RESEARCH ON PHYSICAL-MECHANICAL PROPERTIES AND ENERGY EVOLUTION CHARACTERISTICS OF GRANITE AFTER HIGH TEMPERATURE TREATMENT

by

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Granite is the main carrier of geothermal energy of hot dry rock. Therefore, the study of influence of different temperatures on the physical-mechanical properties and energy evolution characteristics of granite after high temperature treatment is an important way to guide the successful exploitation of hot dry rock geothermal resources. Physical tests and uniaxial compression tests were carried out on granite after high temperature treatment rangingfrom25to350 ℃. The results show that change rates in volume, mass, density, P-wave velocity and porosity of granite increase with increasing temperature. The research results can provide basic data support for the safe and efficient development of hot dry rock in China, and also develop the theory of high temperature rock mechanics.

Keywords:*Granite, High temperature treatment,Physical property,Uniaxial compression test, Energy evolution*

Introduction

With social progress and economic development, the shallow resources of the earth are gradually reduced, and the deep strata are rich in coal, geothermal and other mineral resources. Deep mining has become a necessary way to support sustainable development of economic society[1-5].Hot dry rock (HDR) is a clean and renewable deep geothermal resource, which is regarded as one of the new energy resources that can be vigorously developed by many countries[6, 7].As the main carrier of HDRgeothermal energy, hightemperature granite is bound to cool downduring the construction of artificial thermal reservoir and the exploitation of HDR geothermal energy, and its physical-mechanical properties will change significantly[8, 9].Therefore, studying the physical-mechanical properties of granite after high temperature is helpful to guide the successful exploitation of HDR geothermal energy.

At present, many scholars study the physical-mechanical properties of rock after high

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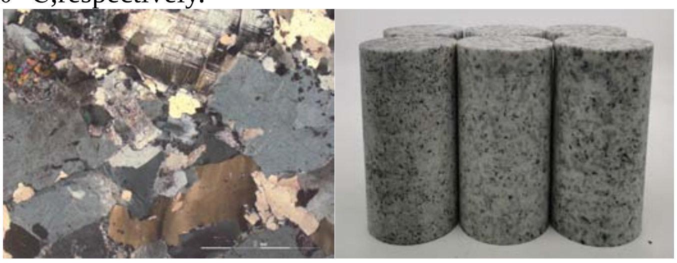
temperaturetreatment. Zhang *et al.* [10]found that the main reason for the inconsistency of changes in uniaxial compressive strength and P-wave velocity of sandstone after different temperature treatments is microstructure and mineral composition.Gao *et al.* [11, 12] studied the differences of thermal expansion of different types of rocks in microwave field, and investigatedthemechanismof3D volume fracturingfrom the macro-meso-micro dimensions. Gautam *et al.* [13] studied interrelationship among massloss, thermal conductivity, P-wave velocity and damage factor of Jalore granite after different temperature treatments. Freire-Lista *et al.* [14] used nine analytical techniques to study the decay of physical-mechanical properties of four types of granite after heat treatment ranging from 20 to 105℃. Rossi *et al.* [15] studied the weakening phenomenon of sandstone and granite after flame-jet heating, and clarified the influence of the heating rate on the formation of microcracks. Zhang *et al.* [16] conducted SEM, XRD and uniaxial compression tests on coal measure mudstone after different high temperaturetreatments, and found that temperature has a significant effect on the physical-mechanical properties of mudstone. Luo *et al.* [17] studied the change of Young's modulus of red sandstone after heating-cooling cycle, and analyzedthe main causes of thermal-induced damages. At present, the research on granite after high temperature treatment mainly focuses on physical-mechanical properties, while the research results on energy are relatively few.Energy transformation has always existed in the process of rock deformation and failure, which can reveal the essence of rock mechanical behavior change [18]. Therefore, the change of rock mechanical properties after high temperature treatment can be reasonably explained from the perspective of energy.

The target of this paper is to show the physical tests of granite after different high temperature treatments to obtain the change law of the physical properties of granite.

Test preparation and plan

Test preparation

The samples used in the test are taken from a homogeneous granite rock mass with an average density of 2.60g/cm^3. The resultofthe lithofacies thin section testisshown in fig. 1a.The minerals are composed mainly of quartz, plagioclase, alkali feldspar and biotite. The content of quartz is approximately 24%, that of plagioclase is approximately 20%, that of alkali feldspar is approximately 55%, and that of biotite is approximately 1%.According to the recommendations of the International Society for Rock Mechanics, theΦ50×100 mmcylindrical samplesare processed, as shown in fig. 1b. In order to reduce the test error, first remove the samples with obvious cracks on the surface, and then use ultrasonic testing to select the samples with similar P-wave velocity. The samples used in the test are numbered as G-25, G-150, G-250 and G-350 in sequence. 25, 150, 250 and 350 indicate that the temperature of granite during high temperature treatment is 25 ℃ (room temperature), 150 ℃, 250 ℃ and 350 ℃,respectively.



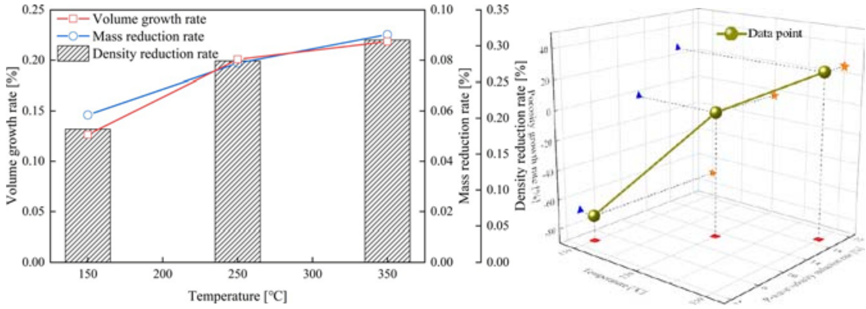
(a)Microstructure characteristics (b) Macrostructure characteristics

Figure 1. Granite samples

Test plan

Firstly, the size, mass, density, P-wave velocity and porosity of the samples are measured and calculated by vernier caliper, balance, ultrasonic equipment and saturation device.Secondly, put the saturated samples into the drying cabinet. The temperature of the drying cabinet rises to the target temperature at 10 °C/min and remains constant for 4hours.Then, hightemperature samplesare placed in the airand cooled to room temperature, and its physical parametersare measured again.Finally, the uniaxial compression test of granite after high temperature treatment is carried out, and the loading rate is set to0.05mm/min, and the stress-strain curve was obtained.

Variationsin physical properties of granite after high temperature treatment



(a) Change ratesinvolume, mass and density(b) Change ratesin porosity and P-wave velocity

Figure 2. Relationship between change rates in physical properties of granite after high temperature treatment and temperature

Fig. 2 shows the relationship between change rates in physical properties of granite after high temperature treatment and temperature. The change rate is defined as the ratio between the change value and the initial value. With the increase of temperature, the volume expands, the mass and density decrease, and the change ratesall increase, as shown in Fig. 2a.This is because thehigh temperature treatment causes the expansionofmineral particles. When it is cooled to room temperature, the residual strain caused by thermal expansion will cause the volume of granite to increase, and there is a positive correlation between temperature and volume growth rate. In addition, different forms of water exist in the granite. When the temperature of high temperature treatment is 100-200 °C, the free water and weakly bound water of granite will evaporate. When the temperature is 200-300 °C, the strongly bound water will vaporize and escape. When the temperature exceeds 300 °C, the crystal water and structuralwater of the granite begin to vaporize and escape. The increase of temperature leads to the decrease of mass and the increase of volume, resulting in the decrease of density.As shown in fig. 2(b), with the increase of temperature, the porosity first decrease and then increase, and the P-wave velocity continues to decrease, and the change rates of both increase.This is because the mineral particles after high temperature treatment expand, resulting in the closure of the primary pores of granite. When the thermal stress formed by the extrusion of mineral particles exceeds the cohesion between particles,the granite cracks, resulting in an increasing trend of porosity growth rate.P-wave velocity can also reflect the structural state of granite[19]. High temperature treatment causesP-wave velocity to decrease, and the two show a positive correlation.

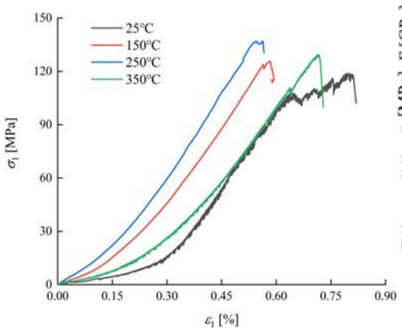
Variationsinmechanical properties of granite after high temperature treatment

The stress-strain curves of granite after different high temperature treatments are shown in Fig. 3. The stress-strain curves of granite after different temperature treatments obviously show four stress stages, namely compaction stage, elastic stage, yield stage and post-peak stage. The first three stress stages are collectively called pre-peak stage. In the compaction stage, the primary pores of granite after different high temperature treatments are closed under axial load, so that the curve shows an upward concave type. With the increase of temperature during high temperature treatment, the compaction stage shortens first and then extended. With the increase of axial load, the curve begins to show a linear shape, which indicates that the granite enters the elastic stage, and there is basically no microcrack in the stress stage.With the increase of temperature, the slope of the curve first increases and then decreases. Then, the granite enters the yield stage, and microcracks begin to develop.The growth rate of the curve gradually slows down, and the curve shows nonlinear changes.In addition, the number of microcracks increases in the stress stage, resulting in a small range of stress dropping phenomenonin granite.When the axial stress increases to the peak stress, the microcracks are connected with each other, resulting in the reduction of the bearing capacityof granite, the peak failure phenomenon occurs. The curve drops sharply and finally the post-peak stageis formed. As the temperature increases, the peak point of the curve first moves to the left and up, then to the right and down.

The maximum axial strain in the compaction stage ε_{ci} is determined by measuring the axial strain corresponding to the dividing point of the upward concave curve and the linear curve, which qualitatively characterizes the pore characteristics of granite after high temperature treatment. Moreover, the axial stress and axial strain corresponding to the peak point of the curve are peak stress σ_p and peak strain ε_p respectively. The elastic modulus E is given as:

$$E = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \quad (1)$$

where E is the elastic modulus, $\Delta\sigma_1$ is the increment of axial stress in the elastic stage, and $\Delta\varepsilon_1$ is the increment of axial strain in the elastic stage.



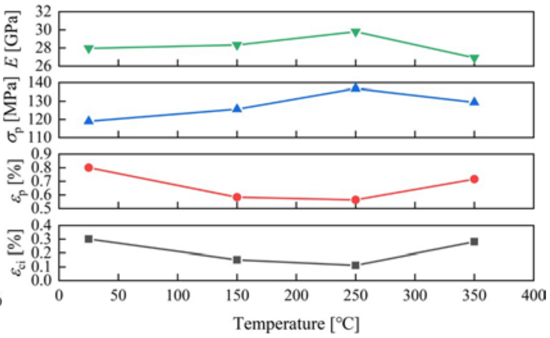


Figure 3. Stress-strain curves of granite Figure 4. Relationship between mechanical
after different high temperature treatmentsparameters of granite after high temperature
under uniaxial compressiontreatment and temperature

Figure 4. Relationship between mechanical parameters of granite after high temperature treatment and temperature

The relationship between mechanical parameters of granite after high temperature treatment and temperature is shown in Fig. 4.With the increase of temperature, the maximum axial strain in the compaction stage and peak strain first decrease and then increase, while the elastic modulus and peak stress of granite show the opposite change.It shows that when the temperature increases in the range of 25-250 ℃, the primary pores are closed and the porosity is reduced due to thermal expansion, resulting in the enhancement of the resistance to elastic deformation and bearing capacity of granite.When the temperature increases in the range of 250-350 ℃, the thermal stress is greater than the cohesion of granite, which leads to the development of pores and the increase of porosity, resulting in the weakening of the resistance to elastic deformation and bearing capacity of granite. And this is consistent with the physical test results. In summary, 250 ℃ is the temperature threshold that leads to the transformation of mechanical properties of granite.

Energy evolution of granite after high temperature treatment

The process of rock deformation and failure is essentially a process of energy evolution, so it is very important to study the differences of energy evolution of granite after different high temperature treatments. Assuming that there is no heat exchange between the rock and the outside during the loading process, the total strain energy formed from the work done of external forces is converted into elastic strain energy and dissipated strain energy. The elastic strain energy is stored in the rock. When the peak failure occurs, the elastic strain energy is released. The dissipated strain energy is mainly used for rock damage and plastic deformation.

The total strain energy U of rock under uniaxial compression is expressed by[20]

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 \tag{2}$$

where σ_1 is the axial stress and ε_1 is the axial strain.

The elastic strain energy U_e of rock under uniaxial compression is given by [20]

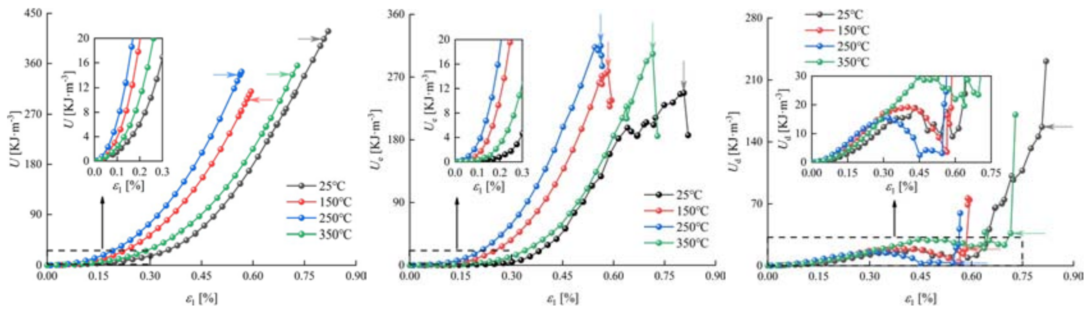
$$U_e = \frac{\sigma_1^2}{2E_u} \tag{3}$$

where E_u is the unloading modulus.

The dissipated strain energy U_d of rock under uniaxial compression reads [20]

$$U_d = U - U_e . \tag{4}$$

It should be noted that the elastic modulus can be used instead of the unloading modulus.



(a) Total strain energy(b) Elastic strain energy(c) Dissipated strain energy

Figure 5.Change in energy parameters of granite after different high temperature treatments during uniaxial compression

Fig. 5 shows the change in energy parameters of granite after different high temperature treatments during uniaxial compression. The total strain energy increases with the increase of axial strain, and the growth rate gradually increases, as shown in Fig. 5a. With the increase of axial strain, the elastic strain energy first stable increases, next fluctuates, and then decreases. The value of elastic strain energy at the peak stress reaches the maximum, as shown in Fig. 5b.Under the same axialstrain, with the increase of temperature during high temperature treatment, the total strain energy and elastic strain energy first increase and then decrease.Both the total strain energy and elastic strain energy of granite are the largest at 250 ℃.With the increase of axial strain, the dissipated strain energy first slowly increases, next decreases, then fluctuates, and finally increases sharply. The dissipated strain energy at the peak stress first decreases and then increases with the increase of temperature, as shown in Fig. 5c.The energy conversion mechanism of granite is different in different stress stages, which is mainly due to the different crack state of rock in different stress stages, thus affecting the storage and dissipation of strain energy of rock.Therefore, the ratio of elastic strain energy to dissipated strain energy is used to study the energy conversion mechanism of granite after high temperature treatment. The ratio γ of elastic strain energy to dissipated strain energy is given as

$$\gamma = U_e / U_d . \tag{5}$$

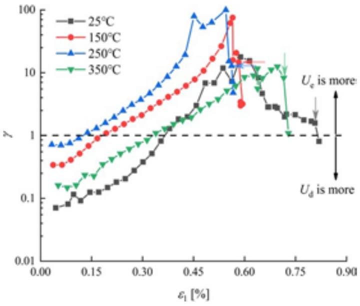


Figure 6. Change in ratio of elastic strain energy to dissipated strain energy of granite after different high temperature treatments during uniaxial compression

Fig. 6 shows the change in γ. It can be found that γ first increases, next fluctuates, and then decreases with the increase of temperature. In the compaction stage, the total strain energy is mainly converted into dissipated strain energy, so γ is less than 1. With the increase of load, the degree of crack closure increases, and the proportion of total strain energy into dissipated strain energy decreases. When the rock is in the elastic stage, the rock mainly undergoes elastic deformation, and most of the total strain energy is converted into elastic strain energy. Therefore, γ gradually increases, and the growth rate is increasing. When the rock enters the yield stage, cracks gradually develop, and the proportion of total strain energy converted into dissipated strain energy increases, so the ratio fluctuates, which is consistent with the fluctuation of the stress curve in the pre-peak stage. When the rock enters the post-peak stage, the value γ decreases rapidly. This is jointly determined by the decrease of elastic strain energy and the increase of dissipated strain energy.

The maximum value of the ratio of elastic strain energy to dissipated strain energy indicates that the proportion of total strain energy converted into elastic strain energy is the largest.It can be found that the axial strain corresponding to the maximum value of γ is not consistent with the peak strain.According to figs. 3 and 5, the stress, total strain energy, elastic strain energy and dissipated strain energy do not change abnormally in the yield stage, but γ decreases sharply. In addition, the decrease of the ratio is closely related to the crack development state. Therefore, it can be regarded as the precursor information of rock peak failure. And with the increase of temperature, the maximum value of the ratio first increases and then decreases, which indicates that high temperature will affect the energy conversion mechanism of granite, and then change its crackstate, resulting in differences in the mechanical behavior of granite after different high temperature treatments.

Conclusion

Through physical tests and uniaxial compression tests of granite after different high temperature treatments, the changes in physical-mechanical properties and energy evolution characteristics with temperature are studied. With the increase of temperature in the range of 25-350 ℃, the volume of granite after high temperature treatment increases monotonically, the mass, density and P-wave velocity decrease monotonically, and the porosity decrease first and then increase, and the change rates all increase accordingly. With the increase of temperature in the range of 25-350 ℃, the maximum axial strain in the compaction stage and peak strain first decrease and then increase, while the elastic modulus and peak stress show the opposite change. 250 ℃ is the temperature threshold that leads to the transformation of mechanical properties of granite. With the increase of axial strain, the total strain energy of granite after different high temperature treatment increases monotonically, and the growth rate increases gradually. The elastic strain energy first stable increases, next fluctuates, and then decreases, and the elastic strain energy reaches the maximum at the peak stress. The dissipated strain energy first slowly increases, nextdecreases, then fluctuates, and finally increases sharply. Under the same axial strain, bothtotal strain energy and elastic strain energy increase first and then decrease with the increase of temperature, and the total strain energy and elastic strain energy of granite are the largest at 250 ℃. The dissipated strain energy at the peak stress first decreased and then increased. With the increase of temperature in the range of 25-350 ℃, γ of granite after different high temperature treatmentfirst increases, next fluctuates, and then decreases. The maximum value of γ first increases and then decreases.

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Nomenclature

E -the elastic modulus, [GPa]

U -the total strain energy, [KJ • m^{-3}]

U_e -the elastic strain energy, [KJ • m^{-3}]

U_d -the dissipated strain energy, [KJ • m^{-3}]

E_u -the unloading modulus, [GPa]

Greek symbols

σ_1 -the axial stress, [MPa]

ε_1 -the axial strain, [%]

$\Delta\sigma_1$ -the increment of axial stress in the elastic stage, [MPa]

$\Delta\varepsilon_1$ -the increment of axial strain in the elastic stage, [%]

γ -the ratio of elastic strain energy to dissipated strain energy, [-]

Acronym

HDR- Hot dry rock

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