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Relations of complete creep processes and triaxial stress-strain curves of rock

LI Yun-peng(李云鹏), WANG Zhi-yin(王芝银), TANG Ming-ming(唐明明), WANG Yi(王 怡)

(Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Beijing 102249, China)

Abstract: Based on the results of triaxial compressive creep tests for five kinds of rock under the different stress loading, unloading and cycle-loading-unloading conditions, the creep deformation is not only a function of stress and time, but also it has the corresponding relations to the triaxial stress-strain curves of rock. The deformation properties of soften-strain, harden-strain and ideal plasticity presented by conventional triaxial compressive test curves under the different stress states were utilized, and the creep characteristics, the creep starting stress and the different entire creep process curves of rock were studied systematically according to creep experiment results, and the relations of the triaxial stress-strain curves to the creeping starting stress, the terminating curve, the different creep processes, and the different creep fracture properties were established. The relations presented in this paper were verified partially by the creep experiment results of five types of rock.

Key words: rock; triaxial stress-strain curve; complete creep process; creep fracture properties; creep starting and ending

1 Introduction

The different kinds of rock or similar rock but under different stress conditions, the creep curves present different non-linear characteristics. In recent years, many researchers have done a mass of tests and theoretical analysis to study the whole process of creep deformation in aspects of constitutive models and formulations of the accelerating creep phase. For example, a non-liner viscous damper which can simulate the accelerating creep process was introduced to establish constitutive models[1−5]. Some researchers introduce the cohesion and the friction coefficient changing with time to the Saint-Venant body included in Nishihara model[6], or introduce damage parameters or damage evolution equations to the viscoplastic coefficient[7]. In addition, other researchers studied the creep deformations and fracture properties associating with the complete stress-strain curves. For instance, Goodman proposed the creep terminating curve according to the complete stress-strain curves and studied the relations between creep deformations and stress levels[8]. The creep characteristics of rock salt are determined by the stress levels after applying the relations given by Goodman to the research of rock salt creep deformation[9]. In this paper, based on the results of triaxial compressive creep tests for five kinds of rock under the different stress loading, unloading and cycle-loading-unloading conditions, the relations of the triaxial stress-strain curves to the creep starting stress, terminating curve, different creep processes, and different creep fracture properties are set up by utilizing the deformation properties of soften-strain, harden-strain and ideal plasticity presented by conventional triaxial compressive test curves under the different stress states. The relations established in this paper have been verified partially by the creep test results of five types of rock.

2 Creep starting stress and long-term strength

Results of triaxial creep tests of five different kinds of rock which are silty mudstone, mica-quartz-gneiss, granite, rock salt and limestone exhibit a big difference in the initial phase of loading. Under low stress levels, there is no obvious creep deformation for the hard rock shown in Figs.1 and 2. However, there is a significant creep deformation for the soft rock shown in Figs.3−5. The creep starting stress and the long-term strength are also different for different types of rock. The creep starting stress and the long-term strength of granite are 65.7%−70.8% and 82.5%−88.0% of the transient strength respectively; while the creep starting stress and the long-term strength of mica quartz gneiss are 57.6%−65.2% and 75.8%−83.3% of the transient strength

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Corresponding author: LI Yun-peng, Professor; Tel: +86−10−89733926; E-mail: liyp996@163.com

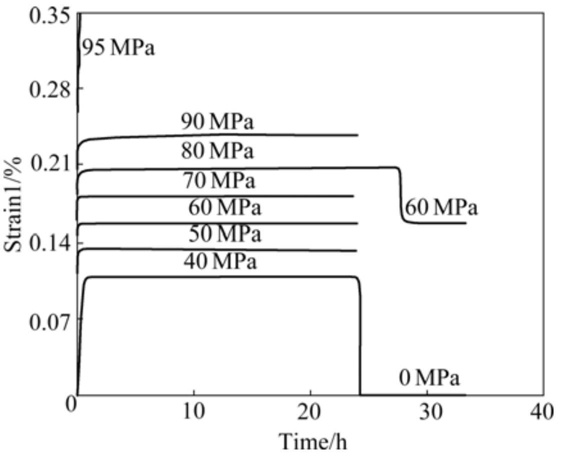

Fig.1 Curves of triaxial creep test of granite (Confining pressure is 5 MPa)

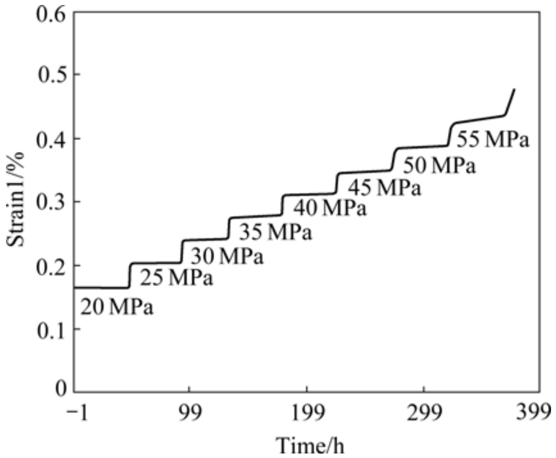

Fig.2 Curve of triaxial creep test of mica quartz gneiss (Confining pressure is 2 MPa)

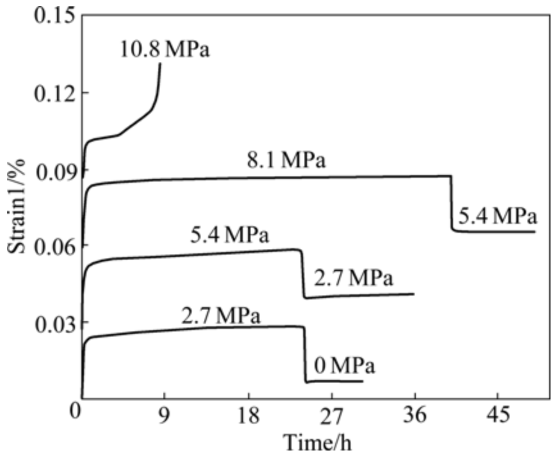

Fig.3 Curves of triaxial creep test of silty mudstone (Confining pressure is 1 MPa)

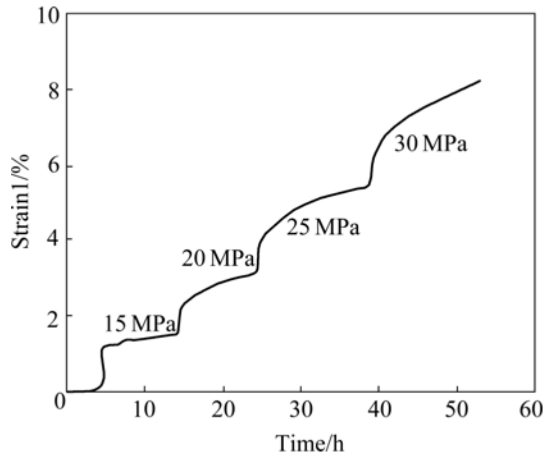

Fig.4 Curve of triaxial creep test of rock salt (Confining pressure is 10 MPa)

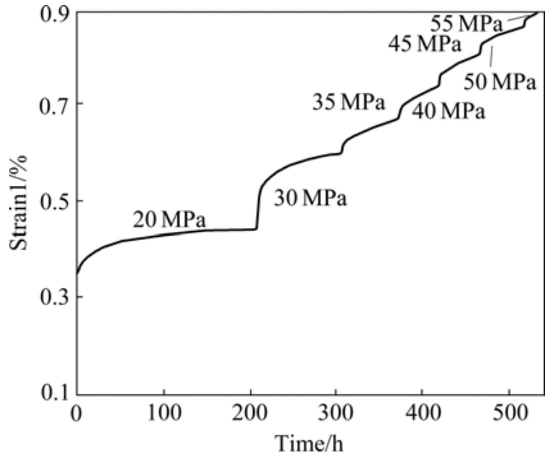

Fig.5 Curve of triaxial creep test of limestone (Confining pressure is 20 MPa)

respectively[7, 10]. The obvious creep deformations for the other rock appear under low stress loading. The results of the creep starting stress, the long-term strength, and the transient compressive strength of granite are listed in Table 1.

3 Relations of creep deformation and triaxial stress-strain curves

According to the typical triaxial stress-strain curves of rock, as shown in Fig.6[11], the deformation curves of rock present different mechanical characteristics due to the change of stress states. The soften-strain phenomena appear under low confining pressure; however, the obvious deformation properties of harden-strain appear under higher confining pressure. The stress-strain curves between soften-strain and harden-strain can be simplified as ideal plastic curves. Therefore, the typical triaxial stress-strain curves can be divided into three types: 1) strain softening curves, 2) strain hardening curves, 3) ideal plastic curves. According to the process characteristics of creep for different kinds of rock and the definition of the creep terminating curve[8], the initial test phase of pore shrinking is ignored, then the relations between creep deformations and the triaxial stress-strain curves are proposed, as shown in Figs.7−9, where the symbols σ_s, σ_p, σ_{cI} and σ_{cL} denote the transient yield

Table 1 Creep starting stresses of granite under different confining pressures[10]

Confining pressure/MPa	Creep starting stress, σ_{cI}/MPa	Long-term strength, σ_{cL}/MPa	Transient compressive strength, σ_s/MPa	$(\sigma_{cI}\cdot\sigma_s^{-1})$/%	$(\sigma_{cL}\cdot\sigma_s^{-1})$/%
5	75	90	109.143	68.717	82.461
8	80	98	115.439	69.301	84.893
10	82	107	116.752	65.730	85.770
12	93	115	133.271	70.846	87.605
15	98	130	147.684	66.358	88.026

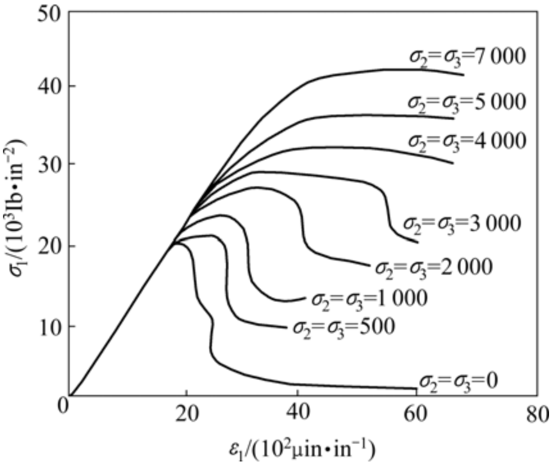

Fig.6 Triaxial stress-strain curves of rock (marble)

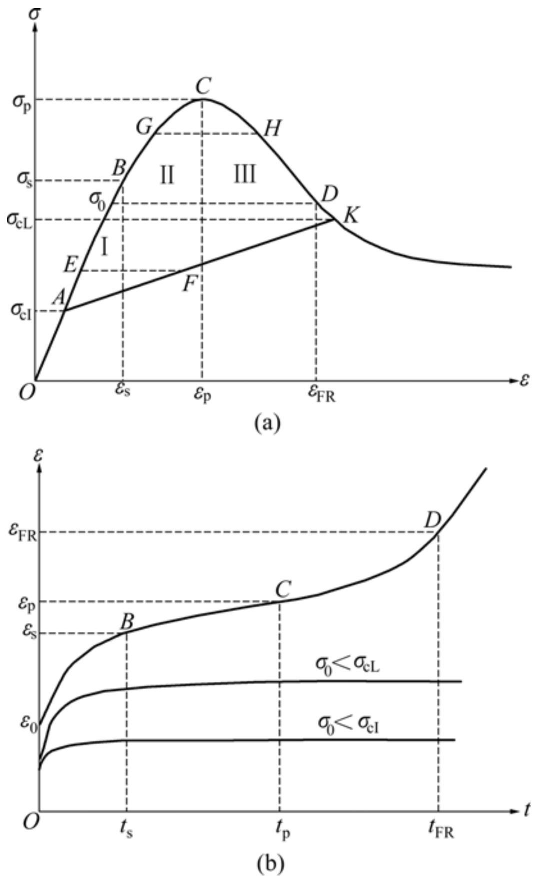

Fig.7 Relationship between creep deformation process and strain softening curves: (a) $\sigma_{cI}\neq 0$; (b) Typical creep curves (strain softening curves)

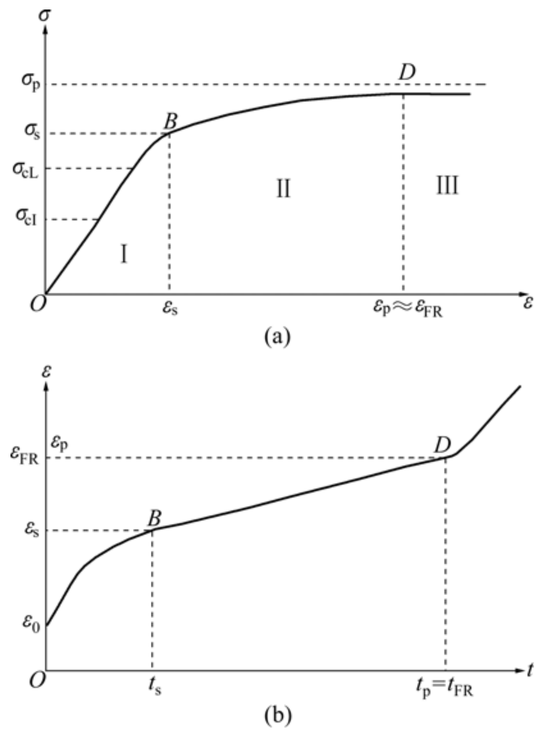

Fig.8 Relationship between creep deformation and strain hardening curve: (a) $\sigma_{cI}\neq 0$; (b) Creep curve of rock (strain hardening curve)

stress, transient compressive strength, creep starting stress and long-term strength, respectively.

3.1 Creep deformation and soften-strain curve

The AK line called the creep terminating curve in Fig.7 is defined by the points that the delayed deformation stabilizes under different stress levels. As seen from Fig.7, under the lower confining pressure conditions, when the axial stress is less than the long-term strength, the rock creep deformation which is denoted by the length of *EF* will increase with the increase of the axial stress (deviatoric stress level), and the deformation will stabilize asymptotically to a maximum value corresponding to the *F* point. So if the axial stress applied is lower than the long-term strength, the creep curve only contains primary creep phase, and for the secondary creep phase the strain rate decreases to zero and the delayed deformation will stabilize at a

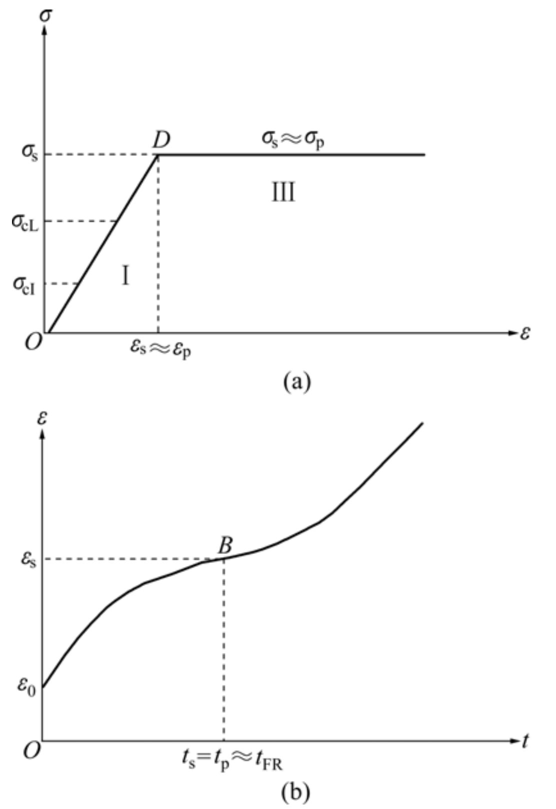

Fig.9 Relationship between creep deformation and ideal plastic curve: (a) $\sigma_{cI} \neq 0$; (b) Creep curve of rock (ideal plastic curve)

constant value over a long period. If the axial stress is higher than the long-term strength but lower than the transient compressive strength, the creep curve contains all the three phases, and the duration of the primary creep phase will decrease with the increase of the deviatoric stress. When the strain reaches ε_s, the strain rate keeps at a constant value more than zero, and the creep deformation turns into the secondary creep phase. If the strain reaches ε_p, the creep deformation turns into the tertiary creep phase. When the strain reaches the value of point *D* corresponding to the creep stress σ_0, the creep ductile fracture happens. If the axial stress is higher than the yield stress, the duration of the primary creep phase is too fugacious to neglect, and the creep deformation contains the secondary creep phase and the tertiary creep phase primarily. The higher the deviatoric stress is, the less the duration of deformation to get to the value corresponding to the creep stress σ_0 is. As shown in Fig.7, the length of *GH* is less than that of *BD*, so the creep deformation and the duration to failure decrease with the increase of deviatoric stress. When the creep stress σ_0 is close to the peak stress, little creep deformation happens, then the rock damages immediately, which belongs to the brittle fracture.

For the condition of $\sigma_{cI}=0$, the creep deformation is similar to that of $\sigma_{cI} \neq 0$, but the difference is that under the same stress level, the deformation and the duration when the failure happens or the creep stabilizes are much larger when $\sigma_{cI} \neq 0$.

3.2 Creep deformation and harden-strain curve

The axial stress-strain curve under the higher confining pressure condition is shown in Fig.8. The rock stress-strain curve exhibits a harden property for the condition of $\sigma_{cI}=0$ or $\sigma_{cI}>0$, no matter how much the long-term strength is, there is no creep terminating curve. The relation between the creep deformation and strain hardening stress-strain curve is shown in Fig.8. If the axial stress is lower than the transient yield stress, the creep deformation contains all the three phases, and the tertiary creep phase is very fugacious. Moreover, the duration of the primary stage will decrease with the increase of the axial stress. If the axial stress is higher than the transient yield stress, the creep deformation will experience two phases primarily, that means, when the axial stress is higher than σ_s, the creep deformation turns into the secondary phase rapidly; when the strain value exceeds ε_p, the creep deformation turns into the tertiary phase which is fugacious, and the creep ductile-brittle fracture happens. Under a certain experimental condition, the creep properties and the deformation process of rock salt, silty mudstone and limestone are shown in Figs.3−5.

3.3 Creep deformation and ideal plastic curve

The deformation property presented in Fig.9 is similar to that in Fig.8. Under the higher confining pressure condition, the creep deformation contains primary and tertiary creep phases and no creep terminating curve exists. The duration of primary creep phase decreases with the increase of the axial stress level, and the duration of tertiary creep phase is very fugacious. In theory, *D* is the starting point of the unlimited plastic flow status, and the *D* point is the fracture point defined by the plastic mechanics. Therefore, the secondary creep phase doesn't appear and the tertiary creep phase is not remarkable in the situation. After the strain value just reaches ε_s, the creep brittle fracture happens.

Based on the above theories, the visco-elastic part and the visco-plastic part are considered in series, then the constitutive equations for different creep phases can be established by using the visco-elastic-plastic medium theory[7]. In the view of the limited space, the remaining will not be described any more.

4 Conclusions

1) For different kinds of rock and different stress levels, the conventional triaxial compressive test curves can be divided into three types: strain softening curves, strain hardening curves, ideal plastic curves. There are

certain relations between the triaxial compressive test curves and creep test curves.

2) The relations of the conventional triaxial stress-strain curves to the creeping starting stress, the terminating curve, the different creep processes and the different creep fracture properties proposed in the paper indicate the creep deformation properties, the creep starting stress, the long-term strength and the different creep deformation curves under different stress levels directly.

3) The relations established in the paper are verified partially by the creep tests of five types of rock and will be further studied in future.

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