Research Article

Transition Threshold of Granite Mechanical Characteristics at High Temperature

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No unified criterion exists for the transition threshold of rock mechanical characteristics. We combine rock stress-strain curves to propose an increment ratio of axial pressure based on uniaxial compression tests on granite at high temperature. The behavior of the increment ratio of strain, elastic modulus, Poisson's ratio, and energy with axial pressure is analyzed, and the following conclusions are drawn. (1) High temperatures aggravate rock deterioration, reduce failure strength, and enhance ductility characteristics. (2) Under loading, the compression-to-elasticity and elasticity-to-plasticity transition thresholds for rock occur, respectively, at 20%–35% and 75%–80% stress levels at temperatures of 25–800°C. (3) The source data for calculating rock deformation parameters or unloading points for unloading tests can be selected over the stress level range of 35%–75%.

1. Introduction

Rock mechanics tests have gathered significant attention worldwide. The tests include uniaxial and triaxial, single-stress and complex-stress paths, dry and saturated environments, freeze-thaw and high-temperature conditions, cracks and pore pressure, and natural and prefabricated samples, as well as auxiliary methods (e.g., acoustic emission, electromagnetic or infrared radiation, and computed tomography scanning) and have provided important results [1–6].

However, some qualitative conclusions are difficult to quantify from the available results as described by the following examples. (1) In the stress-strain curve, the transition zone or conversion threshold in the compaction-to-elastic and elastic-to-plastic stages is not quantified and the selection is inevitably affected by subjective factors. (2) When the stress-strain curve is used to solve for deformation parameters (elastic modulus and Poisson's ratio), the data interval selection varies from user to user and is often chosen on the premise of conforming to objective facts. (3) There is no uniform standard for selecting the unloading point in an

uniaxial or triaxial unloading test. Most previous studies have chosen 80% of the peak rock strength as the unloading point (Table 1). This introduces confusion in the calculation of relevant parameters or design of complex test schemes.

In view of the abovementioned problems, Ji [19] combined conventional triaxial compression tests to explore the critical value of rock damage transitions under triaxial compression [20]. Following on this work, we further study the mechanical properties of rock after high temperature under different stress conditions.

2. Materials and Methods

The granite samples used in the tests were collected from a mine in Weifang, Shandong, China, with an average density of 2.612 g/cm³ at room temperature. The samples were processed into standard cylindrical specimens of $\Phi 50 \text{ mm} \times H 100 \text{ mm}$ (error $\pm 0.5 \text{ mm}$) following the International Society of Rock Mechanics (ISRM) standards, as shown in Figure 1. The tests were performed using an MTS815.02 electrohydraulic servo material test system (Figure 2).

TABLE 1: Statistics of unloading level in rock unloading test.

Lithology	Unloading level (%)	Researchers
Rock masses with interlayer staggered zones	25, 40, 50, 60, 70, 80	Duan et al. [7]
Tuffaceous sandstone	65–75	Zhou et al. [8]
Granite	70–80	Duan et al. [9]
Sandstone	85–95	Liu et al. [10]
Sandstone	70, 80, 90	Liu et al. [11]
Rhyolite	80–90	Zhong et al. [12]
Rock mass inside the composite slope	80	Chang et al. [13]
Granite, red sandstone	80	Du et al. [14]
Sandstone	80	Yang et al. [15]
Granite	80	Qin et al. [16]
Marble	80	Dai et al. [17]
	80	Zhao et al. [18]

FIGURE 1: Granite specimen.

FIGURE 2: MTS815.02 testing system.

- (1) The specimen was subjected to high-temperature treatment at 25, 200, 400, 600, and 800°C. To ensure uniform internal heating, the temperature was raised to the set value and held constant for 2 h and then cooled to room temperature.
- (2) Axial pressure was applied using the displacement control mode at a loading rate of 0.003 mm/s until the specimen broke.

3. Results

The uniaxial compression test data of granite at high temperature are given in Table 2, and the typical data were selected to draw the stress-strain curve as shown in Figure 3.

The compression process goes through several stages including compaction, elasticity, yield, failure, and residue.

TABLE 2: Test data.

T (°C)	No.	$\varepsilon_1 \times 10^{-3}$	$\sigma_{1\max}$ (MPa)
25	#1	4.16	120.37
	#2	4.04	116.61
	#3	4.26	122.28
200	#1	4.83	121.77
	#2	4.72	117.77
	#3	4.88	120.21
400	#1	4.23	97.94
	#2	4.44	95.56
	#3	4.32	98.82
600	#1	5.86	54.62
	#2	5.72	53.69
	#3	5.75	58.95
800	#1	5.45	41.91
	#2	5.15	41.15
	#3	5.33	43.80

FIGURE 3: Stress-strain curves.

With increasing temperature, the strain growth rate is more prominent than the stress growth rate and ductility characteristics are observed. Rock strength is less affected when the temperature is $< 200^\circ\text{C}$. Above 200°C , rock strength reduces approximately linearly. Between 400 and 600°C , the strength drop is more significant [21, 22], as shown in Figure 4.

FIGURE 4: Failure strength-temperature curve.

3.1. Strain Evolution. Under uniaxial compression, rock strain is only related to axial pressure. To study the effect of stress level, we introduce the concept of increment ratio of strain to axial pressure [19, 23–25], namely, the ratio of the increase in strain to the increase in axial pressure, which is expressed as follows:

$$\frac{\Delta \varepsilon_{1(t+1)}}{\Delta \sigma_{1(t+1)}} = \frac{\varepsilon_{1(t+1)} - \varepsilon_{1(t)}}{\sigma_{1(t+1)} - \sigma_{1(t)}}, \quad (1)$$

where $\Delta \varepsilon_{1(t+1)}$ is the increment of axial strain at $t + 1$; $\varepsilon_{1(t+1)}$ and $\varepsilon_{1(t)}$ are the axial strains at $t + 1$ and t ; $\Delta \sigma_{1(t+1)}$ is the increment of axial pressure at $t + 1$; and $\sigma_{1(t+1)}$ and $\sigma_{1(t)}$ are the axial pressures at $t + 1$ and t .

The increment ratio of strain to axial pressure is a physical quantity that characterizes the rapid or slow change of strain with axial pressure. It well reflects the influence of axial pressure changes on rock deformation and damage during loading, as well as the internal structural response to the change of external macromechanical state. Larger increment ratios of strain to axial pressure are associated with higher sensitivity of rock deformation to changes of axial pressure. The relationship between the increment ratio of strain to axial pressure and stress level is obtained by combining the test data and equation (1), as shown in Figure 5.

The increment ratio of strain to axial pressure shows a peak at the approximate compression-to-elastic and elastic-to-plastic transition stages in the stress-strain curve. This indicates that the ratio can be used as an indicator for assessing a change of rock mechanical characteristics. The corresponding stress levels of axial pressure are listed in Table 3.

It should be emphasized that (1) the rock samples are heterogeneous and anisotropic, and the transition points of their mechanical characteristics should be over a small stress range; (2) some specimens also show a strong response in the increment ratio of strain to axial pressure during the compaction stage, which is related to the initial state of their internal pores and fractures.

The compaction-to-elastic transition point in the stress-strain curve changes with increasing temperature, which is

related to the internal cracks [21], whereas the elastic-to-plastic transition point remains essentially unchanged at about 80% stress level.

3.2. Deformation Parameter Evolution. The elastic modulus and Poisson's ratio are important mechanical parameters of rock, and their changes are closely related to deformation and damage. Similarly, the increment ratio of deformation parameters to axial pressure can also be obtained:

$$\left\{ \begin{array}{l} \frac{\Delta E_{t+1}}{\Delta \sigma_{1(t+1)}} = \frac{E_{t+1} - E_t}{\sigma_{1(t+1)} - \sigma_{1(t)}}, \\ \frac{\Delta \mu_{t+1}}{\Delta \sigma_{1(t+1)}} = \frac{\mu_{t+1} - \mu_t}{\sigma_{1(t+1)} - \sigma_{1(t)}} \end{array} \right., \quad (2)$$

where ΔE_{t+1} is the increment of elastic modulus at $t + 1$; E_{t+1} and E_t are the elastic modulus at $t + 1$ and t ; $\Delta \mu_{t+1}$ is the increment of Poisson's ratio at $t + 1$; and μ_{t+1} and μ_t are the Poisson ratios at $t + 1$ and t .

The relationship between deformation parameters and the increment ratio to axial pressure and stress level is shown in Figures 6 and 7.

The results shown in Figures 6 and 7 are consistent with those in Figure 5, further indicating that a significant change of the increment ratio of rock parameters to axial compression can be used as an indicator of its mechanical characteristics. Table 4 lists the stress levels under different temperature conditions.

3.3. Strain Energy Evolution. To further verify the accuracy of the results, we analyzed changes of rock strain energy. The law of energy conservation states that energy transformation occurs during rock deformation and failure. The change of thermal energy is not considered because the specimens were cooled to room temperature after heat treatment and loading was also performed at room temperature. Therefore, according to the law of thermodynamics, energy production mainly comes from the work of external forces. During uniaxial compression, the external forces on the rock specimen are only the axial pressure of the testing machine. The total energy absorbed by the rock sample is therefore the axial strain energy [18, 26], then

$$U_1 = \int_0^{\varepsilon_{1(t)}} \sigma_1 d\varepsilon_1, \quad (3)$$

where $\varepsilon_{1(t)}$ is the axial strain at any t .

According to the concept of definite integral in equation (3), we adopt the method of microelement area, which is

$$U_1 = \sum_{t=0}^{t_0} \frac{1}{2} (\sigma_{1(t+1)} + \sigma_{1(t)}) (\varepsilon_{1(t+1)} - \varepsilon_{1(t)}). \quad (4)$$

In combination with the previously described concept, the increment ratio of strain energy to axial pressure can be expressed as follows:

FIGURE 5: Evolution curve of the increment ratio of strain to axial pressure. (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C.

$$\frac{\Delta U_{t+1}}{\Delta \sigma_{1(t+1)}} = \frac{U_{t+1} - U_t}{\sigma_{1(t+1)} - \sigma_{1(t)}}, \quad (5)$$

where ΔU_{t+1} is the increment of strain energy at $t + 1$, and U_{t+1} and U_t are the strain energies at $t + 1$ and t .

TABLE 3: Statistics of the incremental ratio of strain to axial pressure peak.

T (°C)	Stress level (%)	
	Compaction to elastic	Elastic to plastic
25	35.75	78.17–86.13
200	11.55–28.49	79.65
400	12.34–26.97	76.13
600	20.98	74.98
800	13.23–31.02	78.1

FIGURE 6: Evolution curve of the increment ratio of elastic modulus to axial pressure. (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C.

FIGURE 7: Evolution curve of the increment ratio of Poisson's ratio to axial pressure. (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C.

Figure 8 shows the relationship between strain energy and increment ratio of strain energy to axial pressure and stress level during loading.

The threshold of rock mechanical characteristics is consistent with the conclusions obtained from strain,

elastic modulus, and Poisson's ratio. The corresponding stress levels of axial pressure are listed in Table 5.

Critical points are believed to exist at the compaction-to-elasticity and elasticity-to-plasticity transitions during rock loading. A peak in the increment ratio of

TABLE 4: Statistics of the incremental ratio of deformation parameters to axial pressure peak.

T (°C)	Stress level (%)			
	(Compaction to elastic) ^E	(Elastic to plastic) ^E	(Compaction to elastic) ^H	(Elastic to plastic) ^H
25	35.75	78.17		71.68
200	28.49	79.65	23.24	67.36
400	15.96	74.4		65.83
600	19.9	75.18	20.12	74.56
800	31.02	77.86	30.31	77.86

FIGURE 8: Continued.

FIGURE 8: Evolution curve of the increment ratio of strain energy to axial pressure. (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C.

TABLE 5: Statistics of the incremental ratio of strain energy to axial pressure peak.

T (°C)	Stress level (%)	
	Compaction to elastic	Compaction to elastic
25	34.97	78.49–85.85
200	28.49	80.07
400	12.34	75.56
600	20.12	75.6
800	31.02	77.86

FIGURE 9: Relationship between the transition threshold of the rock mechanical characteristics and temperature. (a) Compression-to-elasticity transition. (b) Elasticity-to-plasticity transition.

different parameters to axial pressure can be used as the basis for evaluating the stress level.

4. Discussion

Figure 9 shows the loads corresponding to the critical compaction-to-elasticity and elasticity-to-plasticity transition points

of granite under compression and variable temperature. The transition thresholds of rock mechanical characteristics obtained from the increment ratio of different parameters to axial pressure are in good agreement. The difference of initial rock state is enlarged to some extent at high temperature. The threshold of the compression-to-elasticity transition is therefore strongly affected by temperature. The transition threshold

FIGURE 10: Relationship between elastic modulus and temperature.

generally occurs at the 20%–35% stress level. The rock enters the elastic stage under low-stress conditions at 400–600°C. However, the relationship between the elasticity-to-plasticity transition threshold and temperature is strong and remains at 75%–80% stress level over the full investigated temperature range (25–800°C).

Based on the above conclusions, the elastic modulus of granite under different temperatures was analyzed using data from the 40%–70% stress level range. The results are shown in Figure 10. The elastic modulus decreases irregularly with increasing temperature, which is consistent with the behavior of failure strength.

Because rock deformation in the elastic stage is reversible and does not cause substantial damage to itself, it is suggested that the unloading point be lower than the elasticity-to-plasticity transition threshold in unloading tests with complex-stress paths to avoid damage caused by higher loads later in the test.

5. Conclusions

We combine high-temperature uniaxial compression tests on granite with the concept of an increment ratio of axial pressure. The following conclusions are drawn:

- (1) With increasing temperature, granite transitions from brittle to ductile failure. When the temperature exceeds 200°C, its strength decreases approximately linearly.
- (2) Based on the analysis of the increment ratio of granite parameters (strain, deformation parameters, and strain energy) to axial pressure, it is considered that the transition thresholds of compaction to elasticity and elasticity to plasticity are 20%–35% and 75%–80% stress level, respectively.
- (3) In general, rock deformation parameters can be calculated over the stress level range of 35%–75%. In unloading tests, we suggest that the unloading point is lower than the elasticity-to-plasticity transition threshold.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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