Influence of temperature and load on creep characteristics of soft rock similar materials

Jianguang Li, Gengyu Sun*, Huisong Zou, Ziyi Zhou and Xiyan Fan
School of Qingdao University of Science and Technology, Qingdao, China

*Corresponding author e-mail:652613157@qq.com

Abstract. The soft rock specimens were prepared by using similar materials. The uniaxial creep experiments were carried out on the soft rock specimens under different temperatures and loads. The influence of temperature and load on the creep of similar soft rock and the empirical equation were obtained. The results show that the stress-strain curve is basically linear at normal temperature. As the temperature increases, the stress-strain curve continually shifts upward. As the temperature increases and the creep time increases, the average creep modulus of similar materials in soft rock decreases. As the axial pressure increases, the creep strain deformation increases continuously, and the larger the axial pressure, the more significant the creep strain changes. Through the analysis of the creep curve law, the empirical equations of three types of creep curves are given.

1. Introduction
The stability problem of soft rock engineering has always been one of the major problems that plague China's coal mine production and construction. As the depth of mining increases year by year, the problem of roadway support is becoming more and more serious [1-4]. Foreign scholars N.L.Carter and Vouille [5] studied the creep deformation of granite and salt rock under different temperatures. Zhang Lianying [6] established a creep constitutive model of mudstone considering temperature. The model established by Gao Feng [7] reflects the viscoelastic-plastic and damage properties of rock under temperature. On the whole, temperature and load have a great influence on the mechanical properties of similar materials in soft rock [8-10]. Taking soft rock similar materials as the research object, it can better reflect the deformation characteristics of soft rock prototypes, and has important reference significance for soft rock engineering.

2. Experimental content
2.1. Test piece preparation
In this paper, paraffin, river sand, iron powder and gypsum were used as raw materials to prepare similar soft rock specimens simulating soft rock. After a large number of different proportioning experiments, it was finally determined that the ratio of the raw materials was 1:6:1:1. The test pieces are numbered for testing after being filled, compacted, demolded, and cured.
2.2. Experimental program
This paper uses TAW-200 multi-functional material mechanics testing machine as the loading and control device. The high and low temperature environment test chamber developed by the Mechanics Research Center of Qingdao University of Science and Technology provides high and low temperature environment for the experiment. The experimental equipment is shown in Figure 1. This paper adopts a grading loading experimental scheme, which can avoid the influence of discrete factors in the preparation and curing process of the specimen.

![Laboratory equipment.](image)

Assuming that the rock mass is a linear viscoelastic element, ignoring its nonlinear characteristics, then setting the loading load will present different creep modes. The load at different temperatures was graded on similar test pieces as shown in Table 1. To eliminate the effects of mechanical errors, a low pressure prestress of 100 N was applied to similar specimens in advance. The soft rock similar test piece has a single stage loading time of 2 hours.

| loading method          | temperatures /℃ | load/MPa     |
|-------------------------|-----------------|--------------|
| gradation loading       | 10              | 1, 1.5, 2, 2.5|
|                         | 20              | 1, 1.5, 2, 2.5|
|                         | 30              | 1, 1.5, 2, 2.5|
|                         | 40              | 0.25, 0.5, 0.75, 1|
|                         | 50              | 0.15, 0.2, 0.25, 0.3, 0.35|
|                         | 60              | 0.1, 0.15, 0.2|

3. Experimental results and analysis

3.1. Effect of axial compression on creep properties of soft rock similar materials
It can be seen from Fig. 2 that under various temperature conditions, the creep strain deformation of soft rock similar specimens increases with the increase of axial pressure, and the larger the axial pressure, the more significant the creep strain changes. At 10 °C, the creep curve exhibits decelerating creep and stable creep under the action of various axial loads. When the temperature rises to 50 °C, similar soft rock exhibits obvious accelerated creep law only when the axial load is 0.35Mpa. Under low axial pressure, the creep deformation of similar soft rock remains basically constant after a certain period of time. At this time, the creep rate can be characterized by a stable creep rate, and the stable creep rate increases as the applied axial pressure increases.
Figure 2. Creep curves of similar soft rock at different temperatures and loads.

3.2. Effect of temperature on creep characteristics of soft rock similar materials

Figure 3 is a stress-strain curve of a soft rock similar specimen subjected to creep for 1 hour at different temperatures. It can be seen that the stress-strain curve is substantially linear at temperatures of 20°C and below, and the temperature has little effect on the stress-strain relationship. As the temperature continues to rise, the stress-strain curve continues to shift upwards, and the higher the temperature, the greater the magnitude of the offset. In order to reflect the influence of temperature on the creep deformation ability of soft rock similar materials, the reciprocal of the slope of the straight line segment
defining the stress-strain curve is the average creep modulus. As shown in Figure 4, as the temperature increases, the average creep modulus decreases, and this tendency to decrease is particularly evident between 30 °C and 40 °C. It can be seen from the experiment that the soft rock similar materials will have large deformation and creep damage in a short time under high temperature and low stress level. With this feature, high temperature and short time creep can be used to characterize low temperature and long time creep. The situation is changed, and the experimental period of the indoor model experiment is greatly shortened.

![Figure 3. Creep stress-strain curves of similar soft rock at different temperatures (1h)](image)

![Figure 4. The average creep modulus varies with temperature (1h)](image)

It can be seen from Fig. 5 that the stress-strain isochronous curve of soft rock similar material is slightly convex at normal temperature, that is, the similar material of soft rock is compacted at normal temperature. At high temperatures, even if the stress level is very low, the convex curvature of the stress-strain curve is still small, and the high temperature makes the soft rock similar material have no obvious compaction stage during the creep process. In addition, under high temperature environment, the creep strain of soft rock similar materials is significantly higher than the normal temperature state. As the creep time increases, the average creep modulus of similar materials in soft rock continues to decrease, as shown in Figure 6.

![Figure 5. Creep stress-strain curves of similar soft rock at different moments and different temperature](image)

(a) 20°C  
(b) 60°C
3.3. Effect of temperature on creep characteristics of soft rock similar materials

There are currently three types of empirical formulas for rock creep:

1. Power function type whose expression is:

\[ \varepsilon(t) = At^n \]  \hspace{1cm} (1)

In the formula, A and n are constants, and the size depends on the stress level, material properties, and temperature conditions.

2. Logarithmic type, whose expression is:

\[ \varepsilon(t) = \varepsilon_0 + B\varepsilon t + Ct \]  \hspace{1cm} (2)

In the formula, \( \varepsilon_0 \) is the instantaneous elastic strain; B and C are constants related to the material properties and experimental conditions.

3. Exponential type, whose expression is:

\[ \varepsilon(t) = A(1 - \exp[f(t)]) \]  \hspace{1cm} (3)

In the formula, A is the experimental constant; f(t) is a function of time t.

Through the analysis of the experimental data, it can be found that the creep process of similar materials in soft rock meets the following rules: creep of similar materials in soft rock when the similar specimens of soft rock are at very low stress and low temperature (below room temperature below 20 °C) The curve only undergoes the decay creep phase and can be fitted by the attenuation exponential equation function. When the soft rock similar specimen is in the lower stress and a certain temperature range, the creep curve of the soft rock similar material contains the decay creep phase and the like. In the fast creep phase, the logarithmic curve can be fitted at this time; when the similar specimens of soft rock are subjected to higher stress and higher temperature, the creep curve of similar materials of soft rock contains decelerating creep phase and accelerated creep. At this stage, you can fit with a power function equation. Taking the creep curves of soft rock similar specimens at 60 °C and different stresses as an example, three different empirical equations for soft rock similar materials under different stress levels are obtained by parameter fitting method, as shown in Fig. 7 and Table 2.
Figure 7. Three different types of empirical equations and experimental data fitting curves.

| Temperature/°C | Load /MPa | Equation form | Parameter | Correlation coefficient |
|----------------|-----------|---------------|-----------|-------------------------|
| 60             | 0.10      | \(\varepsilon = a \exp\left(-\frac{t}{b}\right) + c\) | -0.01938  | 0.65289 0.02219       | 0.99038       |
|                | 0.15      | \(\varepsilon = a - b \ln(t + c)\) | 0.02832   | -0.0035 0.10753       | 0.9915        |
|                | 0.20      | \(\varepsilon = \frac{1}{(a + bt^{c-1})}\) | 32.64165  | -8.96947 1.53762       | 0.99883       |

4. Conclusion
Based on the theory of rock rheology, combined with the uniaxial compression multi-stage creep experiment at six temperature conditions from 10 °C to 60 °C, the effects of different temperatures and loads on the creep of similar materials in soft rock are obtained. Through the analysis of the creep curve law in the experiment, the empirical equations of three kinds of creep curves are given, which have important reference value for soft rock engineering.

Acknowledgments
This work was financially supported by the Natural Science Foundation of Shandong Province (ZR2019MEE082).

References
[1] Manchao He, Heping Xie, Suping Peng, et al. Study on rock mechanics in deep mining[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16): 2803-2813.
[2] Zhaoping Meng, Mingsheng Li, Pengqing Lu, et al. Temperature and pressure under deep conditions and their influences on mechanical properties of sandstone[J]. Journal of Rock Mechanics and Engineering, 2006, 25(6): 1177-1181.
[3] Yanchun Wang. Study on creep law of deep soft rock under thermal-mechanical-chemical coupling effect[D]. Qingdao: Qingdao University of Science and Technology, 2013.
[4] Mingming Tang, Zhiyin Wang, Yili Sun, et al. Experimental study of mechanical properties of granite under low temperature[J]. Journal of Rock Mechanics and Engineering, 2010, 29(4): 787-794.
[5] Carter N L. Mechanical and transport properties of rocks at high temperatures and pressures. task I. the physical nature of fracturing at depth[R]. [s.l.]: [s.n.], 1981.
[6] Lianying Zhang, Xianbiao Mao, Aihong Lu. Experimental study on mechanical properties of rock under high temperature[J]. Chinese Science: Technical Science, 2010, 02: 1674-7259.
[7] Feng Gao, Xiaoli Xu, Xiaojun Yang, et al. Research on thermo-visco-elastoplastic model of rock[J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(1): 74-80.
[8] Huiting Zhang, Yongsheng Zhou, Wenming Yao, et al. Experimental study on the rheolody of natural granulite at high temperature[J]. Chinese Journal of Geophysics, 2016, 59(11): 4188-4198.

[9] Ning Zhang. Research of ceep-penetration-thermal cracking of granite under high temperature and extraction of geothermal energy[D]. Taiyuan: Taiyuan University of Technology, 2013.

[10] Liang Chen, Jianfeng Liu, Chunping Wang, et al. Creeping behavior of beishan granite under different temperatures and stress conditions[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(6): 1228-1235.