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ScienceDirect
Procedia Earth and Planetary Science 1 (2009) 565–570
Procedia Earth and Planetary Science
www.elsevier.com/locate/procedia

The 6th International Conference on Mining Science & Technology

Research status quo and prospection of mechanical characteristics of rock under high temperature and high pressure

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Abstract

The mechanical features of rock have significant relevance to temperature. The problems related to temperature are becoming a hot geotechnical research field. The paper summarized the rheological characteristics, failure, instability modes at high temperature and high pressure, rules of elastic modulus and thermal expand coefficient changing with temperature, as well as the thermal-induced failure characteristics of rock affected by temperature and pressure, and finally prospects the research directions of high temperature rock mechanics.

Keywords: high temperature and high pressure, rock, mechanical characteristics, prospect

1. Introduction

In geophysical studies, high temperatures refer to the temperatures above 50℃, and high pressures are defined as the pressures over 0.3GPa. Generally, the so-called high temperatures and high pressures include all temperatures and pressures ranging from normal temperatures (10℃~50℃) to ultra-temperatures (>1500℃) and low pressures (0.l~3.0MPa) to hyperpressures (>3.0GPa) [1, 2]. The present high temperatures and high pressures are the general concept mentioned above.

2. Mechanical characteristics of rock under high temperatures and high pressures

Geothermal exploitation and deep oil drilling often involve studies on heat stress and thermodestruction in rock mass engineering, therefore, it is necessary to study modes of deformation and failure, rheological characteristics and strength characteristics at high temperatures and high pressures.

2.1. Mechanical behavior of rock under high temperature and high pressure

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doi:10.1016/j.proeps.2009.09.090

As the temperature increases, rock and fluid media become active, which induces rock deformation and failure and makes the mechanism be apt to plastic flow. On the other hand, the increasing of pressure inhibits tension crack while strengthens friction, which is beneficial to the rock deformation activation. Meanwhile, under high temperatures and high pressures, the time effect of rock deformation becomes increasingly evident, and more time also facilitates rock media activation and deformation from brittleness to ductility [2].

1) Rock rheology under high temperatures

Kirby [3] discovered the law of rock rheology in experimental studies

$$\dot{\varepsilon} = A\sigma^n \exp\frac{-Q}{RT} \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate; σ is the deviatoric stress (σ_1-σ_3); R is the gas constant; T is the temperature; Q is the activation energy; A, n are the experimental constants。

The equation of rock rheology stress (creep resistance) can be derived from Equation (1)

$$\sigma = (\frac{\varepsilon}{A})^{\frac{1}{n}} \exp(\frac{Q}{nRT}) \tag{2}$$

From 1970s, plentiful achievements have been made in the experiments of rock mechanics under high temperatures and high pressures, and the three parameters in rock creep deformation Q, A and n have been determined[4-12]。

2) Failure mode of rock under high temperatures and high pressures

Generally, at room temperature, rock is often in brittle failure mode. As the temperature and pressure increase, the rock failure mode changes from brittle (fracture) to semi-brittle and then transits semi-ductility and ductility (yield, flow) [13]. However, the temperature of brittle-ductile transition for different kinds of rocks varies [14-19]. The basic element affecting the transition is the increase of plastic component or fluidity. Other factors such as mineral components of rock, temperature, stress, strain ratio etc. can also affect the transition by changing plastic components.

Fig. 1 is the deformation curve of iherzolite at different temperatures under high confining pressures [20]. It can be seen that, at room temperature, the rock specimen is brittle or totally elastic (Curves1,2), and in this case, the curve appears to be a skew line; when the temperature reaches certain point, the curve of mechanical characteristics will curl and deform, i.e., the deformation changes from brittle mode to ductile mode (Curves 3, 4, 5). It is evident that temperature has great influence on rock deformation characteristics.

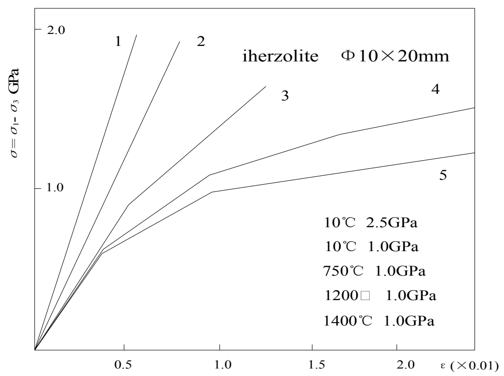


Fig. 1. The influence of temperature on mechanical characteristics of peridotite [20]

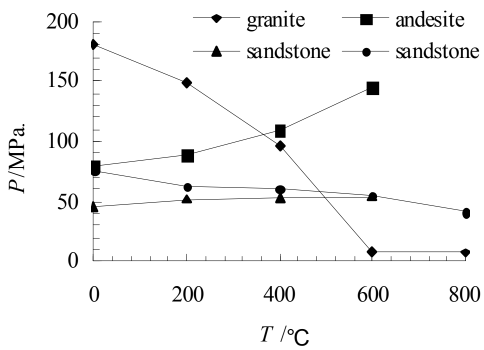


Fig. 2. The relation of experimental temperature and rock strength [23]

The confining pressure also imposes influence on the rock brittle-ductile transition. Tullis et al [17, 18] have conducted an experiment on feldspar aggregation with moisture content of 0.1%, granularity of 2~109 μm. The result shows that, when the temperature gets 900℃, the strain rate is 2×10^{-5}/s, the confining pressure is 600 MPa, the deformation of feldspar is mainly embrittlement cracking flow with little dislocation creep. When confining pressure increases to 1.5 GPa, the deformation is basically creep deformation.

3) Rock instability mode under high temperatures and high pressures [1, 2]

As the confining pressure increases, the discrepancy between peak strength and residual strength of rock becomes smaller and smaller, the minus rigidity segment of stress-strain curve tends to slow down under the same pressure, and there is possibility of transition from outburst instability to progressive instability. Progressive instability is the progress, in which the test specimen chunk dislocated slowly along insequent fracture zone. The process is companied by backing-off cutting of fracture zone jog, equalization of resistance distribution and the decline of the integral sustaining stress of test specimens.

When the confining pressure keeps growing to certain point, the residual strength will be close to or even reach the peak strength because of the significant increasing of frictional resistance on fracture plane. The mode of instability thus takes the form of stable sliding or stick slip along the main fracture zone. Dislocation of progressive instability is basically a stable sliding progress. However, in terms of the initial of equilibrium state, the system of forces is instable, thus the later course is an instable process.

2.2. Variation of rock mechanical parameters under high temperatures and high pressures

1) Effect of temperature on rock strength

The result of effect of temperature on rock strength is shown in Fig. 2. It is clear that the compressive strength of crystalline rock like granite and limestone declines dramatically as the temperature grows, and the strength of noncrystalline rock like sandstone has little change, but the andesite's strength improves remarkably.

The linear decrease of rock strength like granite and limestone is possibly interrelated with following factors. (1)The mineral components of rock have different thermal expansivity. The anisotropy of anisometric crustal leads to the anisotropy of thermal conductivity and coefficient of linear expansion, which enables strain store between crystalline particles, hence there is possibility of defect, stripping, fracture and remnant after cooling;（2）The crystal particle of 400℃ granite slice has considerable amount of fractures, thus thermal fragment expands freely inside the crystal under the temperature.（3）Pre-cracking and some coillquable, labile, evaporable minerals in rock can also cause the strength to decrease.

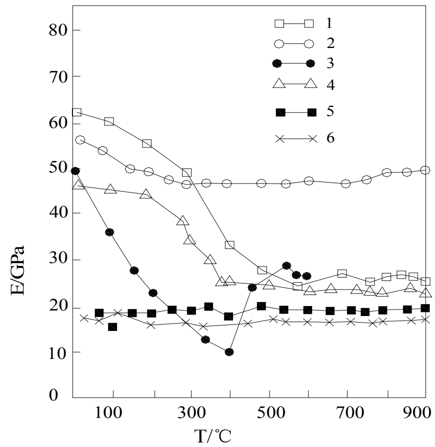
For rocks like andesite and sandstone, the strength increasing with little change after heating is possibly related to agglomeration. This kind of rock contains a lot of clay substance and cement, thus agglomeration makes these particles of umite closer and the strength also increases. The rock particles are free from slippage because of deaquation. In addition, the porosity of these rocks are large, as the temperature increases, the minerals of rock produce thermal expansion, which minimizes the fractures and makes the rock compact, the strength can possibly be improved by chance.

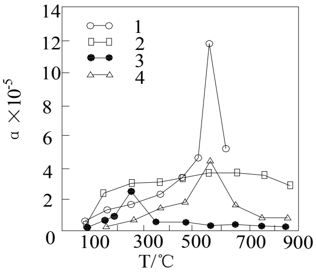
2) Effect of temperature on rock elastic modulus

Rock elastic modulus is a parameter indicating rock elasticity characteristics. It can be divided into the moduli of longitudinal elasticity (Young's modulus of elasticity), shear modulus and bulk modulus of elasticity.

The variation of elastic modulus after rock heating plays an important role in calculating inner rock heat stress and heat failure produced by heating. Fig. 3 is the case/condition of Young's modulus variations with temperatures for all kinds of rocks. It is obvious that under 300℃, for rocks like andesite, granite and quartz trachyte. Young's modulus dramatically decreases while the temperature increases. But over 300℃, Young's modulus almost remains unchanged. However, the elastic modulus of tuft and pottery stone has little change as the temperature increases.

The influence of temperature on Young's moduli of various rocks differs from each other. For rocks with same chemical components, the influence of temperature on Young's modulus is similar. For rocks like SiO_2, the modulus gradually decreases as the temperature increases, for example, when the temperature rises from 20 ℃ to 600℃, Young's modulus decreases about 20% to 30%. For anhydrous carbonate, Young's modulus is a constant when temperature is under 800℃.





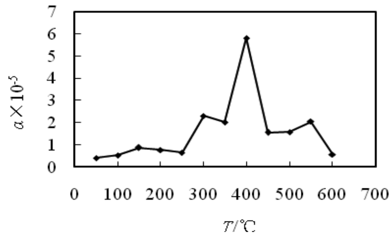


Fig. 3. *E~T* relation curve 1, 2 Andesite; 3 Granite; 4 Quartz trachyte; 5 Pottery stone; 6 Tuft

Fig. 4. The coefficient of rock linear expansion and temperature 1-granite; 2-limestone; 3-andestie; 4-sandstone

Fig. 5. Relationship of granite's linear expansion coefficient and temperature under triaxial pressure

3) Effect of temperature on coefficient of thermal expansion

Coefficient of linear expansion is the strain amount in length when the temperature of test specimen increases 1 ℃. The coefficient affects the heat deformation and heat stress of mechanical engineering, which directly relates to the steady and safety of mechanical engineering. Therefore, the rock linear coefficient should be determined.

Tsutomn has measured the four coefficients of linear expansibility with temperature variation and drawn the *α-T* curve in Fig. 4. The changing for limestone is slow; the coefficient has little change as the temperature grows. The coefficients for sandstone, andesite and limestone change greatly, also with a maximum value.

The discrepancy between the maximum value and α value under room temperature can be 24 to 120 times. The chance of a maximum value for granite is possibly related to the relative humidity of quartz at 573 ℃.

But according to the research of Wan et. al., the granite's linear heat expansion coefficient under triaxial pressure is less than Tsutomn's results. Rock mass is usually in triaxial pressure condition, so the results of Wan et. al. fit practice more.

3. Thermal cracking characteristics of rock

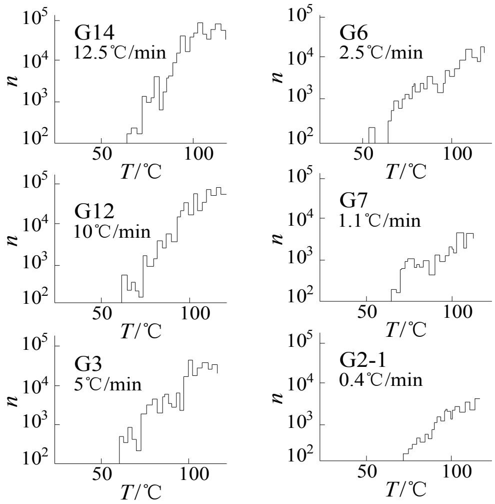
Rock is consisted of many kinds of minerals whose thermal expansion coefficients are different when being heated, leading to cracks in the boundary of these mineral particles and expansion of the inner cracks that result in connection with each other , forming crack network, which gives rise to physical characteristics (extent of porosity, permeability) change of the reservoir rocks. That is the thermal cracking phenomena of rocks. Thermal-cracking is of great theoretical significance and application value to exploitation of the geothermal resources, mining and nuclear waste storage as well as materials science. So the study on thermal-cracking has caused wide public concern.

Many studies (Chen, et al, H. F. Wang, et al) have shown that US Westerly granite experienced thermal-cracking when heated to about 75℃（60~70℃ in Chen's opinion）. The cracking is also companied by AE phenomenon. The higher the heating rate, the higher the AE count rate. Heating rate has no obvious influence on the AE threshold.

Fig. 6 is the experimental results from Chen, et al. The experiment discovers that 60~70℃ seems to be a threshold of the temperature. AE emerges in the rock once the temperature exceeds the threshold value. Although the acoustic emission rate is high when the heating rate is high, the temperature threshold is of no concern to heating rate when acoustic emission appears.

Chen Yong, et al, conducted experiments using rock specimens from Dongying, Shandong province. Firstly, the rock specimens were heated to certain temperature, then cooled to room temperature and soon the permeability was measured. The relation between permeability of the rock specimens and the heating temperatures is shown in Fig. 7. Rock has a temperature threshold of about 110~120℃. Once it meets or exceeds the temperature, the permeability of rock specimens will increase 8~10 times the initial, and as the heating goes on, the permeability increases slowly.

The permeability change can be described by percolation ode. According to the percolation mode, with a temperature increase, the internal cracks of rock increase constantly. Integral permeability changes obviously only when the cracks are connected into network.



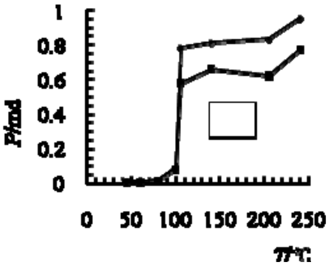


Fig. 6. Experimental results of the acoustic emission variation as the temperature varies [26]
Fig. 7. Relation curve between permeability of carbonate and temperature [29]

4. Prospection

With the advance of human society, more and more problems related to temperature occur, such as UCG, coal's directly liquidation in situ. These problems need research mechanical characteristics of coal under high temperature s and high pressures. Up to now, there have no achievements about this field, especially research of large size coal samples. It will be an important hot field in future [30].

5. Conclusions

The paper summarized the rheological characteristics, failure, instability modes at high temperatures and high pressures, and the rules of elastic modulus and thermal expand coefficient changes with temperature, as well as the thermal-induced failure characteristics of rock affected by temperature and pressure. With the advance of human society, the research of mechanical characteristics of coal under high temperatures and high pressures will be an important hot field in future.

Acknowledgements

Financial support for this work, provided by the key program (50534030) of National Natural Science Foundation of China, is gratefully acknowledged.

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