Experimental research on creep behaviors of sandstone under uniaxial compressive and tensile stresses

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Abstract: The consideration of time dependence is essential for the study of deformation and fracturing processes of rock materials, especially for those subjected to strong compressive and tensile stresses. In this paper, the self-developed direct tension device and creep testing machine RLW-2000M are used to conduct the creep tests on red sandstone under uniaxial compressive and tensile stresses. The short-term and long-term creep behaviors of rocks under compressive and tensile stresses are investigated, as well as the long-term strength of rocks. It is shown that, under low-stress levels, the creep curve of sandstone consists of decay and steady creep stages; while under high-stress levels, it presents the accelerated creep stage and creep fracture presents characteristics of brittle materials. The relationship between tensile stress and time under uniaxial tension is also put forward. Finally, a nonlinear viscoelastoplastic creep model is used to describe the creep behaviors of rocks under uniaxial compressive and tensile stresses.

Key words: laboratory test; creep behaviors; uniaxial compressive and tensile stresses; creep model

1 Introduction

In most cases, rocks bear compressive stress but less tensile stress. Therefore, in the field of rock mechanics, there are various experimental and theoretical results about rocks subjected to compressive stress [1–8], but fewer results about rocks subjected to tensile stress. However, many problems in deformation and damage of rock fracture under tensile stress are encountered. In geotechnical engineering, the stability of structures may be controlled by the tensile zone if existing, such as large cavity roof and floor, mining engineering tunnel, the stability of slope roof, and so on. These all may be dominated by the tensile stress. The tensile stress after excavation of rocks will not cause instability immediately, and the instability will exist in a certain period of time [9]. Thus, it has great theoretical and practical significances for studying the creep behaviors of rocks under compressive and tensile stresses.

Currently, there are relatively few achievements on tensile behaviors, and most of them are concentrated on tensile strength and constitutive relationship [10–12], but research on tensile creep is rare. Zhou [13] introduced the method of creep test on rocks under uniaxial tension. The results of creep tests on 10 kinds of rocks were discussed, and the variant creep compliance was proposed to describe the nonlinear creep behaviors of rocks. Chen and Sun [14] used direct tensile method to conduct tensile and tensile-creep fracture tests on red sandstone. A creep fracture criterion was established, and rheological parameters were discussed. Wang et al. [9] conducted the finite element analysis by using rigidity-variable method, and deduced related formulae followed by an example, simulating the process of tensile rheological destabilization during the first weighting of roof rock beam due to excavation.

On the basis of previous analyses of compressive and tensile creep tests, a typical red sandstone is selected to conduct the uniaxial compressive and tensile creep tests by using the self-developed direct tension device and creep testing machine RLW-2000M.
The creep behaviors of sandstone under uniaxial compressive and tensile stresses are investigated. Finally, a nonlinear viscoelastoplastic creep model is proposed to describe the creep behaviors of sandstone under uniaxial compressive and tensile stresses.

2 Sample preparation

The typical red sandstone taken from Shapingba District, Chongqing, China is selected as the study sample. A rectangular block of 147 mm×273 mm×484 mm is drilled in laboratory. The red sandstone block containing coarse particles is homogeneous and compacted without visible cracks, and its density is 2380 kg/m³. Rock samples are drilled along the same direction to avoid the anisotropic effect on the mechanical properties of rock specimens. According to the International Society of Rock Mechanics (ISRM) testing procedures, two standard cylindrical specimens of φ 30 mm×60 mm and φ 50 mm×100 mm are prepared. Part of the rock specimens are shown in Fig.1. Among them, the specimens of φ 50 mm are for compression tests, while those of φ 30 mm are for tension tests.

3 Short-term compressive creep test

3.1 Testing machine and procedure

The creep testing machine RLW-2000M was manufactured by Chaoyang Instrument Factory, Changchun, China. Its maximum axial load is 2000 kN, and the maximum confining pressure is 80 MPa. Its loading error is less than 200 N, about 0.01% of the maximum axial force.

The testing procedure can be described as follows: (1) Firstly, the specimen is placed and extensometers are installed. (2) Secondly, different stress levels are loaded at a rate of 0.5 MPa/s, and each stress level is kept constant for several hours.

3.2 Test results

It can be observed from Figs.2 and 3 that, under low-stress levels, the creep curves of rock samples consist of decay and steady creep stages; while under high-stress levels, accelerated creep stage is observed, and creep failure has characteristics of brittle materials. Along the axis of sandstone specimens, there are several failure surfaces. Under the uniaxial compressive stress of 28.03 MPa, the decay creep of red sandstone lasts for 0.93 hour and then enters the steady creep stage. In the steady creep stage, the creep rate becomes steady, which is 9×10⁻⁴ per hour. Under the uniaxial compressive stresses of 33.63, 39.24 and 44.84 MPa, the creep curves have the same tendency. Under the uniaxial compressive stress of 50.45 MPa, the accelerated creep stage is observed, and the whole creep at this stress level lasts for 26.3 minutes, including 3.5 minutes of decay creep stage, 18 minutes of steady creep stage, and 4.8 minutes of accelerated creep stage. The brittle fracture process of sandstone can be seen along the axial direction, as shown in Fig.4.

![Fig.2 Creep curves of sandstone under different uniaxial compressive stresses.](image)

![Fig.3 Curves of creep and creep rate of sandstone under uniaxial compressive stress of 50.45 MPa.](image)
4 Uniaxial tensile creep test

4.1 Direct tensile device

The uniaxial tensile creep test is conducted by using the self-developed hanging weight loading device, as shown in Fig. 5. In the device, the high-strength resin is used to bond the specimen at two ends of the puller. The puller and the bearing member with a rolling ball are linked by high-strength nut that forms a connecting device, as shown in Fig. 5(b). The rolling ball can better eliminate bias stress. The load is applied to specimen through putting weights in the bucket at the bottom of the device. Four strain gauges are stuck on the central symmetrical specimens, and the static strain measurement system XL3403B5T is used to measure the strain of specimen.

4.2 Short-term creep test results

The short-term creep test results are shown in Figs. 6 and 7. It seems that the uniaxial tensile creep curves of sandstone are similar to the uniaxial compressive creep curves, i.e. under low-stress levels, the creep curves of sandstone consist of decay and steady creep stages, while under high-stress levels, the accelerated creep stage appears. At the 1st stress level of tensile stress (0.43 MPa), the creep curve of specimen turns into the steady creep stage after the decay creep for 3.42 hours. At this stress level, the total axial strain of sandstone is $1.28 \times 10^{-4}$, and the creep strain is $3.2 \times 10^{-5}$, which is 25% of the total axial strain. Under high-stress levels, the sandstone often shows accelerated creep, and the creep rate increases rapidly. At the 5th stress level of tensile stress (1.26 MPa), the creep curve of specimen turns into the steady creep stage after decay creep for 0.44 hour. In this stage, the axial creep rate remains at about $4.5 \times 10^{-4}$ per hour. After 1.77 hours, the creep rate increases rapidly and the accelerated creep appears, and after 0.2 hour the specimen fails. Under the tensile stress, a nearly horizontal failure surface can be found at the central position of the specimen, and it shows the fracture characteristics of brittle materials, as shown in Fig. 8.
4.3 Long-term creep test results

Figure 9 shows the creep test curves of specimen No.5 under two tensile stresses of 0.62 and 0.83 MPa, with loading times of 297.6 and 185.7 hours, respectively. It can be seen from Fig.9 that, under the tensile stress of 0.62 MPa, the creep rate tends to be constant after 61 hours. The transient strain of the specimen No.5 is $4.23 \times 10^{-4}$, and the total strain is $5 \times 10^{-5}$. The creep strain is 40.54% of the total strain. Under the tensile stress of 0.83 MPa, the transient strain appears first, then the creep curve turns into the decay creep stage, which lasts for nearly 40 hours. The decay creep strain is about $2.49 \times 10^{-4}$. The curve turns into the steady creep stage after nearly 91.28 hours. Therefore, the specimen No.5 shows an accelerated creep stage. Unlike the short-term creep, the accelerated creep stage of long-term creep curve lasts for about 54.42 hours. The curves of creep and creep rate of specimen No.5 under this tensile stress level are shown in Fig.10. Failure of specimens under long-term creep stress is shown in Fig.11, which is similar to the failure of short-term creep.

4.4 Discussion on long-term tensile strength

During the creep tests, it can be found that the applied tensile stress that makes the red sandstone fractured is 0.83 MPa, only 47.43% of the tensile strength of red sandstone. According to the relationship between the creep tensile stress $\sigma$ and time $t$, the long-term tensile strength of red sandstone is fitted below (Fig.12), with a correlation coefficient $R$ of more than 0.62:

$$\sigma = 0.83 + 0.27e^{-2t/20.54}$$

(1)

5 Nonlinear viscoelastoplastic creep model for rocks

From the above analyses, in the whole creep process of sandstone under uniaxial compressive and tensile stresses, several conclusions can be drawn as follows: (1) Once the axial stress is applied, the sandstone will immediately produce transient elastic strain, so the elastic component should be included in creep model. (2) The creep strain of sandstone increases with time, thus creep model should also include a viscous component. (3) Under high-stress levels, the creep strain increasing with time does not converge at a certain value, but an acceleration phase appears. Thus, we can use the nonlinear viscoelastoplastic model to characterize the whole creep curve of sandstone under uniaxial compressive and tensile stresses. Creep models such as traditional Burgers model can reflect the low-stress level of creep behaviors of rocks, but cannot fully reflect the creep acceleration of rocks. So a new nonlinear viscoelastoplastic creep model for tensile and compressive creep behaviors should be built.

5.1 Viscoplastic model

In the traditional creep models, the viscous component is usually represented by an ideal viscous Newtonian fluid body, in which viscosity is consider to be a constant value. Such a model cannot describe the accelerated creep stage. Creep of rock materials will occur under long-term loadings. When the creep curve turns into the accelerated stage, the accelerated creep rate will increase gradually with time and stress. Sun
analyzed a large number of creep test data and believed that, when the applied stress is greater than the long-term strength \( \sigma_\infty \), the viscosity decreases continuously, and the decrease tendency is related to the stress levels. At the same time, the greater the applied stress is, the smaller the viscosity coefficient will be.

In this paper, a nonlinear viscoplastic model is proposed (Fig.13) and expressed as

\[
\varepsilon(t) = \frac{H(\sigma - \sigma_\infty)}{\eta(n, t)} t = \frac{H(\sigma - \sigma_\infty)}{\eta_0} t^{n+1} = \frac{H(\sigma - \sigma_\infty)}{\eta_0} t^n
\]

where \( \varepsilon(t) \) is the creep strain of nonlinear viscoplastic body; \( n \) is the accelerated creep index; \( t_0 \) is the unit time; \( \eta(n, t) \) is the nonlinear viscosity component; \( \eta_0 \) is the original nonlinear viscosity component when the accelerated creep appears; and the function of \( H(\sigma - \sigma_\infty) \) is

\[
H(\sigma - \sigma_\infty) = \begin{cases} 
0 & (\sigma \leq \sigma_\infty) \\
\sigma - \sigma_\infty & (\sigma > \sigma_\infty) 
\end{cases}
\]

Fig.13 Nonlinear viscoplastic body.

5.2 Nonlinear viscoelastoplastic creep model

Connection of nonlinear viscoplastic model with the Burgers creep model in series forms a nonlinear viscoelastoplastic creep model, as shown in Fig.14. It can be used to describe the whole creep process of rocks under uniaxial tensile or compressive stress.

\[
\sigma \rightarrow E_M \rightarrow \eta_M \rightarrow \eta_K \rightarrow \varepsilon \rightarrow \sigma
\]

Fig.14 Nonlinear viscoelastoplastic creep model.

When the stress level is lower than the long-term strength \( \sigma_\infty \) (for short-term compressive creep, it can be replaced by yield stress), the nonlinear viscoplastic body has no effect on the creep model, the model is actually the Burgers model, and the corresponding state can be described as

\[
\begin{align*}
\sigma &= \sigma_M = \sigma_K \\
\varepsilon &= \varepsilon_M + \varepsilon_K \\
\dot{\varepsilon}_M &= \dot{\varepsilon}_M / E_M + \sigma_M / \eta_M \\
\sigma_K &= E_k \varepsilon_K + \eta_k \dot{\varepsilon}_K \\
\varepsilon_N &= \sigma_n + \eta(n, t) \dot{\varepsilon}_N
\end{align*}
\]

where \( \eta_M \) and \( \eta_K \) are the viscosity coefficients of Maxwell body and Kelvin body, respectively; \( \sigma_M \) and \( \sigma_K \) are the stresses of Maxwell body and Kelvin body, respectively; \( \sigma_M \) is the stress rate of Maxwell body; \( \varepsilon_M \) and \( \varepsilon_K \) are the creep strains of Maxwell body and Kelvin body, respectively; \( \dot{\varepsilon}_M \) and \( \dot{\varepsilon}_K \) are the creep strain rates of Maxwell body and Kelvin body, respectively.

The corresponding creep equation is

\[
\varepsilon = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M} t + \frac{\sigma}{E_K} \left[ 1 - \exp\left( \frac{E_K t}{\eta_K} \right) \right] + \frac{\sigma - \sigma_\infty}{\eta_n} t^n
\]

When the stress level is higher than the long-term strength \( \sigma_\infty \), the nonlinear viscoplastic model plays an important role in the accelerated creep stage, and the corresponding state can be described as

\[
\begin{align*}
\sigma &= \sigma_M = \sigma_K = \sigma_N \\
\varepsilon &= \varepsilon_M + \varepsilon_K + \varepsilon_N \\
\dot{\varepsilon}_M &= \dot{\varepsilon}_M / E_M + \sigma_M / \eta_M \\
\sigma_K &= E_k \varepsilon_K + \eta_k \dot{\varepsilon}_K \\
\sigma_N &= \sigma_n + \eta(n, t) \dot{\varepsilon}_N
\end{align*}
\]

where \( \sigma_N \) is the stress of nonlinear viscoplastic body; \( \varepsilon_N \) is the creep strain of nonlinear viscoplastic body, which is equal to \( \varepsilon(t) \); and \( \dot{\varepsilon}_N \) is the creep strain rate of nonlinear viscoplastic body.

The corresponding creep equation is

\[
\varepsilon = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M} t + \frac{\sigma}{E_K} \left[ 1 - \exp\left( \frac{E_K t}{\eta_K} \right) \right] + \frac{\sigma - \sigma_\infty}{\eta_n} t^n
\]

6 Verification and parameter identification

Based on the BFGS algorithm [16], the uniaxial compressive and tensile creep test curves of red sandstone are fitted with the nonlinear viscoelastoplastic creep model, and the parameters are listed in Table 1. Through analyzing the fitting parameters, it can be found that the correlation coefficient \( R \) approaches 1, showing a higher fitting accuracy. It also can be found that the tensile creep parameters are one-third of compressive creep parameters, or even
Table 1 Parameters identification of nonlinear viscoelastoplastic creep model for specimen No.1.

<table>
<thead>
<tr>
<th>Test category</th>
<th>Test characteristics</th>
<th>$\sigma$ (MPa)</th>
<th>$E_M$ (MPa)</th>
<th>$\eta_M$ (MPa·h)</th>
<th>$E_K$ (MPa)</th>
<th>$\eta_K$ (MPa·h)</th>
<th>$\eta_N$ (MPa·h)</th>
<th>$n$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile creep test</td>
<td>0.43</td>
<td>4 133.29</td>
<td>947 869.39</td>
<td>24 206.07</td>
<td>28 149.65</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>5 334.34</td>
<td>393 803.42</td>
<td>9 010.15</td>
<td>1 619.71</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.99</td>
<td>4 289.43</td>
<td>404 149.27</td>
<td>9 252.34</td>
<td>350.33</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.14</td>
<td>2 914.86</td>
<td>401 173.96</td>
<td>19 322.03</td>
<td>4 147.79</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.26</td>
<td>2 248.66</td>
<td>65 030.8</td>
<td>23 813.85</td>
<td>3 415.99</td>
<td>3.2×10¹²</td>
<td>20.87</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Compressive creep test</td>
<td>28.03</td>
<td>14 010.79</td>
<td>2 224 603.18</td>
<td>427 286.59</td>
<td>54 239.60</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.63</td>
<td>14 276.01</td>
<td>4 472 044.73</td>
<td>479 059.83</td>
<td>118 797.35</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>39.24</td>
<td>14 696.63</td>
<td>1 933 004.93</td>
<td>503 722.72</td>
<td>85 110.73</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>44.84</td>
<td>14 709.84</td>
<td>2 989 333.33</td>
<td>360 450.16</td>
<td>214 119.06</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50.45</td>
<td>15 479.31</td>
<td>159 208.46</td>
<td>237 739.71</td>
<td>9 200.14</td>
<td>0.263</td>
<td>14.51</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

lower, which means that focus must be put on the zones controlled by tensile stress in construction or design of geotechnical engineering.

Figure 15 shows the comparisons of test curves with theoretical curves for the uniaxial compressive and tensile creep tests under the stresses of 1.26 and 50.45 MPa, respectively. From the fitting results, the test curves agree well with the theoretical curves, indicating that the nonlinear viscoelastic-plastic creep model can reflect the whole creep process of sandstone in uniaxial tensile and compressive creep tests. Especially, it can better reflect the accelerated creep stage. The results also show that the proposed nonlinear viscoelastic-plastic creep model is reasonable.

7 Conclusions

The uniaxial compressive and tensile creep laws of typical red sandstone obtained from Chongqing are studied by using the self-developed direct tension device and creep testing machine RLW-2000M. Based on the BFGS algorithm, the nonlinear viscoelastic-plastic creep model is built up, and the test results are fitted. The conclusions are drawn as follows:

1. It seems that the tensile creep curve of sandstone is similar to the uniaxial compressive creep curve, i.e. at low tensile stress levels, the creep curve of sandstone consists of the decay and steady creep stages, while at high tensile stress levels, the accelerated creep stage occurs.

2. The duration of accelerated creep stages in short-term uniaxial compressive and tensile creep tests is very short, while that in long-term tension tests is much longer. However, they all have characteristics of brittle materials.

3. The tensile creep parameters are one-third of compressive creep parameters, or even lower.

4. The uniaxial tensile and compressive creep test curves are in good agreement with theoretical curves, indicating that the nonlinear viscoelastic-plastic creep model can well describe the whole creep process of uniaxial tensile and compressive tests.

The results enrich the creep data of red sandstone from Chongqing, and have a positive significance for large-scale geotechnical engineering in this region.

Fig.15 Comparisons of test curve with theoretical curve for uniaxial compressive and tensile creep tests.
References


