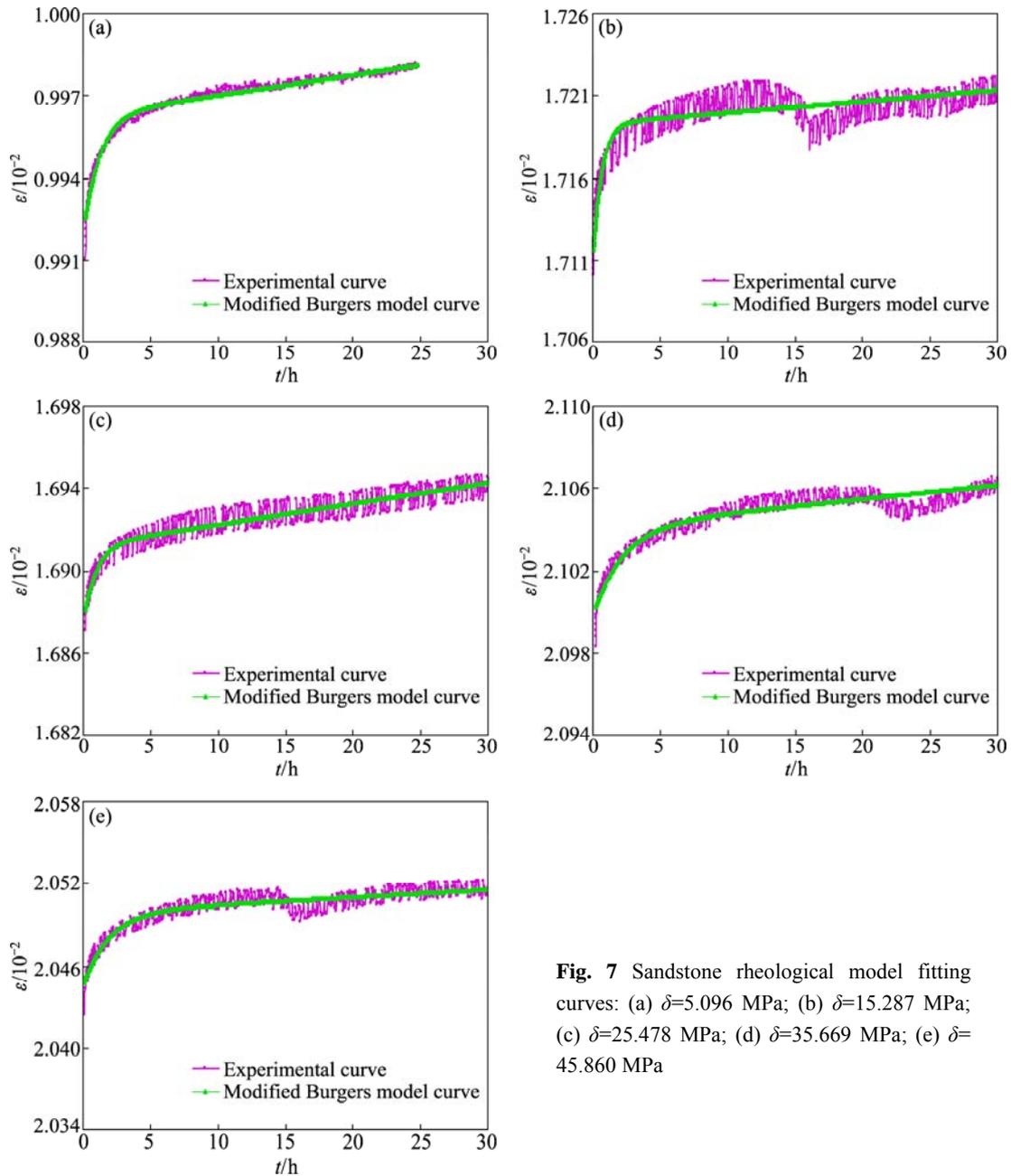| σ/MPa	E_0/GPa	E_1/GPa	P_0/GPa	η_0/(GPa·h)	η_1/(GPa·h)	R^2
5.096	1.676	113.800	238.545	6926.970	136.872	0.982
15.287	1.318	167.573	2.409	21938.764	104.069	0.825
25.478	1.727	675.070	56.556	25025.750	626.428	0.897
35.669	2.122	818.224	4660.895	51841.048	1783.138	0.933
45.860	2.466	827.040	644.786	82903.294	1585.887	0.908

Fig. 7 Sandstone rheological model fitting curves: (a) δ=5.096 MPa; (b) δ=15.287 MPa; (c) δ=25.478 MPa; (d) δ=35.669 MPa; (e) δ= 45.860 MPa

development of the new model can be carried out to analyze the long-term stability of roadway after excavation.

6 Conclusions

1) Based on the analysis of sandstone creep data and the mechanical characteristics of each strain component, instantaneous plastic element and instantaneous plastic modulus P_0 were defined. Physical equation of the instantaneous plastic modulus P_0 was derived by conducting analysis on the relationship among σ, ε_{mp} and t. According to the direct selection method, the modified Burgers model was established initially by series-parallel combination of different model elements.

2) Based on the mechanical characteristics of model elements, one-dimensional creep equation of the modified Burgers model was derived. Combined with the three-dimensional tensor theory, three-dimensional creep equations of the model under different stress conditions were continuously derived.

3) Based on the creep experimental data, Gauss−Newton iterative calculation for the modified Burgers model was carried out, and basic parameters of the model were identified. The results show that the model can be used to fit the experimental curves properly, and the correlation coefficient R^2 is high, the correctness of new model established by using direct selection

method was proved once again, and the model identification by applying posterior exclusive method was also completed.

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三门峡铝土矿砂岩流变模型的综合辨识方法

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摘 要：通过对三门峡铝土矿砂岩进行单轴压缩蠕变实验，获取该类岩石的蠕变实验曲线。通过分析蠕变曲线各应变分量特征，将蠕变总应变细分为瞬时弹性应变 ε_{me}、瞬时塑性应变 ε_{mp}、黏弹性应变 ε_{ce}、黏塑性应变 ε_{cp}。根据瞬时塑性应变数据特征，引入新的瞬时塑性原件，定义瞬时塑性模量，建立改进的伯格斯(Burgers)流变模型，完成模型的直接筛选法辨识。根据模型元件力学性质，推导模型在不同应力等级下的一维和三维蠕变方程。采用最小二乘法辨识一维模型各参数，迭代时采用高斯−牛顿法计算，最后拟合实验曲线，验证直接法模型建立的正确性，完成模型后验排除法检验。研究表明，改进的伯格斯模型较好地描述了砂岩流变特征，实现砂岩流变曲线的微观分析，此外，也验证了流变模型综合辨识方法的正确性。

关键词：单轴压缩蠕变实验；瞬时塑性流变模型元件；改进的伯格斯模型；直接法；后验排除法

(Edited by Sai-qian YUAN)