Experimental Study on Mechanical Property of Highly Weathered Tuff for High-altitude Tunnel

Li Ke¹, Guo Hongyan¹²*, Song Hengxiang¹³ and Jiabao Chen⁴

¹China Merchants Chongqing Communication Research & Design Institute Co., Ltd., Chongqing 400000, China.
²Chongqing University, Chongqing 400000, China.
³Chongqing Jiaotong University, Chongqing 400000, China.
⁴CCCC-SHB Sixth Engineering CO., Ltd, Xi’an 710075, China

*Corresponding author’s e-mail: guohongyan@cmhk.com

Abstract: In the context of Milashan Tunnel in predominantly tuff whose mechanical property quickly deteriorates when in contact with water, it is necessary to study through lab test the creep property of highly weathered tuff surrounding the high altitude tunnel. This paper covers reconstruction of standard specimen with measurements of tuff dry density, natural water content and particle grading curve; analysis of axial stress and strain curves based on triaxial compression test; plotting failure stress circle to obtain tuff strength parameters c and φ; obtaining tuff rheological parameters from triaxial rheological test; deriving creep process curve by multi-specimen method; simulation of its rheological characteristics using Burgers model; and lastly identifying rheological parameters using MATLAB. It provides basic data to study deformation mode and monitoring measurement in actual construction.

1. Introduction

As China’s development activity moves deep into the western region, rock tunneling projects are frequently subject to a complex tectonic stress environment characterized by high ground stress, high hydrostatic pressure, high earth temperature and strong excavation disturbance, leading to severe construction challenges due to surrounding rock creep [1]. During construction of Milashan Tunnel in mainly tuff, the softening of highly weathered tuff in contact with water and sharp deterioration of its mechanical property resulted in frequent large deformations, cave-in, concrete cracking, inadequate clearance of secondary lining support and other problems, posing grave challenges to construction activity [2-5]. Therefore, it is of great engineering significance to conduct lab tests for creep characteristics of the high altitude tunnel in highly weathered tuff.

At present, many researchers worldwide have made achievements in creep test. Zhang Shuguang et al. [6] conducted triaxial creep test on sandstone through incremental loading to describe sandstone creep deformation characteristics, build an improved Nishihara model and discuss the nonlinear nature of stress creep with time. Xiong Liangxiao et al. [7] conducted biaxial creep test with different loading paths and stress levels to expand 1D Burgers model to biaxial compression state and identify the test curve. Wang Gengfeng et al. [8] conducted triaxial compressive strength test and triaxial creep test to build a carbonaceous slate creep model that could simulate time-dependent damage. Yang Chao [9] conducted triaxial loading test to analyze the impact of load increments on triaxial creep.
characteristics of marble and the deformation and failure characteristics of various fractured rock masses under triaxial loading and unloading creep conditions. Zuo Qingjun et al. [10] conducted triaxial compression creep test to examine creep characteristics of stressed argillaceous slate and establish a visco-elasto-plastic creep constitutive equation based on Burgers creep constitutive model.

Prior work demonstrates lab creep tests have become one of the primary means to understand rock creep characteristics. In particular, triaxial creep test is the best study method that matches actual projects. This paper covers analysis of the relationship between axial stress and axial strain and radial strain through triaxial compression test to establish $\tau - \sigma$ curve and obtain tuff cohesion $c$ and internal friction angle $\phi$; establishment of creep curves under varying loads through triaxial rheological test; simulation of its rheological characteristics using Burgers model; and identifying rheological parameters using MATLAB.

2. Lab Test Program for Highly Weathered Tuff

2.1. Test equipment
The test uses a large triaxial apparatus to measure tuff cohesion $c$ and internal friction angle $\phi$, and uses GCTS material tester to measure tuff creep parameters, as shown in Fig. 1.

![Large triaxial apparatus and GCTS material tester.](image)

2.2. Preparation of test specimen
The test specimens were from Milashan Tunnel in the county of Gongbujiangda on the border with Mozhugongka County, Lhasa City. The tunnel passes through Mount Mila from north to south. The surrounding rock at the tunnel site is mainly tuff of cryptocrystalline texture and blocky structure composed of quartz and clay. Measure dry density $\gamma_d$ of the tuff by wax seal method; measure its natural water content $\omega$ by oven drying method; measure the mass of particles of various sizes by sieving method to obtain the particle grading curve of the tuff. Calculate one 50mm×100mm cylindrical standard specimen based on obtained test parameters. Then weigh out particles of various sizes required to reconstruct a standard specimen on an electronic scale and excessive water. Stir fully the particles and water with a stirring rod. Apply a small amount of cooking oil to the interior surface of standard specimen steel form. Pour the fully stirred mixture into the steel form and compact to obtain uniformly dense specimen. Remove the form when the specimen has attained the required strength. Put the specimen in a shade place for curing and measure the mass of each specimen at intervals. When its mass approaches that of standard specimen with natural water content, put the specimen into a freshness protection bag to prevent excessive evaporation of moisture. A total of over 20 specimens were prepared. Fig. 2 shows some reconstructed standard specimens of highly weathered tuff.
2.3. Test program

(1) Test program for cohesion and internal friction angle

Measure tuff cohesion $c$ and internal friction angle $\phi$ by triaxial compression test using standard cylinder specimen of $\Phi=50$mm diameter and $H=100$mm height. Maximum particle size of tuff is generally less than $2$mm. The diameter of the specimen is 10 times larger than the maximum particle size of tuff. Regarding the precision of specimen preparation, the diameter error of the specimen over the entire height shall not exceed $0.3$mm. Nonparallelism between two end faces shall not exceed $0.05$mm. The end faces shall be perpendicular to specimen axis with a maximum deviation of $0.25^\circ$.

The test uses a large triaxial apparatus to measure tuff cohesion $c$ and internal friction angle $\phi$. First number $2^*$4 standard specimens already prepared, place them in rubber mold, install pressure head at both ends and apply load using the large triaxial apparatus. Apply load using displacement control method at a speed of $0.33$mm/min at confining pressure of $0.2$MPa, $0.4$MP, $0.6$MP and $0.8$MPa respectively while controlling the application of confining and axial pressures until specimens fail.

(2) Test program for creep parameters

Obtain tuff rheological parameters from triaxial rheological test. The specimens for tuff compression test are standard cylinders of diameter $\Phi=500$mm and height $H=300$mm. Regarding the precision of specimen preparation, the diameter error of the specimen over the entire height shall not exceed $0.3$mm. Nonparallelism between two end faces shall not exceed $0.05$mm. The end faces shall be perpendicular to specimen axis with a maximum deviation of $0.25^\circ$.

Measure tuff rheological parameters using a GCTS material tester. First number $1^*$5 standard specimens prepared and then place them on the CCTS material tester to solidify them for 120min. Apply stress required by axial stress value within 1min and hold until axial deformation ceases. Repeat the above procedures except with changing axial pressure until axial deformation accelerates or specimens fail. Perform triaxial creep test at a confining pressure of $0.4$MPa by applying axial loads of $0.8$MPa, $1.0$MPa, $1.5$MPa, $1.8$MPa and $2$MPa respectively to multiple specimens.

3. Analysis of Test Results

3.1. Analysis of test results for cohesion and internal friction angle

(1) Check the test results of each specimen from data recorded by the large triaxial apparatus, abandoning suspicious data. According to the in-situ stress, the surrounding rock pressure is taken as $0.2$MPa, $0.4$MPa, $0.6$MPa and $0.8$MPa, and the relationship curve between axial stress and strain and radial strain is established. Fig. 3 shows typical $\sigma - \varepsilon$ curves for some specimens.
As shown in Fig. 3 the rock immediately undergoes instantaneous deformation at various levels of confining pressure, then compression deformation and when stress peaks, creep deformation. And with increasing confining pressure the axial stress created increases, resulting in more noticeable creep.

(2) Take peak values on the axial stress vs axial strain curve as triaxial compressive strength and select peak strength results of tuff at four confining pressures in Group 2 from the triaxial compression test, as shown in Table 1.

| Confining pressure / MPa | Triaxial compressive strength \( f_s \) / MPa |
|-------------------------|-----------------------------------------|
| 0.2                     | 2.0253                                  |
| 0.4                     | 2.8621                                  |
| 0.6                     | 3.7442                                  |
| 0.8                     | 3.7636                                  |

(3) Based on apparatus-recorded data, maximum principal stress at different confining pressures is axial failure stress \( \sigma_1 \) at the confining pressure of \( \sigma_3 \). Draw failure stress circles on the \( \tau-\sigma \) stress plan and their envelopes at different confining pressures. From these envelops strength parameters \( c \) and \( \varphi \) are derived. Fig. 4 displays the \( \tau-\sigma \) relation curves. As shown the internal friction angle \( \varphi \) is 38° and cohesion \( c \) is 0.275MPa.

3.2. Analysis of creep parameter test results
(1) Check the test results of specimens from data recorded by the GCTS material tester, abandoning suspicious data and performing retests. If the test results are correct, draw triaxial compression creep test curves. Fig. 6 displays creep curves under different loads.
Fig. 5 Creep curves under different loads

(2) Simulate rheological characteristics using Burgers model and based on creep curve characteristics from the test. Under triaxial stress effect, the nonlinear visco-elasto-plastic creep constitutive equation for the rock based on Burgers model is as follows:

$$\varepsilon = \frac{\sigma_1 + \sigma_2}{9K} + \frac{\sigma_1 - \sigma_2}{3G_1} + \frac{\sigma_1 - \sigma_2}{3\eta_1} + \frac{\sigma_2 - \sigma_3}{3G_2} \left(1 - e^{-\frac{\eta_2}{\sigma}}\right), \sigma \leq \sigma_1 \quad (1)$$

K —— bulk modulus;
$G_1, G_2$ —— shear modulus;
$\eta_1, \eta_2$ —— viscosity coefficient.

Identify parameters in the above equation using MATLAB, as shown in the table below:

| Stress/MPa | K/MPa  | $G_1$/MPa | $G_2$/MPa | $\dot{h}_1$/MPa·h | $\dot{h}_2$/MPa·h | R2   |
|------------|--------|-----------|-----------|--------------------|--------------------|------|
| 0.8        | 24.78  | 101.25    | 279.70    | 148809.52          | 82.43              | 0.8323 |
| 1          | 31.30  | 141.62    | 382.78    | 46224.96           | 1070.4             | 0.9851 |
| 1.5        | 29.22  | 138.62    | 128.61    | 22271.71           | 56.46              | 0.9904 |
| 1.8        | 26.85  | 132.89    | 289.86    | 584.06             | 4.93               | 0.9891 |

4. Conclusions

For highly weathered tuff, it is possible to reconstruct standard specimens by measuring rock mass dry density, natural water content and particle grading curve and then obtain mechanical parameters of rock mass from triaxial compression test and triaxial rheological test.

The multi-specimen method used for axial loading in the triaxial rheological test satisfies creep test requirements in theory and can directly result in creep all-process curves.

By performing triaxial compression test and drawing envelops of failure stress circles at different confining pressures based on data from the tester, the strength parameters of highly weathered tuff surrounding Milashan Tunnel are determined, i.e., internal friction angle $\varphi = 38^\circ$ and cohesion $c = 0.275\text{MPa}$.

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