C. R. Mecanique 344 (2016) 603–611

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Effect of temperature on the time-dependent behavior of geomaterials

Sheng Zhang [a,b], Shuo Xu [a], Jidong Teng [a,b,*], Yonglin Xiong [c]

[a] School of Civil Engineering, Central South University, Changsha 410075, China
[b] National Engineering Laboratory for High-Speed-Railway Construction, Central South University, China
[c] Department of Civil Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 19 January 2016
Accepted 27 April 2016
Available online 24 May 2016

Keywords:
Equivalent stress
Creep constitutive model
Creep regularity
Optimum temperature

ABSTRACT

In many geotechnical engineering applications, such as nuclear waste disposal and geothermal extraction and storage, it is necessary to consider the long-term mechanical properties. The effect of temperature could have a complicated influence on the creep damage behavior of soft rock. As a consequence, it is meaningful, both in theory and in practice, to establish a constitutive model that can describe the creep damage behavior. Within the framework of continuum mechanics, a thermo-visco-elastoplastic model is proposed on the basis of a sub-loading Cam-clay model and the concept of equivalent stress. Triaxial creep tests under different confining pressures for Tage stone were conducted to validate the proposed model. The experimental results show that an optimum temperature exists for a certain stress state, and this temperature significantly slows down the creep damage rate. In addition, both the retarding and accelerating effects on creep rupture due to limited warming are observed for the same material, and this phenomenon can be predicted well by the proposed model. Finally, a parametric analysis is performed, and the influence of the material parameter on creep regularity is discussed in detail.

1. Introduction

Recently, numerous studies have improved performance assessment predictions for nuclear waste disposal. As a material with an unconfined compressive strength of 1–10 MPa, soft sedimentary rock displays a mechanical behavior between those of soil and rock, and is commonly treated as a continuous material. Thus, the deep burying of nuclear waste in a sedimentary rock ground is considered to be practical. When exposed to the elevated temperature caused by nuclear waste, the thermomechanical properties of geomaterials should be emphasized. Many experiments have studied the thermomechanical properties of geomaterials, e.g., [1–8]. De Bruyn et al. [9] performed uniaxial creep tests on Boom-clay and show that a thermal effect would lead to a continuous increase in the pore pressure. Moreover, high-temperature uniaxial creep tests on soft rocks conducted by Shibata et al. [10] show that creep failure occurs more quickly as the temperature increases. Similar tests conducted by Cui et al. [11] indicate that creep stress and temperature have a significant influence on the volumetric

* Corresponding author at: Railway Campus of Central South University, Shaoshan South Road No. 68, Changsha, Hunan Province, 410075, China. Tel.: +86 0731 82656193; fax: +86 0731 82656193.
E-mail address: jdteng@csu.edu.cn (J. Teng).

http://dx.doi.org/10.1016/j.crme.2016.04.005

strain rate. Most studies mentioned above show that elevated temperatures lead to a change in the creep behavior, with a single trend. But according to the experimental results by Okada et al. [12], who have evidenced, from one-dimensional creep tests on mudstone, an interesting phenomenon in the sense that increasing the heat would either accelerate or retard creep failure. That is to say, contrary creep behaviors, i.e. dual effects of temperature, appear on one material. But dual effects of temperature were not discussed in detail in Okada et al. [12], and are seldom mentioned in the literature. In fact, dual effects of temperature are crucial for truly revealing the creep behavior of soft rock under different temperatures. It highlights the necessity to clarify the dual effect of temperature from both experimental and theoretical approaches.

To describe the thermal mechanical behavior of soils, many models have been proposed. Hueckel et al. [4] proposed a thermoplastic model based on a modified Cam-clay model. While dealing with the thermal effect, this model introduced a state variable in the expression of yield surface and reversible dilation in the elastic part. Based on thermal tests results, Cui et al. [13] and Graham et al. [14] developed thermomechanical models for clays. In these models, modifications have been made to model the effect of the overconsolidation ratio on the thermomechanical behavior of soils. Within continuum mechanics, Zhang et al. [15,16] proposed a simple thermo-elastoplastic model based on a sub-loading Cam-clay model, where the concept of equivalent stress was presented to simulate the mechanical effect caused by an increase in heat. However, most existing models mentioned above aimed at modeling the short-term properties of geomaterials, few study paid attention to the time-dependent behavior of soils under an elevated temperature. For example, Modaressi et al. [17] proposed a thermo-viscoplastic cyclic constitutive model for clays, where a Perzyna-type viscoplastic model was applied. A rate-dependent formulation was established in the model of Modaressi et al. [17] to describe the thermo-viscoplastity of soils, but this model was not validated by creep experiments under high temperature [18]. Therefore, the existing models fail to make a prediction of the dual effect of temperature on creep failure properties.

Aiming to identify the contrary thermomechanical behaviors of a soft sedimentary rock, this paper performs a series of drained triaxial creep tests at various temperatures. In the experiments, the temperature was controlled from 20 °C to 80 °C, considering the engineering background of nuclear waste disposal. Besides, a thermo-viscoplastic model is proposed in this paper, which is an extension for the model of Zhang et al. [16]. The newly proposed model can be distinguished from previous works since:

(1) it can predict the dual effect of temperature on creep failure properties that an increase in heat would either accelerate or retard creep failure for one material;
(2) the sub-loading surface is applied in this model and only one parameter related to temperature is added, which makes it easy for computation. The other parameters involved in this model have clear physical meanings, and can be determined by triaxial test.

2. A thermo-viscoplastic model

In the framework of continuum mechanics, the modified Cam-clay model is able to capture some typical feature of reconstituted soft clays. Many enhancements have since then been proposed to tackle more advanced behaviors of geomaterials, such as over-consolidation, initial structure, anisotropy, time-dependent behavior. Amongst these enhancements, the sub-loading Cam-clay model proposed by Hashiguchi [19] has received particular attention. While it is a material with good continuity, soft sedimentary rocks can be treated as over-consolidated soils. Thus, the sub-loading Cam-clay model raised by Hashiguchi et al. [19] is suitable for constitutive modeling. The sub-loading yield surface, f_s^σ, passing through the present stress state $P(p,q)$ can be expressed as:

$$f_s^\sigma = \ln\frac{p}{p_0} + \frac{1}{M}\frac{q}{p} - \frac{1}{C_p}\left(\varepsilon_v^p - \frac{\rho^\sigma}{1+e_0}\right) \tag{1}$$

where $C_p = (\lambda - \kappa)/(1+e_0)$ and M is the ratio of the shearing stress at the critical state. ρ is a state variable describing the mechanical void ratio difference, which can be expressed as:

$$\rho^\sigma = C_p(1+e_0)\ln OCR^\sigma \tag{2}$$

In the previous work by Zhang et al. [16], the concept of equivalent stress considering the temper impact is developed as:

$$\tilde{\sigma}_{ij} = \sigma_{ij} + \Delta\tilde{\sigma}_{ij} = \sigma_{ij} + \sigma_m \exp\left[\frac{3\alpha_t(\theta-\theta_0)(1+e_0)}{\kappa}\right]\delta_{ij} - \sigma_m\delta_{ij} \tag{3}$$

where θ is the present temperature and θ_0 is the reference temperature, which is commonly determined to be 20 °C.

Fig. 1 shows the definition of the equivalent stress and sub-loading yield surface. A detailed derivation can be found in Zhang et al. [16]. Then, the yield surface considering the thermal impact can be derived as follows:

$$f_s = C_p\ln\frac{p}{p_0} + \frac{C_p}{M}\frac{q}{p} - \left(\varepsilon_v^p - \frac{\rho_\theta^\sigma}{1+e_0}\right) \tag{4}$$

where $\rho_\theta^\sigma = C_p(1+e_0)\ln\frac{p_{N1e}}{p_{N1}}$ represents the mechanical void ratio difference considering the temperature.

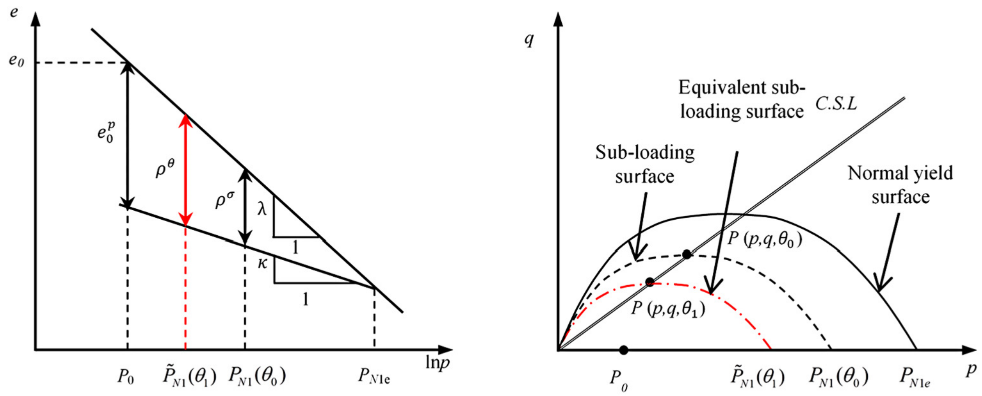


Fig. 1. Concepts of the equivalent sub-loading yield surface and normal yield surface.

In determining the plastic flow direction, the associated flow rule is adopted. The proposed yield function is also the thermoplastic potential. The plastic strain increment can be calculated as:

$$\mathrm{d}\varepsilon_{ij}^{p} = \Lambda \frac{\partial f}{\partial \sigma_{ij}} \qquad \mathrm{d}\varepsilon_{\mathrm{v}}^{p} = \Lambda \frac{\partial f}{\partial \sigma_{ii}} \tag{5}$$

where Λ is a positive scalar, which can be obtained by the consistency equation:

$$\dot{f} = 0 \rightarrow \frac{\partial f}{\partial \sigma_{ij}} \dot{\sigma}_{ij} - \frac{1}{C_p}\left(\dot{\varepsilon}_{\mathrm{v}}^{p} - \frac{\dot{\rho}}{1+e_0}\right) = 0 \tag{6}$$

in which

$$\frac{\partial f}{\partial \sigma_{ij}} = \left(\frac{1}{\sigma_{\mathrm{m}}} - \frac{\sqrt{3}}{M}\frac{\sqrt{J_2}}{\sigma_{\mathrm{m}}^2}\right)\frac{\delta_{ij}}{3} + \frac{\sqrt{3}}{\mathrm{M}}\frac{s_{ij}}{2\sqrt{J_2}}\frac{1}{\sigma_{\mathrm{m}}} \tag{7}$$

$$\frac{\partial f}{\partial \sigma_{ii}} = \frac{\partial f}{\partial \sigma_{ij}}\delta_{ij} = \left(\frac{1}{\sigma_{\mathrm{m}}} - \frac{\sqrt{3}}{M}\frac{\sqrt{J_2}}{\sigma_{\mathrm{m}}^2}\right) \tag{8}$$

Then, it is necessary to determine the evolution equation of ρ. It is noted that the evolution of ρ dissipates with time when the soft rock reaches the creep stage. In the model proposed by Zhang et al. [16], the evolution equation is not related with time. Thus, this model cannot deal with the creep progress. To make an improvement, we introduce an evolution equation proposed by Zhang et al. [20] to consider the time effect. In this way, the model presented here is able to describe the creep progress under high temperatures. Then a similar form of the evolution equation of ρ is derived below:

$$\frac{\dot{\rho}}{1+e_0} = -\Lambda \frac{G(\rho, t)}{\tilde{\sigma}_{\mathrm{m}}} + h(t) \tag{9}$$

where

$$h(t) = \dot{\varepsilon}_{\mathrm{v}}^{0}[1 + t/t_1]^{-\alpha} \tag{10}$$

$$G(\rho, t) = a \cdot \rho \cdot \rho^{C_{\mathrm{n}} \ln(1+t/t_1)} \tag{11}$$

where $\dot{\varepsilon}_{\mathrm{v}}^{0}$ is the volumetric strain rate at time $t = 0$. t_1 is a unit time used to standardize the time. The parameter α is used to describe the time dependency, which mainly controls the gradient rate vs. time in logarithmic axes. C_{n} is introduced to control the strain rate dependency of the soft rock. a is a parameter controlling the dissipation rate of the *OCR*.

By substituting Eqs. (5), (7), (8) and (9) into Eq. (6), the specific value of the plastic factor Λ can be calculated as follows:

$$\Lambda = \frac{\frac{\partial f}{\partial \sigma_{ij}}\mathrm{d}\sigma_{ij} + \frac{1}{C_p}\cdot h(t)}{\frac{1}{C_p}\frac{\partial f}{\partial \sigma_{ii}} + \frac{1}{C_p}\cdot\frac{G(\rho,t)}{\sigma_{\mathrm{m}}\exp[\frac{3\alpha_t(\theta-\theta_0)(1+e_0)}{\kappa}]}} \tag{12}$$

At the stage of creep, the stress does not vary, making the derivate $\dot{f}_\sigma = 0$. By substituting this relationship into Eq. (12), the viscoplastic strain rate can be determined:

$$\dot{\varepsilon}_{ij}^{p} = \Lambda \cdot \frac{\partial f}{\partial \sigma_{ij}} = \frac{h(t)}{\frac{\partial f}{\partial \sigma_{ii}} + \frac{G(\rho,t)}{\sigma_{\mathrm{m}}\exp[\frac{3\alpha_t(\theta-\theta_0)(1+e_0)}{\kappa}]}} \cdot \frac{\partial f}{\partial \sigma_{ij}} \tag{13}$$

Based on Hooke's law and Eq. (19), the incremental stress tensor can be obtained:

$$\begin{aligned} \mathrm{d}\sigma_{ij} &= E_{ijkl}\mathrm{d}\varepsilon_{kl}^{e\sigma} = E_{ijkl}\left(\mathrm{d}\varepsilon_{kl} - \mathrm{d}\varepsilon_{kl}^{p} - \mathrm{d}\varepsilon_{kl}^{e\theta}\right) \\ &= E_{ijkl}\mathrm{d}\varepsilon_{kl} - E_{ijkl}\frac{\partial f}{\partial \sigma_{kl}}\Lambda - E_{ijkl}\alpha_t\delta_{kl}\mathrm{d}\theta \end{aligned} \tag{14}$$

Furthermore, substituting Eq. (14) into Eq. (12), the plastic factor, in the form of a tensor, can be derived as:

$$\Lambda = \frac{\frac{\partial f}{\partial \sigma_{ij}} E_{ijkl}\mathrm{d}\varepsilon_{kl} - \frac{\partial f}{\partial \sigma_{ij}} E_{ijkl}\alpha_t\delta_{kl}\mathrm{d}\theta}{\frac{h_p^\theta}{C_p} + \frac{\partial f}{\partial \sigma_{ij}} E_{ijkl}\frac{\partial f}{\partial \sigma_{kl}}} \tag{15}$$

where

$$h_p^\theta = \frac{\partial f}{\partial \sigma_{ii}} + \frac{G(\rho, t)}{\sigma_{\mathrm{m}} \exp[\frac{3\alpha_t(\theta-\theta_0)(1+e_0)}{\kappa}]} \tag{16}$$

Hence, the plastic strain increment can be easily calculated by Eq. (5).

Additionally, the loading criteria are given as:

$$\left\|\mathrm{d}\varepsilon_{ij}^{p\sigma}\right\| > 0\Lambda > 0, \quad \begin{cases} \dot{f}_\sigma > 0 & \text{hardening} \\ \dot{f}_\sigma < 0 & \text{softening} \\ \dot{f}_\sigma = 0 & \text{pure creep} \end{cases}$$

$$\left\|\mathrm{d}\varepsilon_{ij}^{p\sigma}\right\| > 0\Lambda \le 0, \quad \text{elastic}$$

By considering the time parameter, the proposed model is able to describe the time-dependent thermomechanical behavior of a soft rock. The parameters used in this model have specific physical significances within the continuum framework, and they can be derived from constitutive element tests.

3. Laboratory experiment

A new temperature-controlled triaxial test apparatus is employed to perform experimental work, and it consists of a triaxial cell with a heating system, a loading control unit for axial load and cell pressure, and a data acquisition unit. The schematic diagram of the triaxial cell is shown in Fig. 2. A heater and a temperature sensor are installed inside the triaxial cell. An external temperature controlling unit controls the heater by monitoring the water temperature in the cell. An inclined propeller (inclining angle is 45°) driven by a motor is used to circulate water in the cell. Compared with the vertical propeller that was used in other apparatuses, the inclined propeller can provide both vertical and horizontal water circulation, ensuring a uniform water temperature throughout the cell.

Generally speaking, the uniaxial compressive strength of the rock is less than 20 MPa. Underground structures built in soft rocks, such as storage tunnels for high-level radioactive waste disposal, are usually constructed several hundred meters beneath the ground face and can be exposed to a maximum confining stress of 10 MPa. Therefore, the apparatus was designed in this study with a maximum cell pressure of 10 MPa and a maximum axial load of 50 kN to provide a sufficient loading range for testing programs.

The axial load can be applied by either a stress- or strain-controlled mode. In the stress-controlled mode, the load is applied by an air-pressure actuator, while in the strain-controlled mode, the base of the triaxial cell is jacked up by a speed-controlled motor. The cell pressure is applied through a piston-type water pressure amplifier. The axial load (stress control mode only) and the cell pressure are controlled by two electro-pneumatic (E/P) regulators.

The measured values of the axial load, the axial displacement, the cell pressure, and the pore-water pressure as well as the volume change are collected by a computer through a data-logger. Based on the measured values, a computer program adjusts the necessary pressures and sends out voltage signals to the E/P regulators through a D/A board.

The soft sedimentary rock used in this study is Tage stone, which is a type of Ohya stone. It has a uniaxial compressive strength of 10–20 MPa. The rock was mined from a quarry in northern Japan at a depth of 60 m by the block sampling method. Because the mechanical behavior of soft rock will change a lot if the samples are exposed to air for a long time, the rock samples were kept in a wet state immediately after sampling. The cylindrical specimens are 50 mm in diameter and 100 mm in height. Details of the basic physical properties are listed in Table 1.

The thermal creep tests were conducted under 20 °C, 40 °C, 60 °C, and 80 °C. The cell water was heated to the target temperature at a rate of 0.5 °C/min. During heating, the specimens were kept in the drained condition. Two different creep stresses were chosen for each confining stress strategy. Details of the experimental conditions are listed in Table 2.

4. Result and discussion

The theoretical computation was conducted to validate the ability of the model presented. Parameters involved in the numerical calculation are in accordance with those mentioned in Table 1 to keep the numerical results reliable.

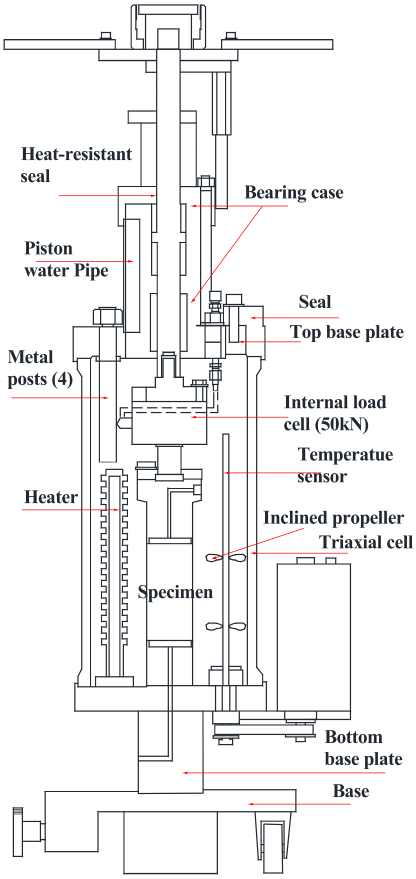


Fig. 2. Triaxial cell with a heater and a propeller.

Table 1
Basic physical properties of the Tage stone.

σ_m (MPa)	E (MPa)	λ	κ	a	α	C_n	υ	R_f	e_0	OCR
0.98	400	0.024	0.02	390	0.043	1.4	0.08	5.04	0.42	250
0.49	400	0.024	0.02	390	0.043	1.4	0.08	7.78	0.42	250

Table 2
Testing scheme of the thermal drained triaxial creep tests.

Temperature (°C)	20, 40, 60, 80
Confining stress (MPa)	0.49, 0.98
Creep stress (MPa)	7.4 ($\sigma_3 = 0.49$ MPa), 9.1 ($\sigma_3 = 0.98$ MPa)
Initial strain rate (%/min)	0.002

Figs. 3 and 4 compare the experimental and theoretical results using this model in logarithmic axes. It can be observed that the theoretical results agree with the experimental results.

From the results in Fig. 3, it is evident that creep failure occurs much more rapidly as heat increases. However, the situation changes when the confining stress is 0.98 MPa, with the creep stress increasing to 9.1 MPa. As shown in Fig. 4, creep failure first occurs slowly as the temperature increases to 40 °C, but then failure happens faster as the temperature increases to 60 °C and 80 °C. This contrary phenomenon can be revealed between different temperature intervals subjected to a certain stress condition. Taking this contrary result into consideration, a much more unified conclusion can be obtained. In a certain stress state, an optimal temperature exists, at which the creep failure occurs at the slowest rate. Therefore, both the results shown in Fig. 3 and Fig. 4 can be explained, and the optimal temperature in Fig. 3 is 20 °C, whereas in Fig. 4, it is 40 °C.

To verify the applicability of the model, another experimental result conducted by Okada et al. [12] is simulated here. The test was a uniaxial creep test for mudstone under 20 °C and 60 °C. The parameters involved in the test and calculation are listed in Table 3. The experimental conditions can be found in Table 4.

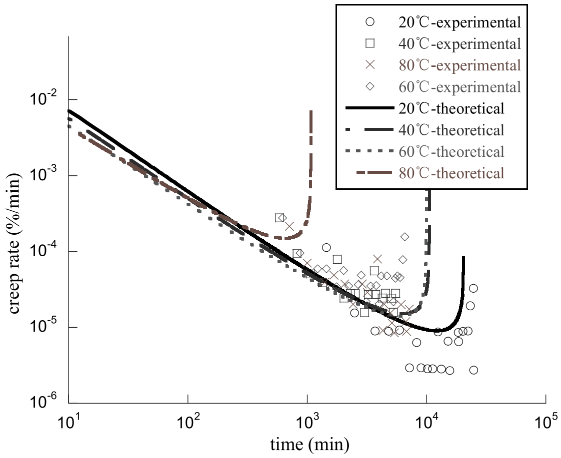


Fig. 3. Experimental and theoretical results of the drained triaxial creep tests for the Tage stone under different constant temperatures with a constant confining stress of $\sigma_m = 0.49$ MPa.

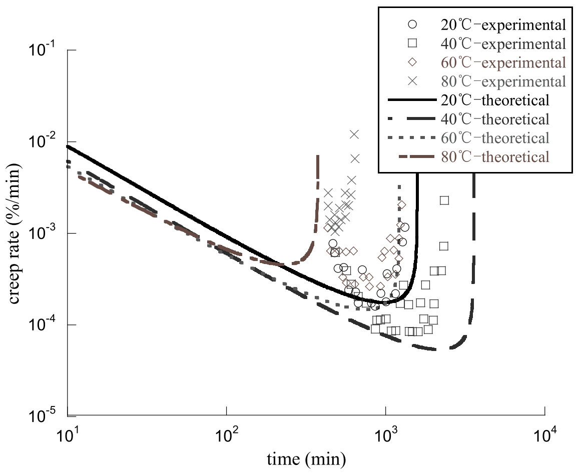


Fig. 4. Experimental and theoretical results of the drained triaxial creep tests for the Tage stone under different constant temperatures with a constant confining stress of $\sigma_m = 0.98$ MPa.

Table 3
Basic physical properties of the mudstone.

σ_m (MPa)	E (MPa)	λ	κ	a	α	C_n	υ	R_f	e_0
0.098	900	0.024	0.02	250	0.043	2.2	0.08	7.78	0.42

Table 4
Testing scheme of the thermal drained uniaxial creep tests.

Temperature (°C)	20, 60
Confining stress (MPa)	0.098
Creep stress (MPa)	3.5, 4.0
Initial strain stress (%/min)	0.009

Fig. 5 shows the theoretical and experimental results of the uniaxial creep tests on mudstone. It can be observed that the theoretical results match the test results well. Additionally, it is obvious that the creep failure time does not decrease monotonously as the amount of heat increases. At a low creep stress level, failure occurs slower as the amount of heat increases. However, when the creep stress increases to 4.0 MPa, failure occurs faster as the temperature is raised. This contrary consequence can be explained by the illustration proposed in the former statement in this text. The optimal temperature is 20 °C under 3.5 MPa and is 60 °C under 4.0 MPa.

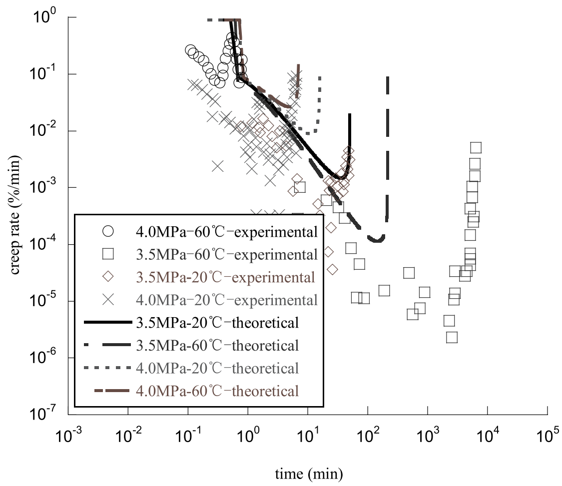


Fig. 5. Theoretical and test results of the unconfined uniaxial creep tests on mudstone (Okada, 2005).

Table 5
Basic physical properties and parameters involved in cases 1–5.

Case	σ_m (MPa)	E (MPa)	λ	κ	a	α	C_n	υ	R_f	e_0	OCR
1	0.98	400	0.024	0.02	390	0.043	1.4	0.08	5.04	0.42	250
2	0.98	400	0.024	0.02	190	0.043	1.4	0.08	5.04	0.42	250
3	0.98	400	0.024	0.02	500	0.043	1.4	0.08	5.04	0.42	250
4	0.98	400	0.024	0.02	390	0.043	1.4	0.08	5.04	0.42	150
5	0.98	400	0.024	0.02	390	0.043	1.4	0.08	5.04	0.42	550

Zhang et al. [16] concluded that the stress–strain relation may change from brittleness to ductility as the temperature increases, and the phenomena of “heat increase” and “heat decrease” were proposed. This transformation may also occur in a contrary way as the amount of heat increases, depending on the type of material and the determination of the *OCR*. In this presented study, a similar explanation could be suitable. Various conditions of creep stress loaded on soft rock element may lead to different transformation procedures between brittleness and ductility. For instance, subjected to a stress level of 0.98 MPa, Tage stone shows more ductility when temperature increases to 40 °C, but if the temperature increases to 80 °C, the material begins to convert from ductility to brittleness. On a macro level, this transformation results in the acceleration or retardation of creep failure.

5. Model characteristics

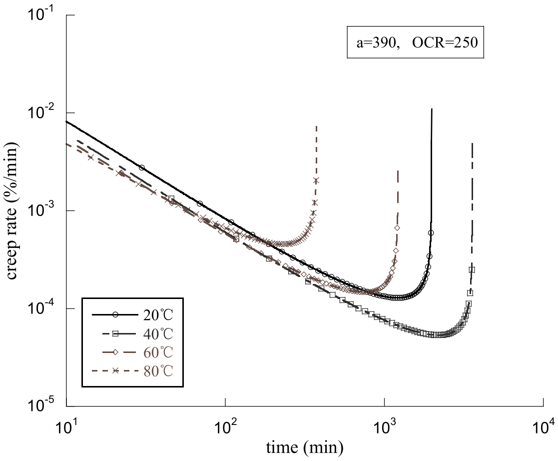
In the newly proposed model, the parameters a and ρ are crucial factors for determining the creep failure of soft rock under various thermal situations. This section mainly performs a parametric analysis on these two parameters to evaluate the model-based thermomechanical behaviors. Details of the parameters can be found in Table 5.

As a reference, case 1 in Fig. 6a shows a study that was simulated by the parameters applied in the testing calculation presented in Fig. 6. In case 2, parameter a, which is used to control the evolution rate of ρ, was decreased at a certain extent.

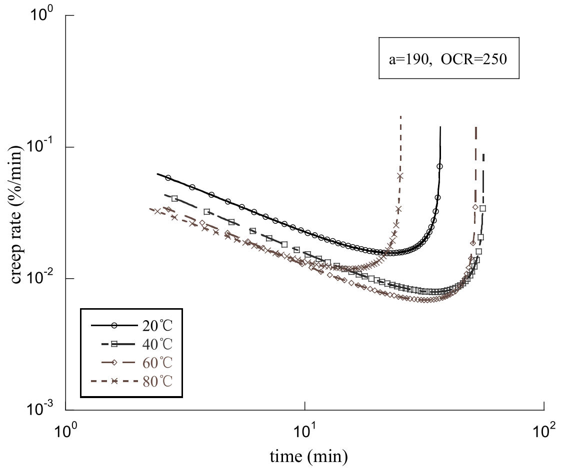
Compared with case 1, a much more obvious “heat-increase” phenomenon was observed. When the temperature was 60 °C, there is a decrease in the failure time. However, at a temperature of 60 °C, it would take a longer time before the sample encounters a failure than for a temperature of 20 °C. Additionally, when the elevation depends on the value of a, case 3 gives a much more regular pattern. Because the heat increase is the secondary consolidation, creep failure occurs earlier, which agrees with the results of Shimizu [21].

Cases 4 and 5 investigate the influence of the *OCR* on the thermomechanical behaviors. At a low *OCR*, a “heat-decrease” phenomenon can be observed directly, as in case 3. In contrast, a totally opposite tendency can be revealed when the *OCR* has a large value. In case 5, as the temperature increases, failure occurs more slowly. This regular tendency is also observed in Okada [12].

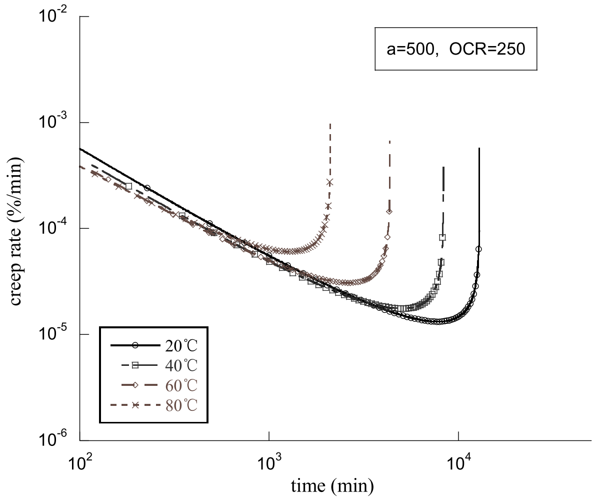
In this present work, it can be observed that the model was able to describe different phenomena of heat-induced behaviors. The creep failure procedure did not depend on the temperature but on the geomaterials themselves. When the parameter a was small, the thermomechanical behavior of soft rock was complicated, and an optimum temperature could be observed. If a was large or if the *OCR* value was small, the regular pattern can be generalized by a “heat-decrease” tendency. Reversely, a “heat-increase” trend can be obtained at a high *OCR*.



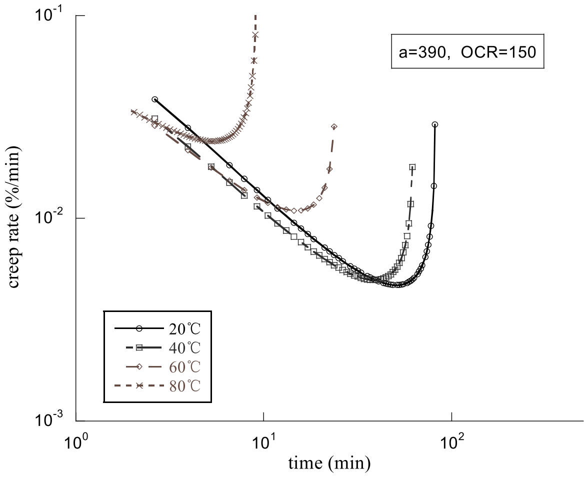
(a) Case 1. Numerical results in accordance with the testing outcome for reference.



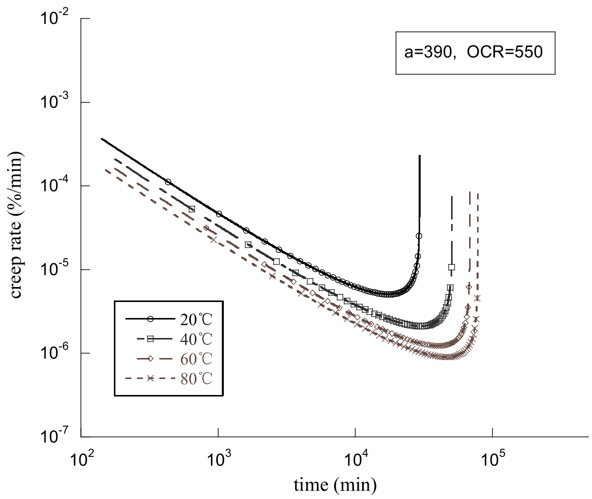
(b) Case 2. Results at a low level of *a*.



(c) Case 3. Results at a high level of *a*.



(d) Case 4. The results at a low *OCR* value.



(e) Case 5. The results at a high *OCR* value.

Fig. 6. Influence of the parameters on the mechanical behavior of the geomaterial.

6. Conclusions

As the long-term mechanical behavior of soft rock is sensitive to a temperature change, it is important to understand and improve the modeling of such behavior. Within the framework of continuum mechanics, a thermo–visco-elastoplastic model is proposed based on the sub-loading Cam-clay model. This model considers the thermal effect by including an equivalent stress, which can be induced by the $\ln p - e$ relationship. Compared with the existing models, the proposed model has an advantage in predicting the dual effect of temperature on creep failure progress. In addition, the fact that less parameters are involved in formulas makes the model easier for application.

A few laboratory tests on Tage stone have been performed to validate the proposed model. The results show that a heat increase would either accelerate or retard the failure of creep. Particularly, this opposite effect of temperature would exist in a specific test because of the present creep stress. In this sense, the stress and temperature are coupled in affecting the failure procedure; these two factors should not be separated in such research. Compared with the experimental results, the theoretical results match the tests well and could also be applied to other experimental results. Both the theoretical and trial results show that there is an optimal temperature subjected to a specific stress state.

The characteristics of the newly proposed model are analyzed. It can be concluded that the “heat-decrease” and “heat-increase” phenomena are related with the material parameters, namely, a and *OCR*. With the specific values of these two parameters, the model can describe the different phenomena of heat-induced behaviors. Moreover, the mechanism of this phenomenon can be ascribed to the transformation between the brittleness and ductility of the material. However, this paper does not pay enough attention to this aspect, and a further study should be conducted on this specific mechanism.

In the present work, the stress state is found to be a key factor in determining whether creep failure of soft rock is accelerated or retarded by a heat increase. But it should be noted that the influence of temperature is also related to the physicochemical properties of the geomaterial. For example, a heat increase in a frozen soil generally leads to more creep deformation, and no dual effects can be detected [22]. A further study on creep properties for different geomaterials is still in need.

Acknowledgements

This research is supported by the National Basic Research Program of China (2014CB047001) and by the Project of Innovation-driven Plan of Central South University (2015CX018).

References

[1] R.G. Campanella, J.K. Mitchell, Influence of temperature variations on soil behavior, J. Soil Mech. Found. Eng. Div. 94 (3) (1968) 709–734.
[2] P. Delage, N. Sultan, Y.J. Cui, On the thermal consolidation of Boom clay, Can. Geotech. J. 37 (2) (2000) 343–354.
[3] X. Gao, C. Yang, W. Wu, et al., Experimental studies on temperature dependent properties of creep of rock salt, Chin. J. Rock Mech. Eng. 24 (12) (2005) 2054–2059 (in Chinese).
[4] T. Hueckel, B. Francois, L. Laloui, Explaining thermal failure in saturated clays, Geotechnique 59 (3) (2009) 197–212.
[5] L. Laloui, H. Modaressi, Modelling of the thermo–hydro-plastic behaviour of clays, in: N. Hoteit (Ed.), Hydromechanical and Thermohydromechanical Behaviour of Deep Argillaceous Rock, Balkema, Rotterdam, The Netherlands, 2002, pp. 161–170.
[6] Y. Xiong, S. Zhang, G. Ye, F. Zhang, Modification of thermo–elasto-viscoplastic model for soft rock and its application to THM analysis on heating tests, Soil Found. 54 (2) (2014) 176–196.
[7] Y. Yao, W. Hou, A. Zhou, UH model: three-dimensional unified hardening model for overconsolidated clays, Geotechnique 59 (5) (2009) 451–469.
[8] A. Yashima, S. Leroueil, F. Oka, et al., Modelling temperature and strain rate dependent behavior of clays: one-dimensional consolidation, Soil Found. 38 (2) (1998) 63–73.
[9] D. De Bruyn, J.F. Thimus, The influence of temperature on mechanical characteristics of Boom clay: the results of an initial laboratory programme, Eng. Geol. 41 (1) (1996) 117–126.
[10] K. Shibata, K. Tani, T. Okada, Creep behavior of tuffaceous rock at high temperature observed in unconfined compression test, Soil Found. 47 (1) (2007) 1–10.
[11] Y.J. Cui, T.T. Le, A.M. Tang, et al., Investigating the time-dependent behaviour of Boom clay under thermomechanical loading, Geotechnique 59 (2009) 319–329.
[12] T. Okada, Mechanical Properties of Sedimentary Soft Rock at High Temperature. Part 2. Evaluation of Temperature Dependency of Creep Behavior Based on Unconfined Compression Test, Central Research Institute of Electric Power Industry, Chiba, Japan, 2006 (in Japanese).
[13] Y.J. Cui, N. Sultan, P.A. Delage, Thermomechanical model for saturated clays, Can. Geotech. J. 37 (3) (2000) 607–620.
[14] J. Graham, N. Tanaka, T. Crilly, et al., Modified Cam–Clay modelling of temperature effects in clays, Can. Geotech. J. 38 (3) (2001) 608–621.
[15] S. Zhang, F. Zhang, A thermo–elasto-viscoplastic model for soft sedimentary rock, Soil Found. 49 (4) (2009) 583–595.
[16] S. Zhang, W.M. Leng, F. Zhang, et al., A simple thermo-elastoplastic model for geomaterials, Int. J. Plast. 34 (2012) 93–113.
[17] H. Modaressi, L. Laloui, A thermo–viscoplastic constitutive model for clays, Int. J. Numer. Anal. Methods Geomech. 21 (5) (1997) 313–335.
[18] Y. Xiong, G. Ye, H. Zhu, S. Zhang, F. Zhang, Thermo-elastoplastic constitutive model for unsaturated soils, Acta Geotech. (2016), accepted.
[19] K. Hashiguchi, Elasto-plastic constitutive laws of granular materials, in: S. Murayama, A.N. Schofield (Eds.), Constitutive Equations of Soils, in: Proc. 9th Int. Conf. Soil Mech. Found. Eng., Spec. Session 9, Tokyo, JSSMFE, Tokyo, 1977, pp. 73–82.
[20] F. Zhang, A. Yashima, T. Nakai, et al., An elasto-viscoplastic model for soft sedimentary rock based on tij concept and subloading yield surface, Soil Found. 45 (1) (2005) 65–73.
[21] M. Shimizu, Quantitative assessment of thermal acceleration of time effects in one-dimensional compression of clays, in: Deformation Characteristics of Geomaterials, in: Proceedings of the Third International Symposium on Deformation Characteristics of Geomaterials, IS Lyon, Lyon, France, 22–24 September, 2003, pp. 479–487.
[22] W. Ma, Z. Wu, Y. Sheng, Creep and creep strength of frozen soil, J. Glaciol. Geocryol. 16 (2) (1994) 113–118 (in Chinese).