Temperature-controlled triaxial compression/creep test device for thermodynamic properties of soft sedimentary rock and corresponding theoretical prediction

Sheng Zhang\textsuperscript{1}, Hirotomo Nakano\textsuperscript{2}, Yonglin Xiong\textsuperscript{2}, Tomohiro Nishimura\textsuperscript{2}, Feng Zhang\textsuperscript{2}\textsuperscript{*}

\textsuperscript{1} School of Civil Engineering and Architecture, Central South University, Changsha, 410083, China
\textsuperscript{2} Department of Civil Engineering, Nagoya Institute of Technology, Nagoya, 4668555, Japan

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Abstract: In deep geological disposal of high-level nuclear waste, one of the most important subjects is to estimate long-term stability and strength of host rock under high temperature conditions caused by radioactive decay of the waste. In this paper, some experimental researches on the thermo-mechanical characteristics of soft sedimentary rock have been presented. For this reason, a new temperature-controlled triaxial compression and creep test device, operated automatically by a computer-controlled system, whose control software has been developed by the authors, was developed to conduct the thermo-mechanical tests in different thermal loading paths, including an isothermal path. The new device is proved to be able to conduct typical thermo-mechanical element tests for soft rock. The test device and the related testing method were introduced in detail. Finally, some test results have been simulated with a thermo-elasto-viscoplastic model that was also developed by the authors.

Key words: temperature control; soft sedimentary rock; thermal triaxial compression test; thermal triaxial creep test

1 Introduction

It is commonly known that nuclear power is one of the most expectable energy sources to replace fossil fuels for solving the largest environmental issue in the 21st century—global warming. In fact, the nuclear electricity generation itself has the best record of any industry \cite{1}. The crucial problem, however, is the disposal of radioactive waste, especially the high-level radioactive waste, because of the facts that not only the half-decaying span of many nuclear elements is very long, but also the amount of the thermal energy generated during the radioactive decaying period is so huge. Therefore, it is natural that shielding material like rock mass for deep geological disposal should be stable in a long time under high temperature conditions. Until now, deep geological disposal is the most viable and the safest way of permanent disposal of high-level radioactive waste \cite{2}. The soft sedimentary rock is one of the most suitable host rocks for geological disposal of nuclear waste.

Therefore, it is necessary to study carefully the interacting factors related to the mechanical properties of host rock, especially the thermo-mechanical properties. Many researches have been done on this issue, among which laboratory test is the most common method. Hueckel et al. \cite{3–5} investigated the mechanical properties of soils in single and multiple heating-cooling cyclic tests. The results showed that change in temperature could generate plastic strain, depending on thermal loading path. Kato et al. \cite{6–8} conducted undrained compression tests and creep tests under different constant temperatures. From these tests, it is known that: (1) strength of soft rock decreases with increasing temperature; (2) failure pattern changes from brittle to ductile with increasing temperature; and (3) creep failure occurs more quickly as temperature increases.

Based on the conventional triaxial compression test device, a new temperature-controlled triaxial compression and creep test device, operated automatically by computer-controlled system, whose control software has been developed by the authors, was
developed for the above-mentioned tests to investigate the influence of temperature on the mechanical behaviors of soft rocks. Meanwhile, Zhang et al. [9, 10] proposed a thermo-mechanical constitutive model for soft rock. Therefore, simulation of the test results of the soft rocks was also conducted based on the proposed model.

2 Test device and specimen

Usually, a thermo-mechanical triaxial test device is developed based on the conventional triaxial compression test device. Certainly, the former is more complex than the latter because additional parts are needed in controlling temperature environment. The device should be able to deal with different thermo-mechanical loading paths, e.g. thermal loading only (Path-1), isothermal-mechanical loading (Path-2) and thermo-mechanical loading (Path-3). Path-1 represents the behavior of the tested materials subjected to a temperature variation at a constant stress. Path-2 corresponds to a mechanical loading at a given constant temperature. Path-3 includes both thermal and mechanical loadings and is the most complicated case in which the changes in stress and temperature should be controlled during test. In this paper, only the test results in Path-2 are introduced in detail because other tests are still under development.

2.1 Test device

Figure 1 shows the temperature-controlled triaxial compression and creep test device. It consists of a load controlling unit for cell pressure and axial load, and a temperature controlling unit (Fig.2). The axial load can be applied under both stress and strain controlling conditions. Under the stress loading condition, the load is applied with an actuator driven by hydraulic pressure; while under the strain loading condition, the upper loading plate is fixed and the lower platform is pushed upward by a servo-controlled motor whose speed can be controlled at any prescribed value. The axial load and cell pressure are totally controlled by computer program using Visual Basic language in Window-X operation system through an AD-DA board.

The typical uniaxial compressive strength of soft rocks 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 surface where the largest confining stress is as high as 10 MPa. Accordingly, the device in this study was designed with a maximum axial load of 50 kN and a maximum cell pressure of 10 MPa to provide a sufficient loading range for testing the soft rocks. Important measuring and controlling assemblies are listed in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Model</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-contacting sway current gap sensors</td>
<td>PU-20-038-401</td>
<td>5 mm (accuracy: 1 m)</td>
</tr>
<tr>
<td>Displacement transducer (×2)</td>
<td>TCL-20FA</td>
<td>20 mm (accuracy: 10 m)</td>
</tr>
<tr>
<td>Air pressure transducer (×2)</td>
<td>PG-10KU</td>
<td>1 MPa</td>
</tr>
<tr>
<td>Pore water pressure transducer</td>
<td>TP-HVR10MP</td>
<td>10 MPa</td>
</tr>
<tr>
<td>Cell pressure transducer</td>
<td>TP-HVR10MP</td>
<td>10 MPa</td>
</tr>
<tr>
<td>Volumetric transducer</td>
<td>DP15-28</td>
<td>25 mL</td>
</tr>
<tr>
<td>Vertical loading transducer</td>
<td>KLP-50-H10</td>
<td>50 kN</td>
</tr>
<tr>
<td>Voltage-air pressure converter (×2)</td>
<td>RT・E/P-8-2</td>
<td>1 MPa (10 V)</td>
</tr>
</tbody>
</table>

2.2 Heating system

The heating system includes a heater, a mixer and a temperature sensor that is installed within the pressure cell chamber and connected to the temperature controlling unit. The temperature controlling unit can stably adjust increasing rate of temperature by a voltage regulator. Heating of the sample is not obtained directly by a heater, but by the water within the triaxial cell chamber. To reduce the difference of temperature of the water inside the triaxial cell...
chamber, an inclined propeller (45°) was installed within the cell to keep the temperature of water distributed uniformly and quickly, as shown in Fig.3. Besides, the rotating speed of the inclined propeller is adjustable.

![Fig.3 Schematic illustration of pressure cell chamber.](image)

The temperature sensor can instantaneously feedback the temperature inside the triaxial cell to the temperature controlling unit. Meanwhile, some heat-resistant seals were also installed in the device, as shown in Fig.3. During the test, for safety, the highest temperature within the chamber was set at 90 °C.

### 2.3 Preparation of specimen

It is known that the homogeneity of the test samples is a very important factor to acquire reliable test results, especially for studying thermo-mechanical properties of soft sedimentary rocks. Meanwhile, mineral compositions of the soft rock should be stable under high temperature conditions.

Therefore, Ohya stone, a typical green tuff that is distributed widely in the northeastern part of Japan, is used as the test specimen in this experiment. The stone is a typical soft volcanic tuff formed in Miocene age, and is widely used in laboratory tests for their mechanical properties in Japan. Ohya stone is also suitable for studying the thermal properties of soft rocks because it is mainly composed of buseoksa glassy, plagioclase and quartz, with a few biotite hornblende pyroxenes. Its mineral matrix is chemically stable under high temperature conditions. Ohya stone usually has a uniaxial compressive strength of around 10 MPa, and some of its basic physical properties are given in Table 2.

<table>
<thead>
<tr>
<th>Initial void ratio e₀</th>
<th>Specific gravity of solid particles Gₛ</th>
<th>Pre-consolidation stress p’₀ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>2.51</td>
<td>15.0</td>
</tr>
</tbody>
</table>

The sampled rectangular stone block (Fig.4(a)), was immediately covered with wetted paper and then sealed with plastic bags to avoid any water evaporation. The cylindrical test specimen of Ohya stone is 100 mm in height and 50 mm in diameter, as shown in Fig.4(b). When preparing the specimen, a rock block was firstly mined at a depth of 30–60 m, at Ohya Village of Tochigi Prefecture, Japan. The block samples with the fewest crevices/pockets and with best quality were chosen. The block was then bored with a boring machine to produce a cylindrical specimen with a size of 50 mm in diameter and about 150 mm in height, as shown in Fig.5. Finally, by cutting and polishing both ends of the cylinder, the height of the triaxial specimens was adjusted to 100 mm.

![Fig.4 Soft sedimentary rock specimens (Ohya stone).](image)

![Fig.5 Process of preparing cylindrical specimens.](image)
time, its mechanical properties would be subjected to some changes due to the slaking effect. Therefore, during the process of preparing the specimen, the rock sample was kept in a wet state during temporary storage, transportation and trimming. Meanwhile, to obtain a satisfactory degree of saturation (≥95%) for the specimens in the test, saturation using vacuum pump was conducted. Due to the relatively small size of the specimens and careful treatment of avoiding any evaporation of the rock sample during its sampling, transportation and polishing, the specimens can reach almost a fully-saturated state (≥99%) after one-week vacuumizing, as shown in Fig.6. During an isothermal-mechanical loading path (Path-2), the temperature of the specimen was kept constant during the test from isotropic consolidation under a prescribed confining stress to the end of creep loading, as shown in Fig.7.

![Specimens saturation process.](image)

**Fig.6 Specimens saturation process.**

Due to the relatively small size of the specimens and careful treatment of avoiding any evaporation of the rock sample during its sampling, transportation and polishing, the specimens can reach almost a fully-saturated state (≥99%) after one-week vacuumizing, as shown in Fig.6. During an isothermal-mechanical loading path (Path-2), the temperature of the specimen was kept constant during the test from isotropic consolidation under a prescribed confining stress to the end of creep loading, as shown in Fig.7.

![Thermo-mechanical loading conditions.](image)

**Fig.7 Thermo-mechanical loading conditions.**

### 3 Test procedures and results

#### 3.1 Thermal triaxial compression test

Based on the test specification [11] of the Japanese Geotechnical Society, the thermal triaxial compression tests were conducted under the room temperature (20 °C), 40 °C and 60 °C, respectively. The procedures include three stages:

1. Heating stage. The temperature was increased at a rate of 0.5 °C/min to the target temperature under drained condition and then was kept constant.

2. Consolidation stage. Isotropic consolidation was conducted for 24 hours under the prescribed confining pressure and the target temperature.

3. Compression stage. Shearing was conducted under drained condition and the constant target temperature.

The detailed thermo-mechanical conditions are listed in Table 3. Besides, a constant back pressure of 0.4 MPa was applied during all cases of compression tests to measure negative pore water pressure.

<table>
<thead>
<tr>
<th>Case</th>
<th>θ(°C)</th>
<th>̇ε(10^-2 min^-1)</th>
<th>σ3 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0.001</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>0.001</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>0.001</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Figure 8 shows the stress-strain relations of the tested soft rock subjected to compression under different constant temperatures. From Fig.8, it is known that the temperature does influence the peak strength of the soft rock. Figure 9 shows the relations between the volumetric strain and the axial strain. It can be seen that the volumetric strain in all tests first contracts and then expands, and the amount of expansion generally decreases as the temperature increases. Moreover, the temperature has a larger influence on the expansion characteristic of material than the contraction characteristic.

![Axial stress vs. axial strain.](image)

**Fig.8 Axial stress vs. axial strain.**
3.2 Thermal triaxial creep test

The thermal triaxial creep tests were first conducted under the room temperature (20 °C) with different creep loads. In the creep tests, instead of abrupt loading, the axial creep load was applied at a constant rate until the specified creep stress was reached. The specified creep stress, which is defined as the percentage of the peak strength obtained from the drained compression tests, is listed in Table 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>θ (°C)</th>
<th>Confining stress σ′ (MPa)</th>
<th>Creep stress σ′ creep (MPa)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>20</td>
<td>0.5</td>
<td>7.90 (95%)</td>
<td>Completed</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.5</td>
<td>7.47 (90%)</td>
<td>Underway</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>0.5</td>
<td>7.06 (85%)</td>
<td>Underway</td>
</tr>
</tbody>
</table>

In the planned test cases, only Case 4 was completed. The volumetric strain measured in Case 4 was plotted against time on a logarithmic scale, as shown in Fig.10. It should be pointed out that, whenever a creep rupture happens, creep strain always increases abruptly and goes beyond the measuring range of the swial current gap sensor. Therefore, the measuring data should be obtained from both the gap sensor and the additional two displacement transducers.

4 Theoretical prediction of thermal compression/thermal creep test

A thermo-elasto-viscoplastic model for soft sedimentary rock was proposed by Zhang and Zhang [9]. In this model, plastic volumetric strain that consists of two parts, a stress-induced part and a thermodynamic part, was taken as the hardening parameter. Both parts can be derived from an extended e-lnp relation, in which the thermodynamic part is deduced based on a concept of “equivalent stress”. Moreover, by a concept of “extended subloading yield surface”, the model can be used to simulate both the thermal compression test and the thermal creep test.

In this paper, the proposed model was used to simulate the thermodynamic behavior of the soft sedimentary rock. Figure 11 shows the comparisons between theoretical and experimental results for the compression tests at different constant temperatures (test by Okada [7]), in which the physical properties of soft rock and material parameters are listed in Table 5.
Fig. 11 Comparisons between theoretical and experimental results for compression tests at different constant temperatures (test by Okada [7]).

Table 5 Material parameters used in the new model for compression test simulation.

<table>
<thead>
<tr>
<th>$\alpha$ (K$^{-1}$)</th>
<th>$\beta$</th>
<th>$\alpha$</th>
<th>$\nu$</th>
<th>$R_c$ (MPa)</th>
<th>$E$ (MPa)</th>
<th>$E_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.0 \times 10^{-4}$</td>
<td>1.00</td>
<td>900.0</td>
<td>0.02</td>
<td>3.00</td>
<td>950</td>
<td>0.0125</td>
</tr>
</tbody>
</table>

Note: $E_p = \lambda - \kappa$, where $\lambda$ is the compression index, and $\kappa$ is the swelling index.

It can be seen from Fig. 11 that strength reduction and shifting of stress-strain curves from brittle to ductile due to temperature increase can be simulated using this model.

Figure 12 shows the comparisons between theoretical and experimental results for creep strain rates at different constant temperatures (test by Okada [8]). In the simulation, the properties of soft sedimentary rock and the material parameters are listed in Table 6. It can be seen from Fig. 12 that the general characteristics of creep behavior, such as the initial creep rate, the steady creep and the creep rupture, can be simulated properly. Moreover, the calculated results can describe the fact properly that the creep failure time is largely dependent on the temperature, and the higher the temperature is, the sooner the creep rupture will occur.

5 Conclusions

In this paper, a new temperature-controlled compression and creep test device for soft rock and corresponding preparation method for test specimens were introduced in detail. The thermal triaxial compression tests and thermal triaxial creep tests were carefully conducted. Moreover, the comparisons of experimental and theoretical results were presented. The following conclusions can be drawn:

1. A temperature-controlled triaxial compression and creep test device was developed, which was fully controlled by computer program written by Visual Basic language in Window-X operation system through an AD-DA board. The temperature controlling unit and mechanical loading controlling unit can work simultaneously. The new test device is suitable for investigating the thermo-mechanical properties of soft sedimentary rocks.

2. The temperature does influence the peak strength and the dilatancy of the soft rock. In the triaxial compression tests, the volumetric strain in all tests first contracts and then expands the amount of expansion, however, generally decreases as the temperature increases. Moreover, the temperature has a larger influence on the expansion characteristic of material than the contraction characteristic. The fact that the stress-strain relations change from brittle to ductile as temperature increases, however, cannot be confirmed in the present tests due to the lack of...
adequate number of tests, meaning that further tests are needed.

3 From the comparisons between experimental and theoretical results, it is shown that the proposed thermo-elasto-viscoplastic model can describe the thermo-mechanical behaviors of soft sedimentary rocks in not only drained conventional triaxial compression tests but also drained triaxial creep tests.

References


