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Comparison of mechanical properties in high temperature and thermal treatment granite

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Abstract: Static mechanical experiments were carried out on granite after and under different temperatures using an electro-hydraulic and servo-controlled material testing machine with a heating device. Variations in obvious form, stress−strain curve, peak strength, peak strain and elastic modulus with temperature were analyzed and the essence of rock failure modes was explored. The results indicate that, compared with granite after the high temperature treatment, the brittle−ductile transition critical temperature is lower, the densification stage is longer, the elastic modulus is smaller and the damage is larger under high temperature. In addition, the peak stress is lower and the peak strain is greater, but both of them change more obviously with the increase of temperature compared with that of granite after the high temperature treatment. Furthermore, the failure modes of granite after the high temperature treatment and under high temperature show a remarkable difference. Below 100 °C, the failure modes of granite under both conditions are the same, presenting splitting failure. However, after 100 °C, the failure modes of granite after the high temperature treatment and under high temperature present splitting failure and shear failure, respectively.

Key words: granite; thermal treatment; high temperature effect; static mechanical properties; failure properties

1 Introduction

A hot topic, namely the effect of temperature on rock properties, has drawn the attention of researchers, given an increasing mining depth of underground resources. Up to now, many studies have related to deep exploitation of hard rock metal mines [1−3]. And, it has been recognized that temperature is one of the vital factors influencing the mechanical behavior of rock. Temperature plays a significant role in many engineering practices [4−6], such as the disposal of highly radioactive nuclear waste, the underground storage and mining of petroleum and natural gas, the development and utilization of geothermal resources, and the post-disaster reconstruction of underground rocks engineering [7]. In order to solve the engineering problems, many researchers studied the effect of temperature on physical and mechanical properties of various rocks [8−15]. ZHAO et al [16] developed a servo-controlled triaxial rock testing system of high temperature and high pressure for rock testing. LAM DOS SANTOS et al [17] researched temperature effects on mechanical behaviour of engineered stones. The results reveal the different characteristics of the materials. CHEN et al [18] found that the peak stress and elastic modulus of heated granite decrease while the peak strain increases as the heating temperature increases. OZGUVEN et al [19] studied the temperature effect on properties of thermal treated limestone and marble and discovered that the structure of natural building stone becomes damaged or changes when heated above 800 °C. BROTÓNS et al [20] investigated the effect of high temperatures in the mechanical properties of a calcarenite. The results show that uniaxial compressive strength and elastic parameters decrease as the temperature increases for the tested range of temperatures. LIU and XU [21] studied the static mechanical properties of thermal treatment biotite granite by using an electro-hydraulic and servo-controlled material testing machine. The results show that the physical and mechanical characteristics are changed after thermal treatment.

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There were already some rock mechanical properties studies related to temperature, but barely came down to static mechanical properties of rocks under high temperature. And, the mechanical properties of rocks after high temperature treatment and under high temperature can certainly be different. Thus, research on the mechanical properties of rock after high temperature treatment and under high temperature is extremely urgent. By using an electro-hydraulic and servo-controlled material testing machine with a heating device, uniaxial compression tests on granite samples after high temperature treatment and under high temperature, from room temperature to 800 °C, were carried out. The variations in apparent form, stress−strain curve, compressive strength, peak strain, elastic modulus and failure modes under the two types of conditions with the change of temperatures are analyzed and compared. The results can provide a reference for problem-solving related to high temperature rock engineering.

2 Experimental

2.1 Sample preparation

Rock samples were processed into cylindrical specimens of *d*50 mm × 100 mm by cutting and polishing. In particular, to ensure parallelism and flatness, both ends of the samples were polished. Precision control of the specimens was exercised in accordance with the standard requirements of the International Society of Rock Mechanics [22] with the parallelism controlled within ±0.05 mm and surface flatness within ±0.02 mm. Samples of similar wave velocity were selected by wave velocity determination. According to the experimental program, the specimens were numbered and heated to designed temperatures by using an auxiliary heating device. Some prepared specimens are shown in Fig. 1. In addition, the main components of granite, as shown in Table 1, were obtained throughout the diffraction experiment and an experimental graph is given in Fig. 2.

2.2 Experimental equipment

The electro-hydraulic and servo-controlled material testing machine used here, as shown in Fig. 3, mainly consists of main equipment, a heating device, a control and data-processing device and a water pump. The main equipment includes a pressure device, a strut bar and support. The heating device with a maximum designed temperature of 1000 °C includes an insulating layer used as heat preservation, resistance used for heating and a temperature controller, which has three built-in thermocouples used for heating control. The control and data-processing device is used for test control and data processing. The water pump is used to cool the pressure bar. The auxiliary heating device of the type SX-4-10, with a rated power of 4 kW and a maximum designed temperature of 1050 °C mainly contains a high temperature furnace and a temperature controller.

2.3 Experimental procedure

The test temperature is classified into 6 groups: 25, 100, 200, 400, 600 and 800 °C. Each group is equipped with no less than five specimens. For the test of granite after the high temperature treatment, the wave velocity of the specimens is measured by using a rock and soil engineering mass detector of type CE9201 no less than three times, and the mass of specimens is measured by

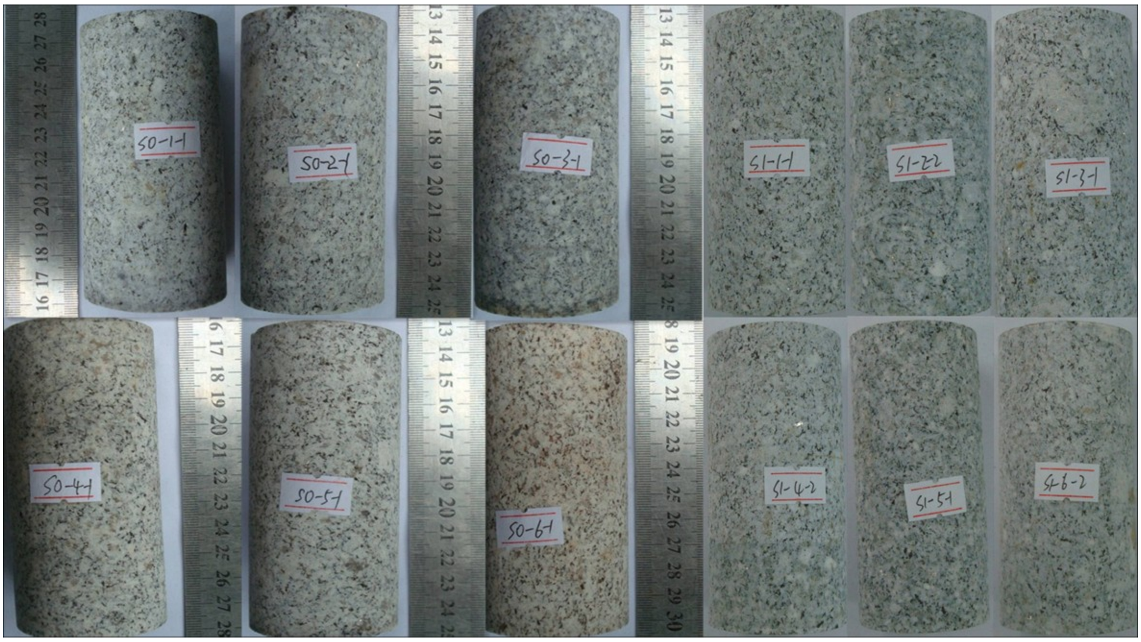

Fig. 1 Photos of some prepared specimens

Table 1 Main components of granite

Quartz	Feldspar	Mica	Montmorillonite	Others
46.54	37.95	9.72	5.76	0.03

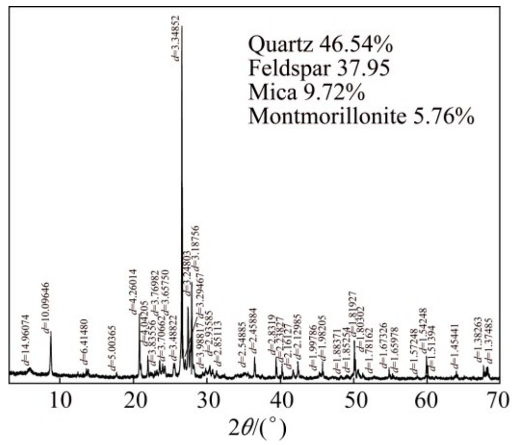

Fig. 2 Analysis chart of components

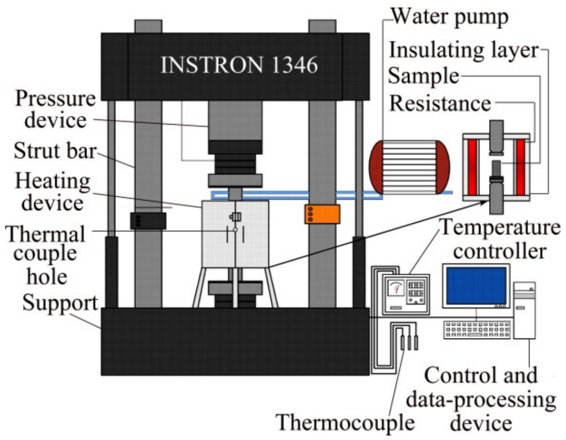

Fig. 3 Apparatus of the electro-hydraulic and servo-controlled material testing machine with a heating device

a electronic balance before high temperature treatment. The target temperature with the heating rate of 2 °C/min, once reached, is kept constant for 2 h in order to ensure uniform heating of the samples. Then, the wave velocity and the mass are measured again after the specimens cooled in the heating body. Finally, the stress and strain can be calculated from the data recorder. For the test of granite under high temperature, the target temperature with the heating rate of 2 °C/min, once reached, is kept constant for 2 h in order to ensure uniform heating of the samples. Then, the test can be started.

3 Results comparison and analysis

3.1 Stress−strain curve

As shown in Fig. 4, the complete stress−strain curves of granite samples after and under different temperatures have the same change law and all go

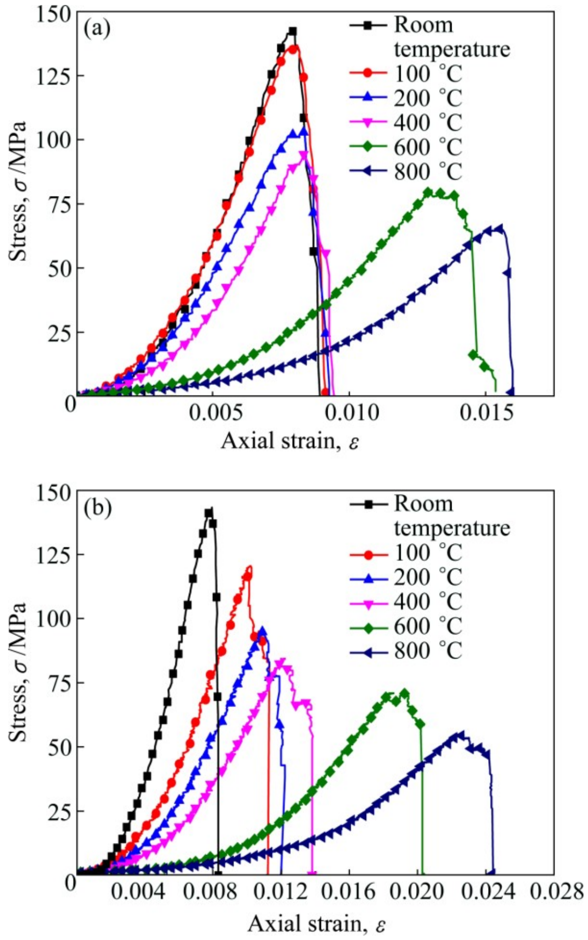

Fig. 4 Stress−strain curves of granite for two kinds of temperature conditions: (a) After high temperature treatment; (b) Under high temperature

through four stages, namely, densification, elasticity, yielding and failure. The experimental results are given in Table 2. As for the stress−strain curves of granite after the high temperature treatment and under high temperature, when the temperature rises, the densification stage prolongs, the slope decreases, the curve moves towards the right and the yielding stage extends gradually. For both stress−strain curves under the two types of temperature conditions, a quick stress decline after reaching peak stress appears. However, compared with the stress−strain curves of granite after the high temperature treatment, the stress−strain curves of granite under high temperature show a quick stress decline, and then a short yielding stage appears again after reaching peak stress. By a comparison of the complete stress−strain curves of the granite samples after the high temperature treatment and under high temperature, it is obvious that the brittleness decreases and the ductility increases gradually as temperature rises under the two kinds of temperature conditions. But granite has different brittle−ductile transition critical temperatures under the two kinds of temperature

Table 2 Experimental results of main mechanical characteristics for two kinds of temperature conditions samples

Temperature/°C	After high temperature treatment				Under high temperature			
	Number	Peak stress/MPa	Peak strain	Elastic modulus/GPa	Number	Peak stress/MPa	Peak strain	Elastic modulus/GPa
25	S0-1-1	143.34	0.00793	26.68	S1-1-1	143.34	0.00793	26.68
	S0-1-2	140.31	0.00751	27.17	S1-1-2	140.31	0.00751	27.17
	S0-1-3	136.55	0.00814	27.53	S1-1-3	136.55	0.00814	27.53
	S0-1-4	137.78	0.00763	26.48	S1-1-4	137.78	0.00763	26.48
	S0-1-5	140.34	0.00834	27.45	S1-1-5	140.34	0.00834	27.45
100	S0-2-1	135.7	0.00799	23.4	S1-2-1	120.25	0.0098	17.81
	S0-2-2	132.78	0.00851	22.65	S1-2-2	117.58	0.00967	16.53
	S0-2-3	127.9	0.00754	22.45	S1-2-3	123.54	0.00901	16.25
	S0-2-4	129.76	0.00773	22.55	S1-2-4	116.45	0.00943	16.51
	S0-2-5	134.65	0.00842	22.35	S1-2-5	121.48	0.00915	16.52
200	S0-3-1	101.81	0.00787	16.02	S1-3-1	95.24	0.0106	13.33
	S0-3-2	99.21	0.0075	16.24	S1-3-2	94.68	0.00989	13.46
	S0-3-3	102.09	0.00801	16.05	S1-3-3	98.68	0.0115	13.36
	S0-3-4	103.67	0.00721	15.83	S1-3-4	97.25	0.0115	13.14
	S0-3-5	97.34	0.00799	15.72	S1-3-5	92.45	0.0125	13.1
400	S0-4-1	94.22	0.00833	14.33	S1-4-1	80.32	0.01185	11.37
	S0-4-2	90.33	0.0081	14.37	S1-4-2	79.5	0.01052	11.3
	S0-4-3	97.8	0.00855	14.65	S1-4-3	82.67	0.00939	11.51
	S0-4-4	95.43	0.00869	14.35	S1-4-4	78.65	0.01256	11.29
	S0-4-5	92.69	0.00899	14.46	S1-4-5	83.48	0.01125	11.3
600	S0-5-1	74.27	0.01065	10.08	S1-5-1	70.81	0.01843	7.38
	S0-5-2	75.6	0.01285	9.54	S1-5-2	67.34	0.01726	7.05
	S0-5-3	78.34	0.00969	10.14	S1-5-3	72.53	0.01901	7.45
	S0-5-4	76.54	0.01168	9.75	S1-5-4	74.65	0.01865	7.62
	S0-5-5	73.65	0.01254	9.83	S1-5-5	69.25	0.01756	7.81
800	S0-6-1	65.11	0.01551	8.04	S1-6-1	54.72	0.02248	5.41
	S0-6-2	69.1	0.01751	6.92	S1-6-2	57.65	0.02448	5.05
	S0-6-3	63.94	0.01468	7.35	S1-6-3	50.21	0.02046	5.15
	S0-6-4	64.48	0.01485	8.23	S1-6-4	55.68	0.02654	5.35
	S0-6-5	67.76	0.01658	6.85	S1-6-5	52.98	0.02534	4.66

conditions. When the temperature is below 400 °C, granite after the high temperature treatment experiences brittle failure. When temperature exceeds 400 °C, the ductility of granite is obviously enhanced and strain can still increase slowly, relative to the lower temperature samples after reaching peak stress.

As seen from Fig. 5, for granite under a high temperature, the brittle−ductile transition critical temperature is lower, the densification stage is longer, the slope decreases more obviously, the curve also moves towards the right, but more evidently, and the yielding stage, apparently comparable to that of granite under high temperature treatment, extends. The brittle−ductile transition critical temperature of granite under high temperature is between 100 °C and 400 °C, but it is between 400 °C and 600 °C after a high temperature treatment. As shown in Fig. 5, the stress under high temperature is lower and the strain is greater; especially when the temperature exceeds 800 °C, the differences are obviously.

The slope of the straightway in the stress−strain curves of granite after the high temperature treatment falls, and the strain enlarges with the increase of temperature. The main reasons are as follows. Firstly, because of the difference among the thermal expansion coefficients of the internal mineral components of rock, the strain is stored between the crystalline grains and fissures, and flawed and exfoliation come out after the

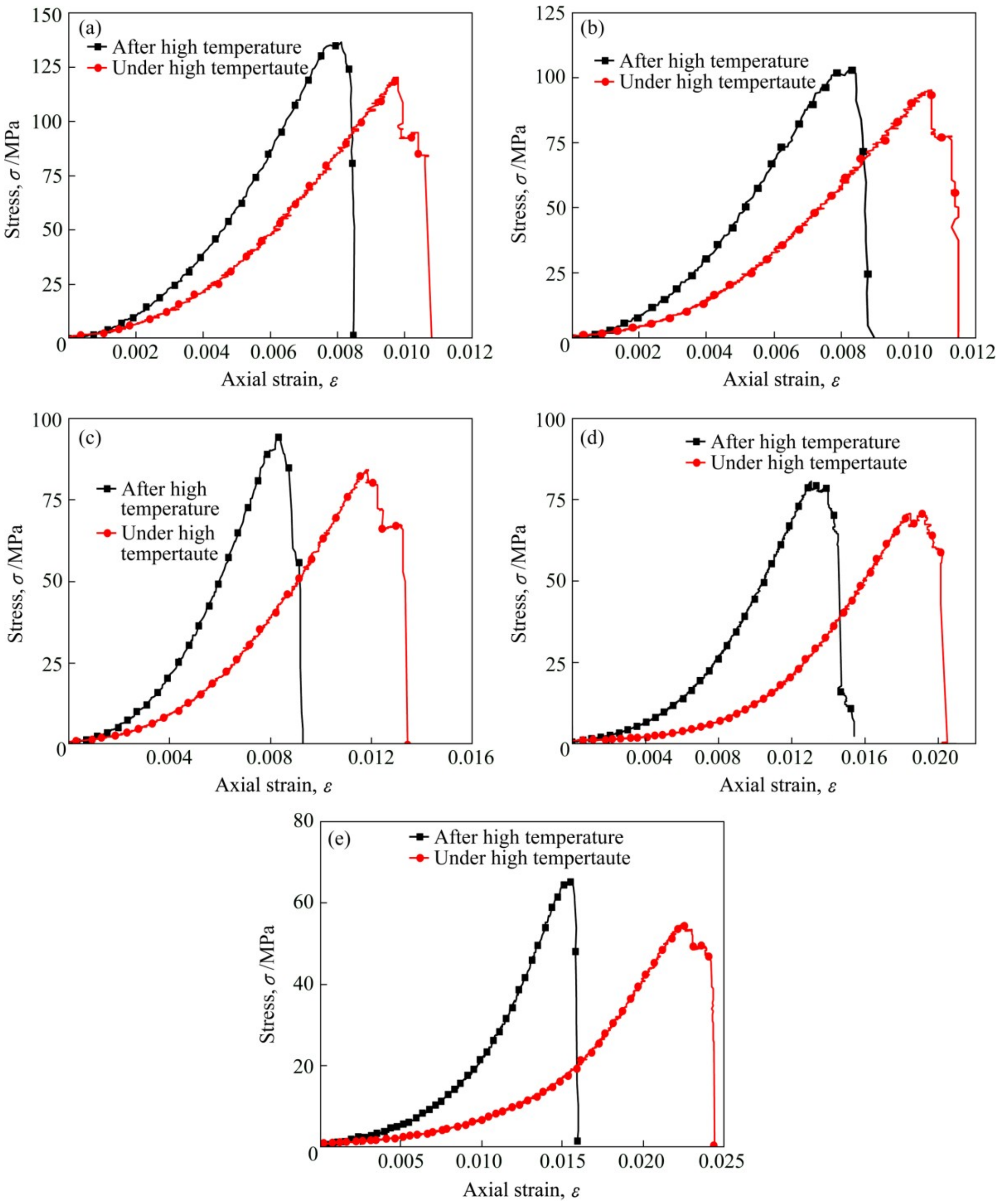

Fig. 5 Comparison of stress−strain curves of granite at different temperatures: (a) 100 °C; (b) 200 °C; (c) 400 °C; (d) 600 °C; (e) 800 °C

high temperature treatment. Secondly, after 400 °C, the fissuring between the crystalline grains in the interior of rocks shows a cracking phenomenon and the rock can not get back into shape. At 575 °C, α-quartz becomes β-modification, which causes volumetric increase, and thermal crack opening. Thirdly, due to moisture and holes, some mineral substances contained in rocks, which are easily to melt, decompose and evaporate through fissures during high temperature treatment. All these factors lead to the enlargement of holes, the elastic modulus falls and strain increases with the increase of temperature. For granite under high temperatures, due to moisture and holes, some mineral substances contained in rocks, which easily melt, decompose and evaporate through fissures during high temperature treatment. The fissuring between the crystalline grains in the interior of rocks shows a cracking phenomenon, and this phenomenon increases as temperature increases. Also, at

575 °C, α-quartz becomes β-modification, which causes volumetric increase, and thermal crack opening. In addition, some mineral substances soften under high temperatures and enhance the ductility and enlarge the strain. High temperatures speed up fissure expansion, and thermal stress makes the densification stage longer. The slope of the elasticity stage is smaller compared with granite after the high temperature treatment. And a short yielding plane comes out after the peak stress.

3.2 Peak stress

The change rules of the peak stress of granite after the high temperature treatment and under high temperature can be seen from Fig. 6. The peak stresses under both types of temperature conditions show a significant correlation with temperature and a trend of gradual reduction with the increase of temperature, but the patterns of change under the two types of temperature conditions are different. The peak stress of granite under high temperature is lower than that of granite after the high temperature treatment but decreases more obviously with the increase of temperature. For granite after the high temperature treatment, when the temperature ranges from 100 °C to 800 °C, the peak stress shows a decrease of 5.67%, 27.68%, 32.81%, 45.69% and 52.85% respectively compared with room temperature. Although the peak stress of granite after the high temperature treatment at 200 °C is higher than that at 100 °C, the difference is only 5.67%, still in the normal dispersion range and possibly the result of rock sample heterogeneity. For granite under high temperature, when the temperature ranges from 100 °C to 800 °C, the peak stress shows a decrease of 14.00%, 31.32%, 42.29%, 49.86% and 61.31% respectively compared with room temperature. Compared with granite after high temperature treatment, the peak stresses of granite under 100, 200, 400, 600 and 800 °C decrease 11.67, 4.84, 13.29, 5.84 and 13.17 MPa, which decrease by 8.83%, 4.79%, 14.12%, 7.68% and 17.95%, respectively. By using a quadratic function, experimental fitting formulas of peak stress of granite after the high temperature treatment and under high temperature are respectively obtained as follows:

$$\sigma = 147.49 - 0.19T + 1.127\times10^{-4}T^2 \tag{1}$$

$$\sigma = 142.14 - 0.21T + 1.36\times10^{-4}T^2 \tag{2}$$

where σ is the peak stress, T is the temperature.

Within 400 °C, dehydration forms in holes in the interior of rock. The crystalline grains undergo a transformation, and some small fissures gradually develop into larger fissures under high temperature, and, then, the static compaction strength falls. From 400 °C to 800 °C, mineral compositions and the internal structure of granite change; evidently, some mineral substances contained in granite, which easily melt, decompose and evaporate and pre-cracking come into fissures after high temperature. Therefore, the strength shows a decline. For granite under high temperature, some factors aside from these affect the strength at the same time. Some mineral compositions of granite create stress and softening under high temperature; in addition, thermal stress speeds up the fissure expansion in the loading process. These added factors cause a smaller peak stress, compared with that of granite after the high temperature treatment.

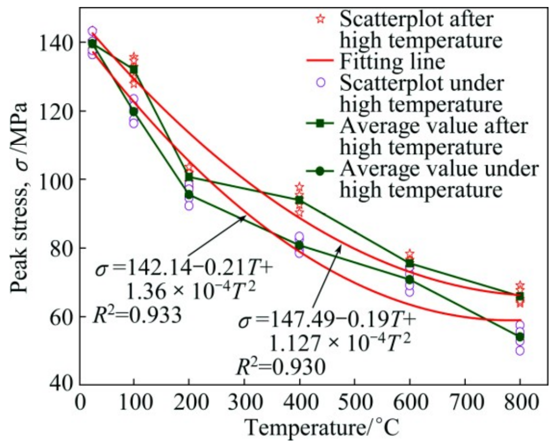

Fig. 6 Peak stress−temperature curves after and under high temperature

3.3 Peak strain

Variations in the peak strain of granite after the high temperature treatment and under high temperature are shown in Fig. 7. With a rise in temperature, the peak strains of granite under both types of temperature conditions increase gradually, but the patterns of change under the two types of temperature conditions are different. For granite after high temperature treatment, the peak strain roughly does not change before 400 °C, compared with room temperature. When the temperature reaches 600 °C, the peak strain enhances remarkably and increases by 33.74%, compared with 400 °C. The peak strain continues to increase as the temperature reaches 800 °C and increases by 43.24% compared with 600 °C. For granite under the high temperature treatment, the peak strain shows a different change rule. When the temperature reaches 100 °C, the peak strain starts to show an apparent increase and increases by 20.25% compared with room temperature. The peak strain still increases when the temperature reaches 200 °C and increases by 12.63% compared with 100 °C. However, although the peak strain at 400 °C has a large increase compared with room temperature, it almost does not change compared with 200 °C. As temperature increases, reaching 600 °C, the peak strain has an evident increase, more than 71.69% compared with 400 °C. When the temperature achieves 800 °C, the peak strain increases by

23.63 % compared with 600 °C. After 400 °C, the peak strain of granite under high temperature changes more acutely than that of granite after the high temperature treatment. Also, by using the quadratic function, the experimental fitting formulas of the peak strain of granite after the high temperature treatment and under high temperature are respectively obtained as follows:

$$\varepsilon = 0.0083 - 6.36\times10^{-6}T + 1.46\times10^{-8}T^2 \tag{3}$$

$$\varepsilon = 0.0085 - 9.04T + 2.2T^2 \tag{4}$$

where ε stands for the peak strain.

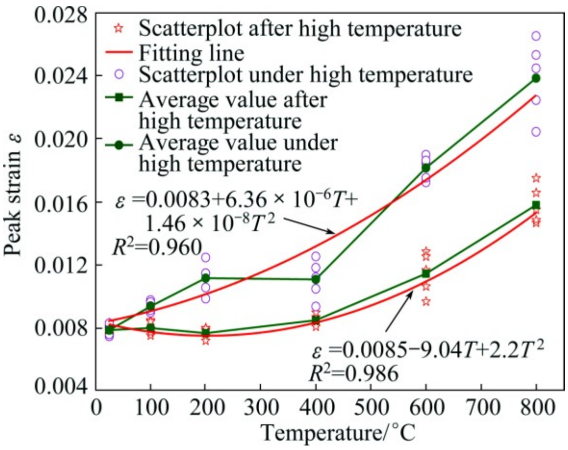

Fig. 7 Peak strain−temperature curves after and under high temperature

The peak strain can represent the deformation of rock before the peak stress, especially deformation caused by the densification stage. Dehydration, increased fissuring and the enlargement of voids result in an increased peak strain. In addition, for granite under high temperature, some softening mineral compositions result in an enlargement of ductility. With the rising temperature, the structure's thermal stress enhances remarkably. Hence, the peak strain under high temperature is greater.

3.4 Elastic modulus

Usually, an elastic modulus can be calculated through fitting an approximate straight line segment of the stress−strain curve prior to the peak stress. An elastic modulus in this work means a slope corresponding to 40% and 60% of compression strength during the rising phase of the stress−strain curve. The elastic modulus can be computed by the following formula:

$$E_C = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{5}$$

where subscripts 1 and 2, respectively, correspond to the two points $0.4\sigma_0$ and $0.6\sigma_0$ of the rising stress−strain curve, σ stands for axial stress and ε stands for axial strain.

The change rules of the elastic modulus with temperature variation can be seen from Fig. 8. As temperature rises, the elastic modulus of granite under the two types of temperature conditions shows a trend of gradually decreasing. The elastic modulus of granite under high temperature is smaller than that of granite after the high temperature treatment. For granite after the high temperature treatment, the elastic modulus falls rapidly with increasing temperature. From room temperature to 200 °C, the elastic modulus decreases from 27.06 GPa to 15.97 GPa, a loss of 40.98%. From 200 °C to 800 °C, the elastic modulus decreases from 15.97 GPa to 7.48 GPa, a decrease of 50.16%. For granite under high temperature, the elastic modulus falls more rapidly with increasing temperature than the elastic modulus of granite after the high temperature treatment. Especially from room temperature to 200 °C, the elastic modulus falls from 27.06 GPa to 17.80 GPa, a decline of 50.92%. From 200 °C to 800 °C, the elastic modulus lessens from 13.28 GPa to 5.12 GPa, a decrease of 54.89%. The elastic moduli of granite after the high temperature treatment and under high temperature are respectively obtained as follows:

$$E = 27.11 - 0.047T + 3.004T^2 \tag{6}$$

$$E = 25.16 - 0.054T + 3.8\times10^{-5}T^2 \tag{7}$$

where E is the elastic modulus.

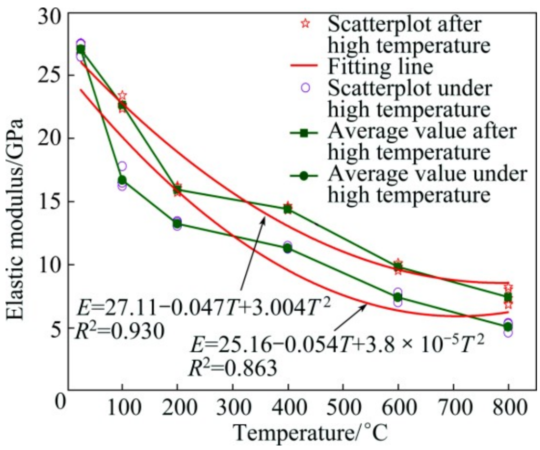

Fig. 8 Elastic modulus−temperature curves after and under high temperature

Because of the difference among the thermal expansion coefficients of the internal mineral components of rock, fissuring, flaws and exfoliation come after high temperature. After 400 °C, the fissuring between the crystalline grains in the interior of rocks shows a cracking phenomenon and the fissures cannot get back into shape. The moisture, holes and some mineral substances contained in rocks, which easily melt, decompose and evaporate through fissures after high temperature. Therefore, the elastic modulus decreases under impact loadings as the temperature increases. In addition, some mineral compositions of granite show softening under high temperature and lead to the elastic modulus being smaller than that of granite after the high temperature treatment.

3.5 Failure modes

The failure modes of granite after the high temperature treatment and under high temperature can be seen from Fig. 9 and can be simplified into a schematic diagram as shown in Fig. 10. In Fig. 10, the red dotted line stands for the failure plane. The amount of granite fragments after and under high temperature produced in static tests is changed as the temperature increases. The failure modes of granite under the two types of temperature conditions both change, apparently with the increasing temperature. Along with the increase of temperature, small blocks and powder come out; in addition, two to three large blocks appear. However, there are also some differences. Granite after the high temperature treatment, before 100 °C, shows the same failure modes. As can be seen from Fig. 9, the specimen failure in two main blocks, along with a failure plane at a certain angle to the axis of the rock sample, presents a splitting failure. When the temperature reaches 200 °C, the specimen failure occurs in three or more main smaller blocks, along with the parallel failure planes at a certain angle to the axis of the rock sample, still presenting a splitting failure. As the temperature continues to increase, reaching 400 °C or higher, the specimens failure occurs in two to three main blocks,

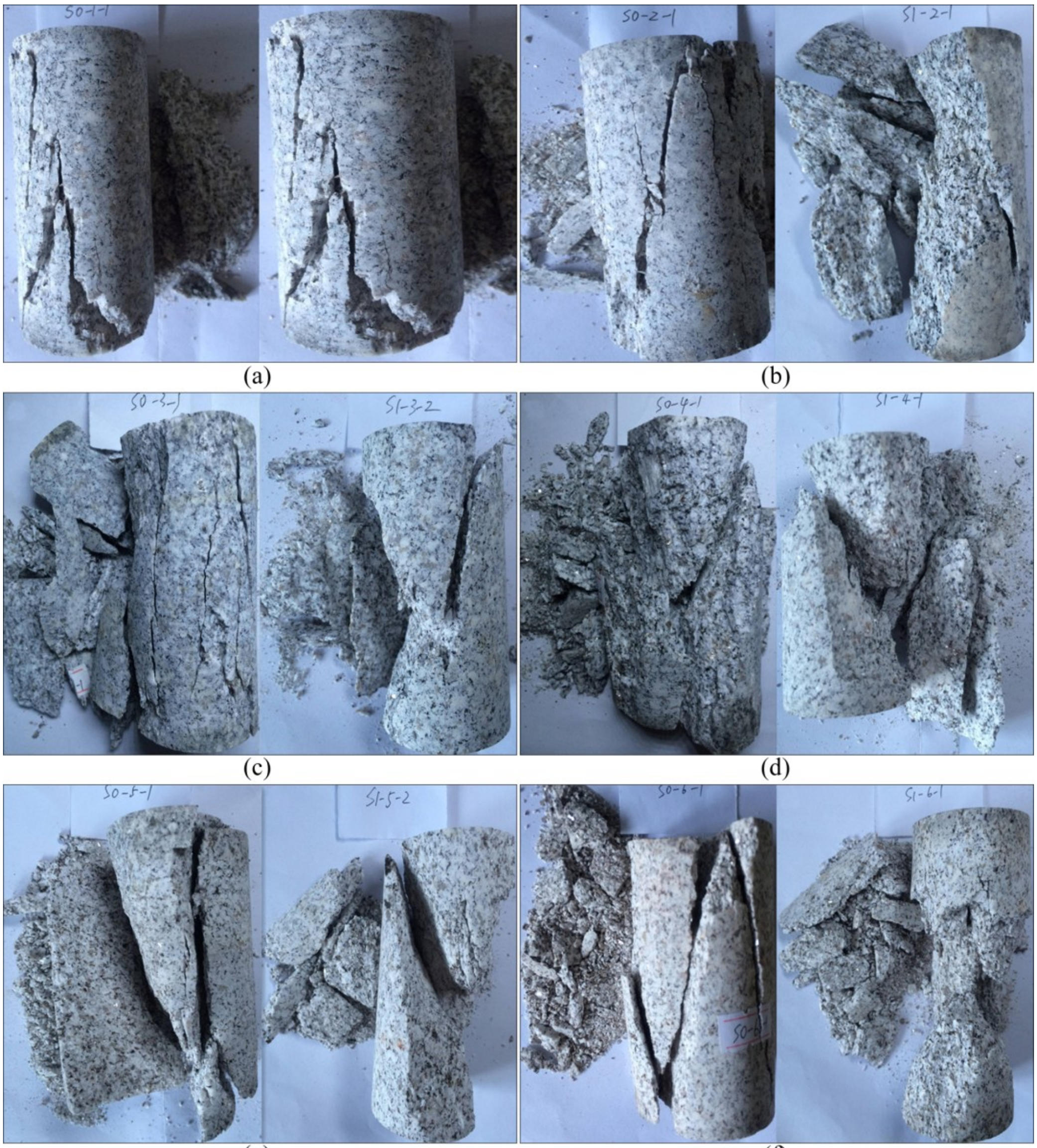

Fig. 9 Comparison in failure modes of granite after and under high temperature: (a) Room temperature; (b) 100 °C; (c) 200 °C; (d) 400 °C; (e) 600 °C; (f) 800 °C

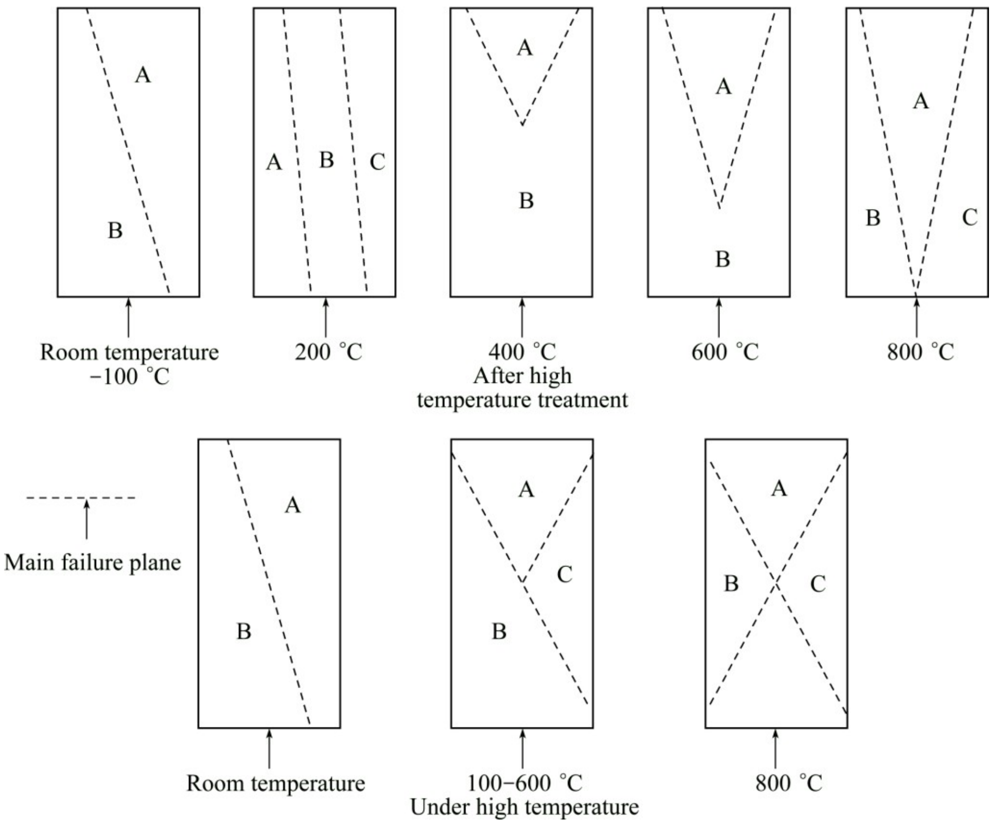

Fig. 10 Main schematic diagrams of failure modes of granite after and under high temperatures

along with the main failure planes at different angles to the axis of the rock sample, but the failure modes still exist in terms of certain differences with the increase of temperature. As can be clearly seen from Fig. 9 and be simply seen from Fig. 10, compared with 400 °C, the two failure planes of the rock specimen after 600 °C join in a deeper plane relative to the top plane. When the temperature reaches 800 °C, the two failure planes join in the bottom plane of the specimen. For granite under high temperature, the failure modes present a great difference, as shown in Fig. 9; from 100 °C to 600 °C, the specimen's failure into two main blocks, along with the main failure planes at the different angles to the axis of the rock sample and some little blocks and powder, presents a shear failure. As shown in Fig. 10, from 100 °C to 600 °C, the two main failure planes join in middle plane of the specimen; one stop in the middle plane of the specimen, and another continues to expand until it occurs through out the specimen. When the temperature continues to increase, reaching 800 °C, the specimen's failure into one main block and more small blocks and powder, compared with 100 °C to 600 °C, presents a conjugate shear failure. As shown in Fig. 9, for granite under 100 °C to 600 °C, there are some small blocks. In Fig. 10, part C stands for the small blocks. When the temperature reaches 800 °C, parts B and C both fail into small blocks and powder.

The change of the internal structure of granite and force condition can result in different failure modes. All the above reasons cause the internal structure to change remarkably, such as fissure expansion, dehydration and the enlargement of voids. Therefore, with the increase of temperature, the apparent internal structural changes result in different failure paths; consequently, the failure modes occur in different forms. In addition, for granite under high temperature, the thermal stress can be simply considered as the confining pressure. As shown in Fig. 11, the enlargement of the thermal stress is equivalent to the increase of the confining pressure. Some studies show that the work stress increases to some extent with the rising confining pressure. In this work, although thermal stress increases, the peak stress decreases. This is because the thermal stress, to a certain degree, is different from the confining pressure. In the loading process, except for the function of the confining pressure, the thermal stress speeds up fissure expansion and some mineral compositions result in stress softening. Therefore, the peak stress decreases with the increase of temperature. The failure modes are evidently different from those of granite after the high temperature treatment. The changes in mineral components and mineral particles of high temperature granite are important reasons leading to the changes in the static mechanical characteristics.

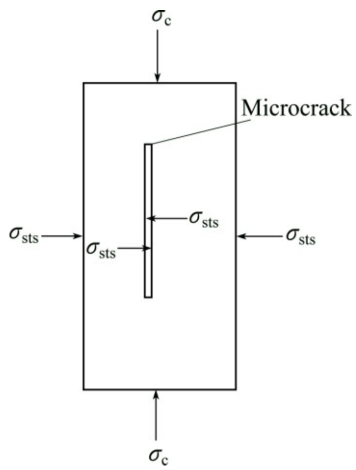

Fig. 11 Simple equivalence force diagram of specimen under high temperature

4 Discussion

Many tests show that the dynamic parameters of rocks after the high temperature treatment and under high temperature are different. This also appears in static mechanic parameters. In this work, the differences of granite after the high temperature treatment and under high temperature are described and analyzed. It is definite that the differences between the mechanic characteristics of granite after the high temperature treatment and under high temperature are related to physical and chemical properties. The density and wave velocity can be obtained and represented as follows:

$$P_d = \frac{m_2 - m_1}{m_1} \times 100\% \tag{8}$$

$$P_v = \frac{v_2 - v_1}{v_1} \times 100\% \tag{9}$$

where P_d stands for the density decrease rate, P_v stands for the longitudinal wave velocity rate, m_1 and m_2 are the masses of granite before and after the high temperature treatment, respectively, v_1 and v_2 are the longitudinal wave velocity of granite before and after the high temperature treatment, respectively. As can be seen from Fig. 1, with the increase of temperature, the color of granite changes from gray to claybank, especially when the temperature reaches 800 °C, the change is more evident. At high temperature, the physical properties have changed; this may lead to the change of mechanical properties. The density also changes apparently after high temperature and particularly when the temperature increases to 800 °C. The density decreases greatly, from 2639.07 kg/m^3 to 2542.13 kg/m^3, a decline of 3.67% as shown in Fig. 12. And the decrease of density also leads to the stress falling. The longitudinal wave velocity is more sensitive with the increase of temperature. As can be seen in Fig. 13, the longitudinal wave velocity gradually shows a linear decrease along with the rising temperature. All the above changes can be seen as macroscopic damage. In addition, by using the linear function, the fitting formula is obtained as

$$v=5221.42-5.17T \tag{10}$$

where v is the longitudinal wave velocity.

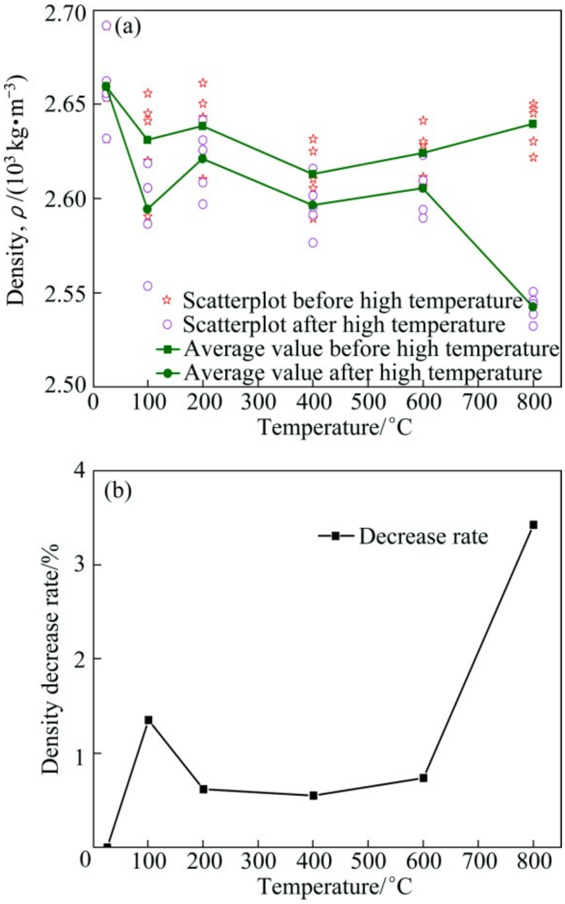

Fig. 12 Variations of density (a) and density decrease rate (b) of specimens with temperature

For granite under high temperature, the damage is larger. The obvious damage difference value can be seen from Table 3. The elastic modulus used to describe the damage of granite after the high temperature treatment and under high temperature can be calculated by the following formula:

$$D(T) = 1 - \frac{E_T}{E_0} \tag{11}$$

where $D(T)$ stands for thermal damage, E_T is the elastic modulus at temperature T, and E_0 is the elastic modulus at room temperature.

It can be seen from Fig. 14 that the damage of granite under high temperature is larger than that of granite after the high temperature treatment. Compared with granite after the high temperature treatment, there is thermal stress under high temperature. The fitting

Table 3 Relationship between damage and temperature

Temperature T/°C	Damage after high temperature $D_1(T)$	Damage under high temperature $D_2(T)$
25	0	0
100	0.162	0.382
200	0.410	0.510
400	0.467	0.580
600	0.635	0.724
800	0.724	0.811

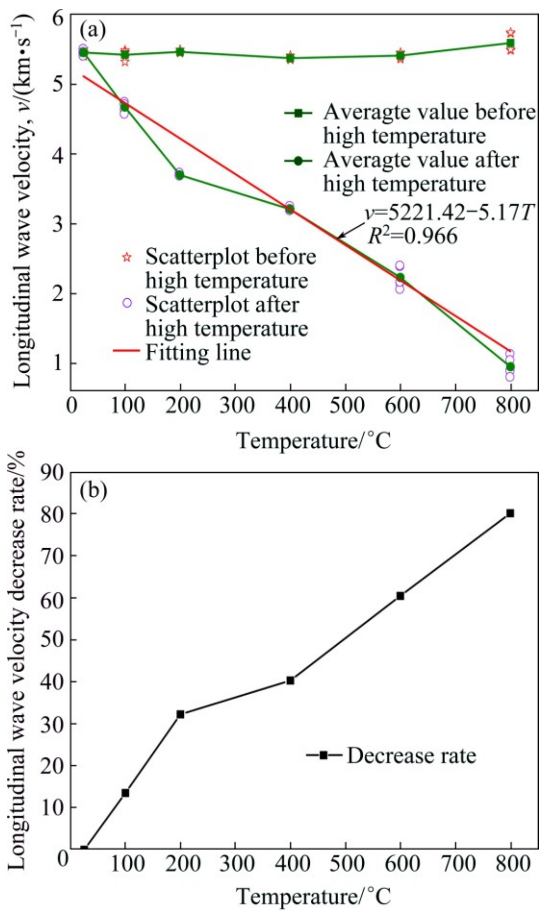

Fig. 13 Variations of longitudinal wave velocity (a) and longitudinal wave velocity decrease rate (b) of specimens with high temperature

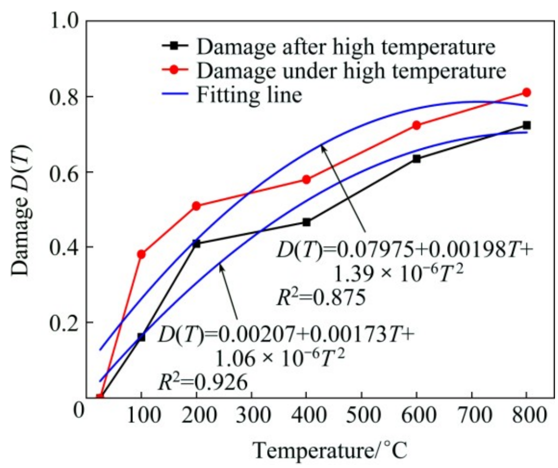

Fig. 14 Damage of specimens after and under high temperature

formulas of damage of granite after the high temperature treatment and under high temperature are respectively obtained as follows:

$$D(T)=0.07975+0.00198T+1.39\times10^{-6}T^2 \tag{12}$$

$$D(T)=0.00207+0.00173T+1.06\times10^{-6}T^2 \tag{13}$$

where $D(T)$ is the damage of granite.

In all, static mechanical parameters show differences under the two types of temperature conditions. The change of physical properties can cause the variation of mechanical characteristics and different outside conditions lead to different mechanical characteristics.

5 Conclusions

1) Compared with granite after high temperature treatment, the brittle−ductile transition critical temperature is lower and the densification stage is longer for granite under high temperature.

2) For granite under high temperature, the peak stress is lower, the peak strain is greater, and the elastic modulus is smaller compared with that of granite after the high temperature treatment.

3) The failure modes of granite after the high temperature treatment and under high temperature show remarkable differences. Before 100 °C, the failure modes of granite under both conditions are the same, present splitting failure. However, after 100 °C, the failure modes present splitting failure and shear failure respectively. Also, for granite after high temperature treatment, the two failure planes of the rock specimen join in a deeper plane relative to the top plane when the temperature reaches. When the temperature reaches 800 °C, the two failure planes join in the bottom plane of the specimen. For granite under high temperature, the failure modes present a great difference; from 100 °C to 600 °C, the failure modes are the same, present shear failure. When the temperature continues to rise, reaching 800 °C, the failure mode presents a conjugate shear failure.

4) The damage of granite under high temperature is larger than that of granite after the high temperature treatment. At 575 °C, α-quartz becomes β-modification, which causes volumetric increase, and thermal crack opening. Both the physical properties and outside conditions are important factors that affect the mechanical properties of rock.

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高温作用下和加热冷却后花岗岩力学性能的比较

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摘 要：运用带有加热装置的电液伺服材料试验机对热处理后和高温下的花岗岩进行了静态力学实验。分析了两种状态下花岗岩的应力−应变曲线及峰值强度、峰值应变和弹性模量随温度的变化规律，并且探讨了两种状态下岩石的破坏形态。结果显示，与热处理后的花岗岩相比，高温下花岗岩脆−延转变的临界温度更低, 压密阶段更长，弹性模量更小且损伤更大。此外，与热处理后的花岗岩相比较，高温下花岗岩的峰值应力更小，然而峰值应变却更大，且两者都随着温度的升高变化更加显著。另外，高温处理后和高温下花岗岩的破坏形态明显不同。低于 100 °C 时，两种状态下花岗岩的破坏形态相同，皆表现为劈裂破坏。然而，高于 100 °C 后，热处理后和高温下花岗岩的破坏形态分别表现为劈裂破坏和剪切破坏。

关键词：花岗岩；热处理；高温作用；静态力学性质；破坏特性

(Edited by Yun-bin HE)