

Research for time-temperature equivalence effect of rock (II): Experimental research

ZHU Yuan-guang, LIU Quan-sheng

(State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China)

Abstract: With the creep test data of granite taken from Three Gorges, the existence of time-temperature equivalence effect (TTEE) of granite is investigated. Based on the creep test data at different temperatures, which are 20 °C, 60 °C, 80 °C, 100 °C, 200 °C, 300 °C, four-component viscoelastic Burgers model is presented to characterize the creep curves. The parameters of elasticity modulus and viscosity coefficient in the constitutive model at different temperatures and their functional dependences on temperature are obtained. Then, according to the basic theory of TTEE presented in research (I), the TTEE of granite is investigated through modifying the compliance curves with vertical shift function and checking the coincidence of the modified curves with horizontal shift functions. It is concluded that: ① Burgers model could appropriately characterize the creep property of granite in a short time scale. ② Both elastic modulus and viscosity coefficient in the Burgers model decay exponentially with temperature. ③ The coincidence of the curves at different temperatures after vertical shift modification and horizontal shift is fine, which indicates the existence of TTEE of granite. ④ The master curves which reflect the long time scale test data at temperatures 20 °C, 100 °C, 200 °C are obtained.

Key words: granite; time-temperature equivalence effect (TTEE); viscoelasticity; Burgers model

1 Experiment

In this paper, we will study the time-temperature equivalence effect of granite in terms of experimental results of granite^[1]. All the test samples are from the same rock mass, which ensure the uniformity and comparability. The granite, collected from the excavation of Three Gorges dam at the Yangtze River, is black and composed of quartz, feldspar, hornblende, biotite and some cement. The test samples are obtained by drilling method with diameter 50 mm and height 100 mm. During the experiment, we should rise the temperature of triaxial cell to the setting temperature with rate of two centigrade per-minute and keep the temperature for four hours before loading. Uniaxial compression creep tests of rock, at the temperature of 20 °C, 60 °C, 80 °C, 100 °C, 200 °C and 300 °C respectively, are carried out with axial force 120 MPa.

According to the creep curves, we could see that the creep deformation is very small, which may be ignored for a short time scale engineering. However,

the tendency of keeping deformation could not be ignored for the engineering with ten thousand years service time, such as nuclear radioactive waste disposal.

1.1 Rheological constitutive model of granite

At present, many element models have been developed to describe the linear viscoelastic property. In this paper, four-parameter Burgers model is chosen to characterize the creep behavior of granite under uniaxial load. The Burgers model (Fig.1) could be express by

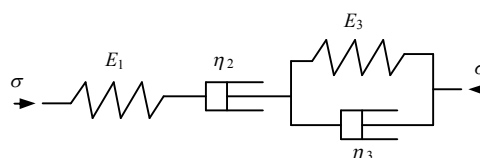


Fig.1 Burgers model

$$\varepsilon(t) = \sigma \left[\frac{1}{E_1} + \frac{t}{\eta_2} + \frac{1}{E_3} \left(1 - e^{-\frac{E_3}{\eta_3} t} \right) \right] \quad (1)$$

where $\varepsilon(t)$ is uniaxial strain and σ is uniaxial stress;

E_1 and E_3 represent elastic moduli; η_2 and η_3 are viscosity coefficients.

The method, which is based on the result of XU Zhi-ying^[2], is taken to identify the parameters in Burgers model. We suppose that the creep curves content equation (1), and then we could obtain

$$\varepsilon(t=0) = \frac{\sigma}{E_1} \quad (2)$$

when time equals to zero. We also could obtain

$$\varepsilon(t \rightarrow \infty) = \sigma \left[\frac{1}{E_1} + \frac{t}{\eta_2} \right] \quad (3)$$

when time tends to infinite, and the creep curve is nearly a straight line with gradient σ/η_2 . In actual applications, due to the force could not be instantaneously loaded, we usually take the following method. We define

$$q(t) = \frac{\sigma}{E_3} \left(1 - e^{-\frac{E_3 t}{\eta_3}} \right) \quad (4)$$

where $q(t)$ represents the vertical distance between creep curve and its extended line which represents the asymptotic line of the second stage of creep curves. Let us take logarithm to both sides of equation (4)

$$\ln q(t) = \ln \frac{\sigma}{E_3} - \frac{E_3}{\eta_3} t \quad (5)$$

We see, from equation (5), that the relationship of $\ln q$ against t is a straight line with gradient m_q and intercept ε_q , that is

$$\left. \begin{aligned} m_q &= -\frac{E_3}{\eta_3} \\ \varepsilon_q &= \ln \frac{\sigma}{E_3} \end{aligned} \right\} \quad (6)$$

According to the Burgers model and the identification method, the parameters at different temperatures are obtained (Table 1). We could see that the fitting effect is good by comparing the experiment curves and the fitting curves, which state that four-parameter Burgers model could well describe the uniaxial creep property of granite (Fig.2 to Fig.7). The parameters obtained could be use to analyze the

time-temperature effect of granite.

Table 1 Burgers parameters at different temperatures

temperature $T/^{\circ}\text{C}$	E_1 /GPa	η_2 /(10^{10} GPa·s)	E_3 /GPa	η_3 /(10^9 GPa·s)
20	1.66	25.0	10.00	33.3
60	1.58	15.0	9.69	8.65
80	1.51	10.0	9.48	5.94
100	1.44	6.0	9.32	2.66
200	1.34	1.0	9.11	0.94
300	1.20	0.5	9.03	0.60

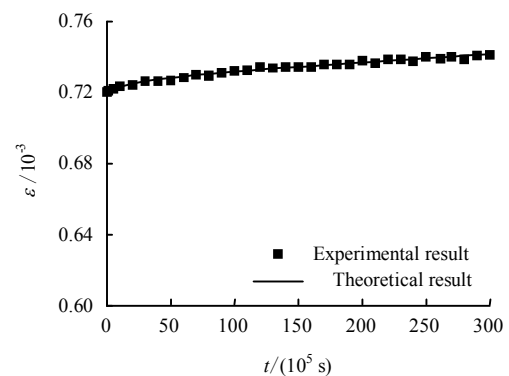


Fig.2 Creep curve of three gorges granite (20 °C)

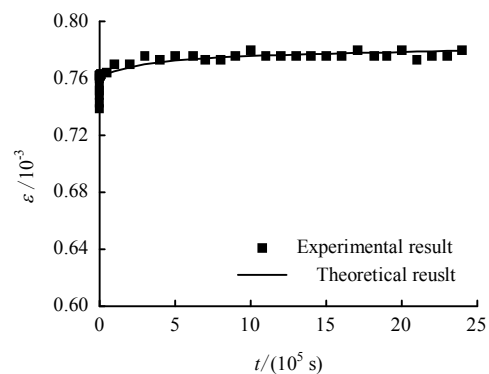


Fig.3 Creep curve of three gorges granite (60 °C)

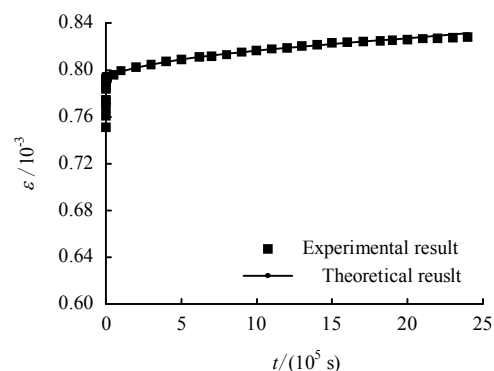


Fig.4 Creep curve of three gorges granite (80 °C)

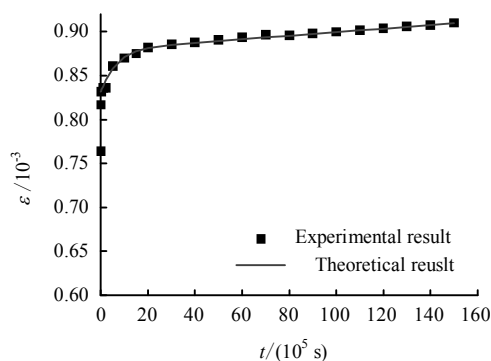


Fig.5 Creep curve of three gorges granite (100 °C)

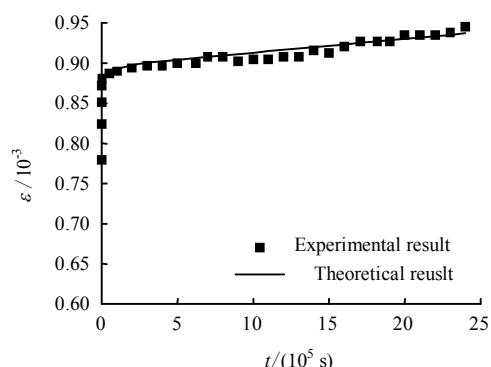


Fig.6 Creep curve of three gorges granite (200 °C)

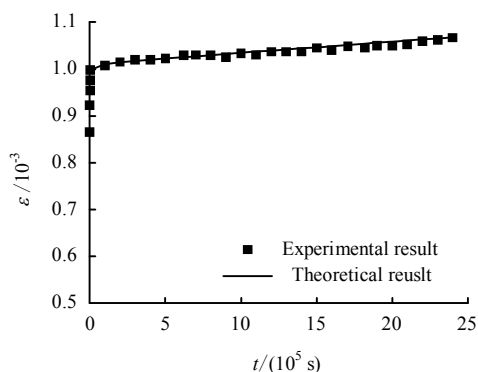


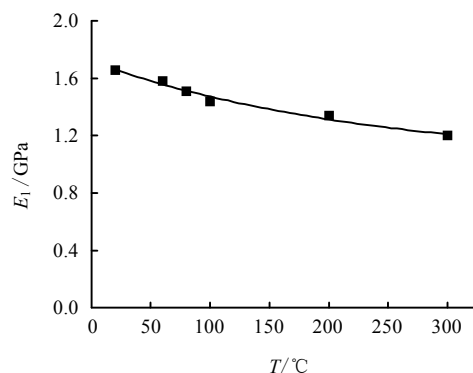
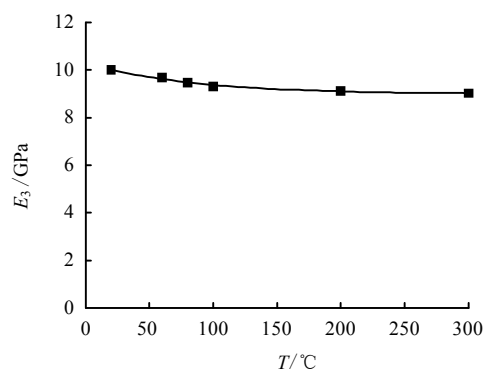
Fig.7 Creep curve of three gorges granite (300 °C)

1.2 Temperature effect

From Table 1, we could plot the parameters change with temperature, which are showed in Fig.8 to Fig.11.

From the variation trend displayed in figure 8 and figure 9, we see that the elastic modulus reduces with increasing of temperature. Elastic modulus E_1 reduces from 166 MPa to 120 MPa and elastic modulus E_3 reduces from 1.0×10^4 GPa to 0.9×10^4 GPa when temperature rising from normal temperature to 300 °C.

We could see that elastic modulus E_1 reduces much larger by contrast to elastic modulus E_3 .

Fig.8 Elastic modulus E_1 of granite at different temperaturesFig.9 Elastic modulus E_3 of granite at different temperatures

According to the elastic modului E_1 and E_3 at different temperatures, the fitting functions are obtained through exponential fitting, which are

$$E_1 = 70.047 \exp\left(-\frac{T}{236.91}\right) + 101.79 (R^2 = 0.9831) \quad (7)$$

$$E_3 = 1314.12 \exp\left(-\frac{T}{81.94}\right) + 8989.61 (R^2 = 0.9874) \quad (8)$$

The result is coincide to the result has been published^[3]. We should point out that the fitting functions only suitable in our temperature range.

From the variation trend, displayed in Fig. 10 and Fig. 11, we see that the viscosity coefficients η_2 and η_3 reduce remarkably with increasing of temperature. According to the coefficients η_2 and η_3 at different temperatures, the fitting functions are obtained through exponential fitting, which are

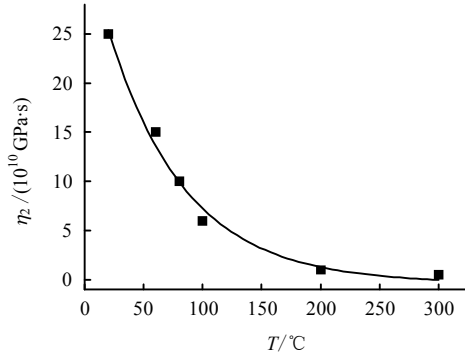


Fig.10 Viscosity coefficient η_2 of granite at different temperatures

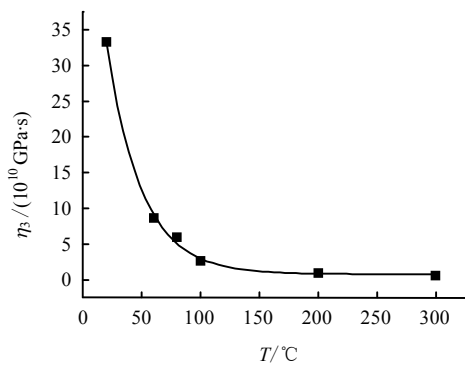


Fig.11 Viscosity coefficient η_3 of granite at different temperatures

$$\eta_2 = \left[34.92 \exp\left(-\frac{T}{65.64}\right) - 0.3672 \right] \times 10^{10} (R^2 = 0.9910) \quad (9)$$

$$\eta_3 = \left[63.88 \exp\left(-\frac{T}{29.56}\right) + 0.7846 \right] \times 10^{10} (R^2 = 0.9984) \quad (10)$$

We could see, in terms of Fig. 8 to Fig. 11, that the fitting results are fine. The elastic modulus and viscosity coefficient of granite reduce with negative exponential function of temperature, which reflect the rheological property of granite contents thermal activation mechanism to a certain degree.

2 Time-temperature equivalence effect of granite

In the first part of our theoretical research, the investigative method and procedures of time-temperature equivalence effect were developed. In this section, based on the procedures, we investigate the time-temperature equivalence effect of creep

property of granite.

Firstly, we calculate the creep compliance in terms of creep test data and plot creep compliance against logarithm time curves as showed in Fig.12.

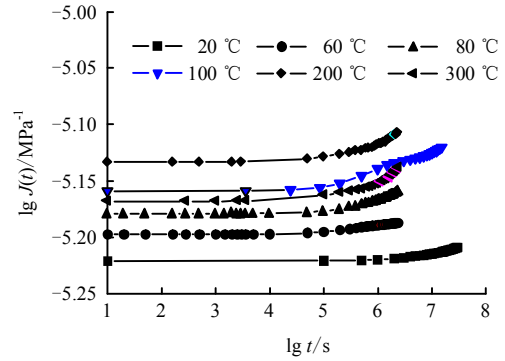


Fig.12 Curves of creep compliance vs. logarithm time at different temperatures

Secondly, we consider the influence of variation of temperature on instantaneous elastic modulus, which could be expressed by

$$\varepsilon_1(T_0) = \frac{\sigma}{E_1(T_0)} = \sigma \left(\frac{1}{E_1(T)} + b(\Delta T) \right) \quad (11)$$

where ε_1 is instantaneous strain; T_0 is reference temperature; $\Delta T = T - T_0$ is temperature variation. We could obtain the specific function of $b(\Delta T)$ in terms of the fitting function of E_1 , that is equation (7),

$$b(\Delta T) = \frac{1}{70.047 \exp\left(-\frac{T}{236.91}\right) + 101.79} - 6.006 \times 10^{-3} \quad (12)$$

if we set 20 °C as the reference temperature. Therefore, the vertical shift of creep compliance could be expressed as following

$$S_v(T) = \lg' J(T) - \lg J(T) \quad (13)$$

where $S_v(T)$ is vertical shift function. From equation (11) and equation (13), we see that

$$S_v(T) = \lg(J(T) + b(\Delta T)) - \lg J(T) \quad (14)$$

According to equation (12) and equation (14), we take vertical shift to modify the creep compliance curves, and then we obtain the modified curves as showed in Fig. 13.

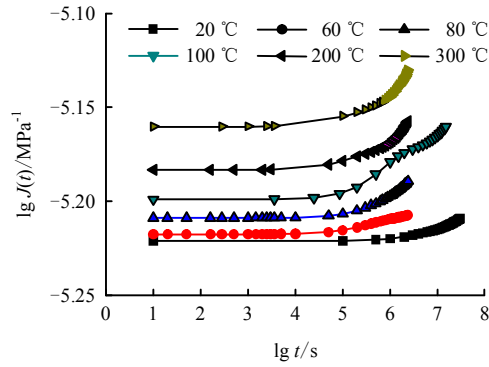


Fig.13 Modified curves of creep compliance vs. logarithm time

Thirdly, we take horizontal shift in terms of modified creep compliance curves. According to equation (9), we see the logarithm formation

$$\eta_2 = 11.543 + \lg \left[\exp \left(-\frac{T}{65.64} \right) - 0.3672 \right] \quad (15)$$

Then, the horizontal shift function could be expressed by

$$S_H(T) = \lg \left[\frac{0.37015}{\exp \left(-\frac{T}{65.64} \right) - 0.3672} \right] \quad (16)$$

According to the modified creep compliance curves, we take horizontal shift with horizontal shift function and obtain the master curves at the reference 20 °C showed in Fig.14. We could see that the curves is coincident, which means that the shifts of Newton flow and retard elastic is consistent. Therefore, we state the existence of time-temperature equivalence effect of granite. Furthermore, the time scale of creep compliance showed in Fig. 14 is as long as $10^{11.38}$ s, that is seven thousands of years, which is far beyond the scale that we could obtained in laboratory.

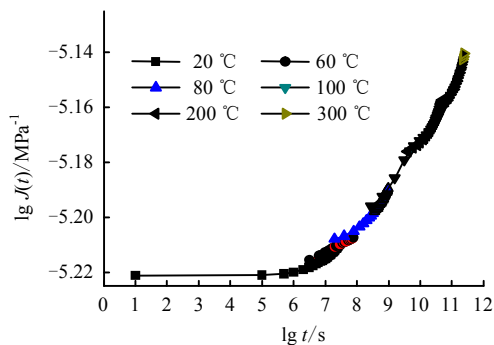


Fig.14 Major curves of creep compliance at referential temperature of 20 °C

Taking the same procedure, we obtain the master curves of creep compliance at temperatures 100 °C and 200 °C (Fig. 15 and Fig.16), which time scale are from 0 to $10^{7.88}$ s and from 0 to $10^{7.08}$ s, that is 900 d and 140 d respectively. We should increase the temperature and the test time scale if we want to obtain a longer time scale rheological data.

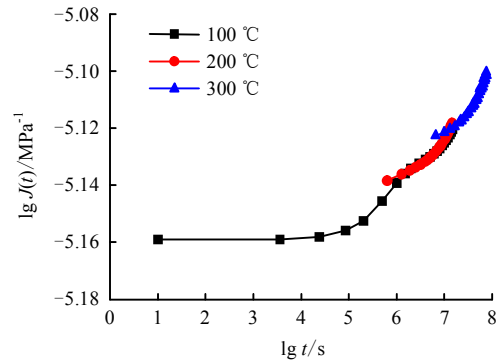


Fig.15 Major curves of creep compliance at referential temperature of 100 °C

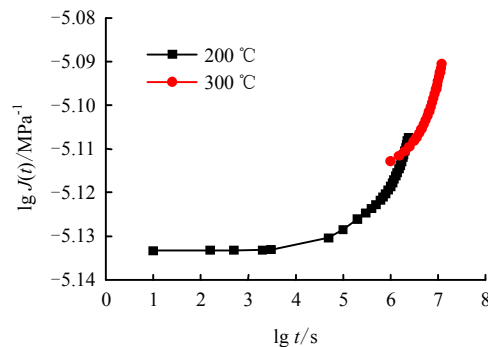


Fig.16 Major curves of creep compliance at referential temperature of 200 °C

3 Conclusions

According to the theoretical and experimental research results, the time-temperature equivalence effect of granite is discussed. We obtain the following results:

(1) The Burger model is sufficient to characterize the creep property of granite in a short time scale, and the parameters could be used to analyze the time-temperature equivalence effect of granite.

(2) Both elastic modulus and viscosity coefficient reduce with negative exponential function of temperature.

(3) Based on the procedures in part one, the existence of time-temperature equivalence effect of

granite is proved in terms of vertical shift modification and horizontal shift check.

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(未完, 见第 1192 页)