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Evaluation of thermal properties of geothermal reservoir rocks under high temperature and stress

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ABSTRACT

The thermal physical parameters of rocks are the main controlling factors of the temperature field in geothermal engineering. Firstly, the thermal conductivity of Republican granite, Kangding granite, and Songliao sandstone at different high temperatures and axial stress loading were determined based on the steady-state plate method and the mechanism of the evolution of thermal conductivity for rocks with different porosity was further analyzed. Secondly, the evolution of thermal expansion coefficients of the three types of rocks at ultra-high temperatures was determined. Finally, the evolution of the specific heat capacity of the three types of rocks at different temperatures was determined based on the hybrid cooling method. The study shows that the thermal conductivity of all three types of rocks decreases slightly with increasing temperature and increases slightly with increasing stress and that the thermal conductivity of rocks with high porosity is more sensitive to stress and decreases with further increase in stress; the thermal storage capacity and thermal deformation behavior of all three types of rocks increase with increasing temperature. In particular, the larger the mineral grains, the more significant the thermal deformation behavior of the rocks. This study helps to provide a basis for the design and construction of geothermal projects and enriches the study of rock thermal properties.

1. INTRODUCTION

Geothermal energy as a stable and renewable clean energy source has received widespread attention from countries around the world[1]. Geothermal energy can be classified by temperature and depth characteristics into shallow geothermal, medium and deep hydrothermal type geothermal, and dry heat rock types geothermal. The lithology of geothermal reservoir rocks includes sandstone, carbonate rock, and granite. The thermal physical parameters of the rocks are one of the controlling factors for the temperature field distribution characteristics of the engineered rock mass. However, geothermal reservoirs are located in a high-temperature and high-pressure underground environment [2], and the accurate acquisition of thermal physical parameters of reservoir rocks under high temperatures and high stress has been a difficult task in geothermal engineering design and heat recovery potential assessment.

Deep high-temperature geothermal resources have huge reserves and are widely distributed. Under the action of thermal coupling, the accurate acquisition of thermal property parameters of rocks in thermal reservoirs and their evolution laws are important guides for the engineering design and reasonable operation of dry heat rock projects, and they are significantly different from the unconstrained case. In recent decades, the accurate acquisition of the thermal properties of rocks has received much attention, mainly around the evolution of the thermal conductivity, thermal expansion, and specific heat capacity of rocks with temperature, stress, and the properties of the rocks themselves [3]. The thermal properties of rocks are very complex and difficult to express in mathematical models. They depend not only on the stress and temperature of the host environment but are also significantly influenced by their structure, such as the type and content of minerals, the distribution and density of pores and fractures in the rock, and the presence of multiphase fluids in the rock pores.

In terms of heat transfer, the physical process involved is heat transfer from a high-temperature matrix rock to a low-temperature fractured rock. Currently, the thermal conductivity of rocks is accurately obtained mainly through indoor tests, and the methods of determination are divided into steady-state and non-steady-state methods[4]. The steady-state method is affordable, simple to operate, and provides accurate results Non-steady-state methods are fast and allow the non-homogeneity of the thermal conductivity distribution at the sample scale to be studied. Rocks are typically multi-phase porous materials, resulting in numerous heat transfer patterns and their complex influencing factors. Currently, studies on the influence of the thermal conductivity of rocks on their properties have focused on mineral fraction, saturation, pore fluid type, porosity, and pore structure [5-8]. The effects of temperature and stress on the thermal conductivity of deep dry-heated rocks in high-temperature and high-pressure environments have also received increasing attention, with the temperature effect focusing on heat treatment, thermal cycling, and real-time high-temperature conditions [7, 9, 10] and the stress effect on the evolution of the thermal conductivity of rocks under uniaxial stress, conventional triaxial compression, and cyclic loading and unloading conditions [11-13]. A large number of studies have pointed out that the volatilization of free and bound water, the generation of thermal fractures, and the reduction in the thermal conductivity of minerals are the main reasons for the reduction in thermal conductivity of rocks under the effect of temperature; the reduction in the thermal resistance of contact between pore compacted mineral particles under the effect of stress leads to an increase in thermal conductivity, but the further increase in stress causes damage to the rock resulting in a reduction in thermal conductivity. It can be seen that the mechanism of the evolution of the thermal conductivity of rocks under the effect of thermal coupling is not clear. The local geothermal heat flow background can be assessed by drilling temperature gradients and determining the thermal conductivity of rocks to locate the regional geothermal distribution for resource assessment [14].

In geothermal numerical simulations, such evolution inevitably leads to corresponding changes in the thermal physical parameters of the rock, which involve numerous physical parameters of bedrock, fractures, workings, thermal physical parameters, and related coupling parameters in the numerical simulation of geothermal mining. In previous studies, the definition of thermal physical parameters was mostly selected empirically or by reference to others' literature, without experimental data support [15, 16]. Most studies have assumed that the thermal properties of rocks are constant and do not vary with temperature and pressure, but in reality, the thermal properties of rocks vary with temperature and pressure, which inevitably leads to the evolution of the temperature field during geothermal mining. Therefore, a numerical model of thermal energy extraction, combined with the results of indoor experiments on thermal physical parameters, is particularly necessary to assess the thermal recovery performance of thermal reserves.

In summary, the thermal physical parameters of rocks have been widely studied, but there is no comparative study of the thermal physical parameters of rocks from a variety of geothermal reservoirs. In this paper, the evolution of the thermal conductivity, thermal expansion coefficient and specific heat capacity of three types of rocks subjected to temperature, stress or coupled temperature-stress are compared, using the rocks from the high geothermal background of China, Kangding Granite, Republican Granite, and Songliao Sandstone, as the objects of study.

2. APPARATUS AND METHOD FOR TESTING THERMAL PROPERTIES

2.1 Rock specimen preparation

The three types of tested rock samples for the determination of rock thermal property are cored from the geothermal storage deep boreholes in the Kangding area, Qinghai Gonghe area, and Songliao Basin area in China. The geothermal heat flow is an important parameter to characterize the regional geothermal background. The geothermal heat flow in the three study areas are Kangding: 64~101mw/㎡; Gonghe: 77.6~106.2mw/㎡; Songliao: 56.9~84.9mw/㎡, the heat flow values are higher than the average geothermal heat flow value in China: 61.5±13.9MW/㎡ indicates that the study areas have a high geothermal background[17, 18].

In this study, the three types of rock samples were cut into Φ50×25mm cylinders to determine the thermal conductivity. The rock samples were cut into Φ8.5×50mm cylinders to determine the coefficient of thermal expansion. Each cylinder sample was ground and polished to ensure that both ends and sides were smooth and complete. Part of the original rock is crushed and ground into powder for the determination of specific heat capacity (see Fig. 1). To reduce the influence of water on the test results, the samples were processed for 3 days after natural drying before the determination of thermal properties.

2.2 Determination of the thermal conductivity of rocks

Heat transfer from high-temperature rock regions to low-temperature rock regions is one of the important heat transfer problems involved in geothermal extraction, where thermal conductivity is a central parameter in assessing the process. The thermal conductivity of three types of rock was determined using the split-bar method of the steady-state method recommended by the International Society of Rock Mechanics [4]. The instrument used for the rock thermal conductivity experiments was the DRPL-3B thermal conductivity test system, which determines the thermal conductivity at different axial stresses and temperature states. The load range of the system is from 0 to 30,000 N (±0.1 N) and the heating range is from room temperature to 180°C (±0.1°C).

To investigate the heat transfer properties of rocks under thermal coupling, the experimental temperatures in this study were 30°C, 60°C, 90°C, 120°C, 150°C and 180°C, and the test temperatures reached the temperature levels of dry-heat rock-type geothermal resources. For each set of experiments, the rocks were first heated to the target temperature and then the thermal conductivity of the rocks was measured at 0MPa, 3MPa, 6MPa, 9MPa, 12MPa, and 15MPa axial stresses in turn.

According to Fourier's law, the expression for the thermal conductivity of the rock is as follows.

$$\lambda = \frac{qL}{(T_1 - T_2)} \tag{1}$$

where λ, q, L, T_1, and T_2 are thermal conductivity, heat flux, sample thickness, hot surface temperature, and cold surface temperature, respectively.

2.3 Determination of the coefficient of linear expansion of rocks

The study of the thermal deformation behavior of rocks at high or ultra-high temperatures is of great importance for geothermal development projects, and this thermal deformation is usually characterized by the coefficient of thermal expansion. The coefficient of thermal expansion of rocks was determined using the ZRPY-1000 thermal expansion meter at temperatures up to 1000°C (±0.1°C) and deformations in the range of 1.5 mm (±0.1 um).

To investigate the thermal deformation behavior of rocks under high-temperature action, the specimens were raised from room temperature to 1000°C at a heating rate of 10°C/min in this study, with the test temperature covering the temperature level of the geothermal reservoir. The coefficient of thermal expansion was calculated as follows.

$$\alpha = \frac{\Delta L_t - K_t}{L(t - t_0)} \tag{2}$$

where L, ΔL_t, K_t, $(t\text{-}t_0)$ are the length of the sample at room temperature, linear deformation of the specimen when heated to t °C, test system compensation value at t °C and temperature difference between sample heating temperature and room temperature, respectively.

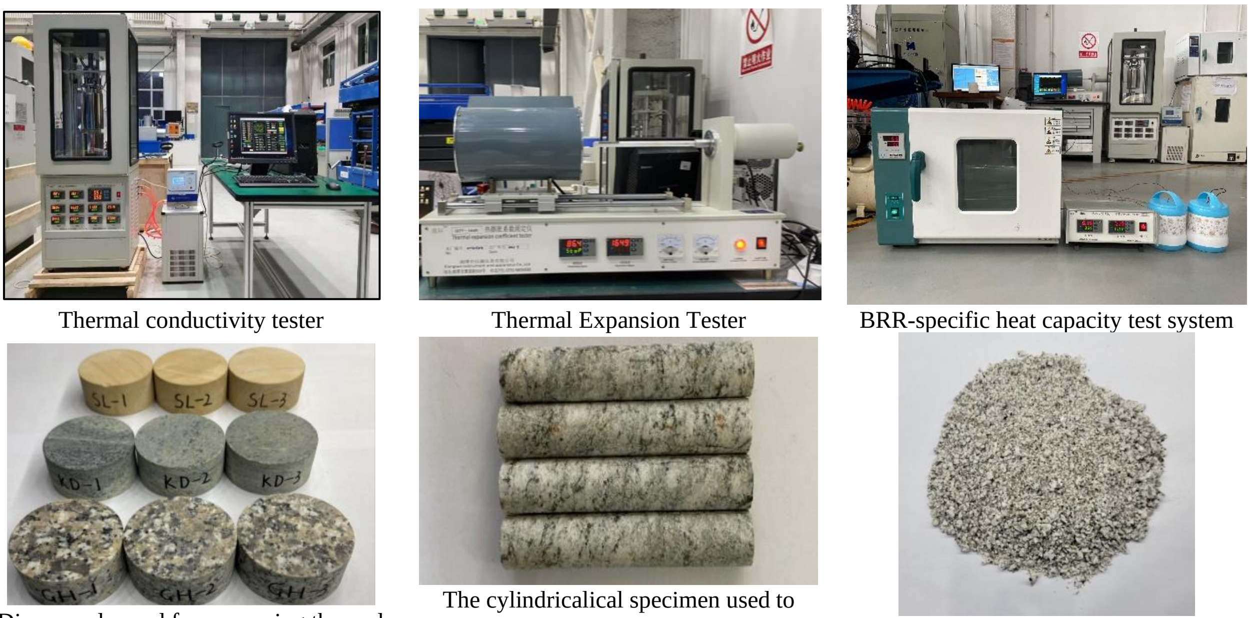
2.4 Rock-specific heat capacity determination

The specific heat capacity of rocks is an important parameter for assessing the total thermal energy contained in thermal reserves. In this paper, the specific heat capacity of three types of rocks was determined using the BRR-specific heat capacity test system based on the hybrid cooling method of energy conservation.

The powder specimens were first heated to 50°C, 100°C, 150°C, 200°C and 250°C using a muffle furnace, followed by rapid mixing of the specimens with water to test temperatures up to the temperature level of a dry-heat rock-type geothermal resource. Experimental results were more accurate when the ratio of water to rock is 4:1. In this study, we chose the mass of the rock to be 80g and the mass of the water to be 320g, and the specific heat capacity is calculated as:

$$C_m = \frac{G_1 \times C_w (t_3 - t_2)}{G_2 (t_1 - t_3)} \tag{3}$$

where C_m, C_w, t_1, t_2, t_3, G_1, and G_2 are the specific heat capacity of the rock, the specific heat capacity of the water, the temperature of the rock powder after heating, the temperature of the water, the temperature of the mixture, the weight of water and weight of the specimen, respectively.



Thermal conductivity tester | Thermal Expansion Tester | BRR-specific heat capacity test system

Disc sample used for measuring thermal conductivity | The cylindricalical specimen used to determine the coefficient of thermal expansion | Powder sample used to determine the specific heat capacity

Figure 1:Thermal property measurement systems and test specimens

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Thermal conductivity

3.1.1 Effect of temperature and axial stress

The porosity and thermal conductivity of the three rock types were first determined at ambient temperature and pressure. In particular, porosity is a fundamental physical characteristic of rocks that determines the flow path of heat in the heat transfer process of rocks, and the porosity of rocks is one of the essential characteristics that causes the variability in the thermal conductivity of rocks. According to the saturated drainage method, the principle of which is to calculate the mass difference after drying by vacuum saturation treatment, the expression for the porosity of a rock is as follows:

$$\phi = \frac{4(M_S - M_d)}{\pi D^2 L \rho_w} \tag{4}$$

where D, L, $(M_s\text{-}M_d)$ are the the diameter of the sample, the height of the sample, and the difference between full water mass and dry mass, respectively.

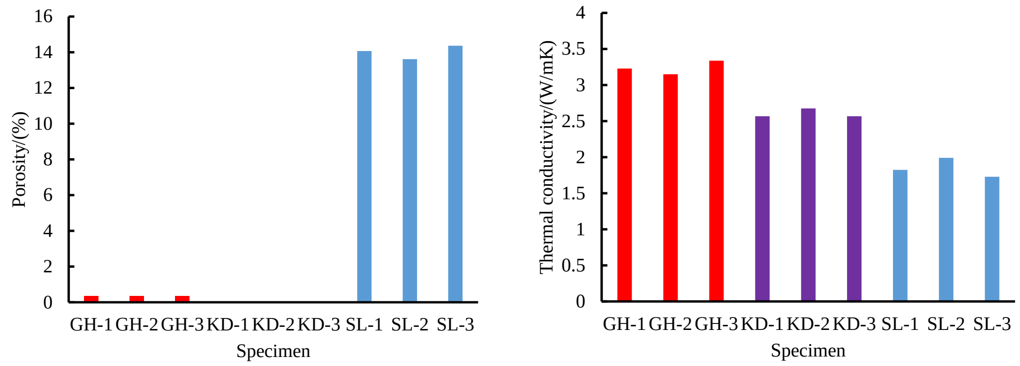


Figure 2: (a) initial porosity of the three rock types; (b) initial thermal conductivity of the three rock types

The test results show that the porosity in descending order is Songliao Sandstone, Republican Granite, and Kangding Granite; the thermal conductivity in descending order is Republican Granite, Kangding Granite, and Songliao Sandstone.

The graph below gives the evolution of the thermal conductivity of the three types of rock with axial stress at different temperatures. From the figure, it can be found that the thermal conductivity of the rocks gradually decreases with increasing temperature and gradually increases with increasing axial stress.

Usually, the microfractures within the rock gradually close under stress, increasing the contact between mineral grains and reducing the thermal resistance, resulting in a higher thermal conductivity of the rock. At 30°C when the axial stress exceeds 3 MPa the thermal conductivity of Republican and Kangding granites barely varies with the axial stress, indicating that it becomes difficult to compress the fractures at this point and 15 MPa the thermal conductivity increases by 4%, and 2% respectively. The thermal conductivity increases non-linearly at 150°C when the axial stress is below 3 MPa, and almost linearly with axial stress after 3 MPa, increasing by 12.3% and 7.7% at 15 MPa, respectively, indicating that the increase in temperature increases the thermal conductivity with stress. This is because higher temperatures can induce more thermal fractures to sprout in the rock, and the closure of thermal fractures occurs under stress.

The Songliao sandstone is more porous than granite, and there is a difference in the evolution pattern of thermal conductivity under high temperature and pressure. From the test results, it can be found that the thermal conductivity of Songliao sandstone increases more significantly with stress. The thermal conductivity increases by 27% at an axial stress of 15 MPa at 30°C. The thermal conductivity of rocks with high porosity is more sensitive to stress. In addition, sandstone thermal conductivity is highest at 60°C, due to the expansion of mineral grains in the lower heating range, which increases contact and reduces thermal resistance, which in turn leads to an increase in thermal conductivity.

Thus, temperature and stress have an important influence on the thermal conductivity of rocks, and rocks with high porosity are more sensitive to stress.

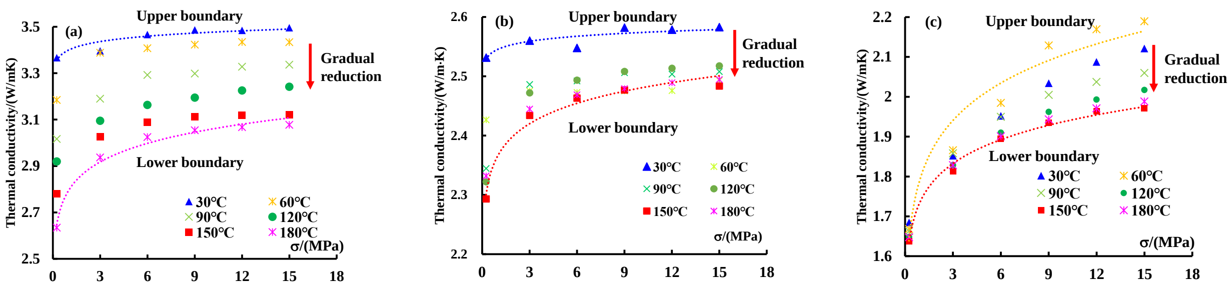


Figure 3: Evolution of the thermal conductivity of rocks under temperature and axial stress (a) Republican granite (b) Kangding granite; (c) Songliao sandstone.

<u>3.1.2 Effect of high axial stress</u>

Mid-deep geothermal resources are endowed with a high temperature and pressure environment in the subsurface, and as the depth of burial increases, the temperature and ground stress levels to which the rocks are exposed also gradually increase. Therefore, the evolutionary mechanism of the thermal conductivity of rocks under real-time high temperature and high-stress conditions needs to be further considered. In this paper, the evolution of the thermal conductivity of the Songliao sandstone under axial stresses of up to 60 MPa at room temperature is initially investigated. The test results show that the thermal conductivity increases and then decreases with increasing axial pressure. The uniaxial stress-strain curve of the Songliao sandstone shows that the yield stress is about 40 MPa and the peak stress is about 80 MPa, indicating that with the gradual increase of the axial stress, the internal rupture of the rock occurs, which hinders the heat energy transfer path and increases the thermal resistance of the rock, thus decreasing the thermal conductivity.

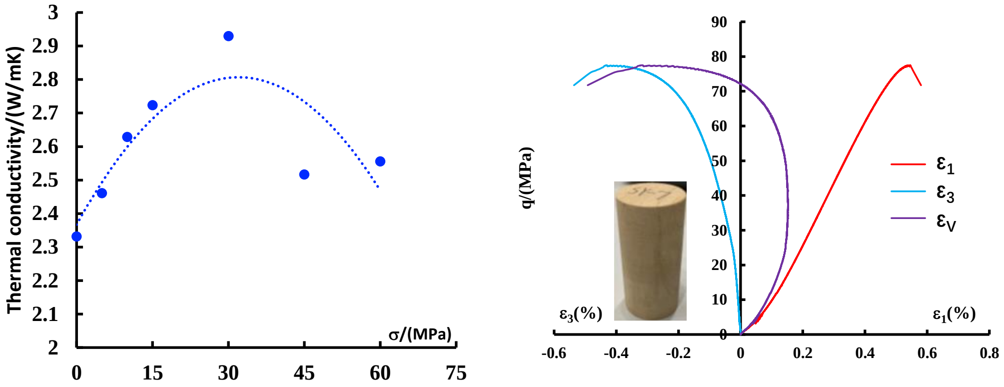


Figure 4: (a) Evolution of the thermal conductivity of Songliao sandstone with axial pressure at room temperature, (b) Uniaxial stress-strain curve of Songliao sandstone

3.2 Thermal expansion

The graph below gives the variation curves of thermal strain and thermal expansion coefficient with increasing temperature for the three types of rocks. As can be seen from the graphs, the thermal strain and coefficient of thermal expansion of the three types of rocks generally increase with increasing temperature, but the change process shows a multi-stage characteristic, with a sudden change point of the linear expansion coefficient at around 573°C, which has a significant non-linearity, mainly because the quartz in the rock undergoes a phase change at 573°C, thus sprouting a large number of micro-cracks, which makes the specimen expand rapidly in volume; with further increase in temperature, the reaches the temperature at which the phase change or even decomposition of other minerals within the granite occurs, allowing the thermal strain to continue to grow. Furthermore, the evolution of thermal expansion with temperature is consistent for all three rock types and is on the order of 10-6. The thermal expansion of the Republican granite is greater than that of the Kangding granite, reflecting the sensitivity of the different grain sizes to temperature, which will provide some reference for the macroscopic mechanical behavior of the rocks at high temperatures and pressure under different grain sizes.

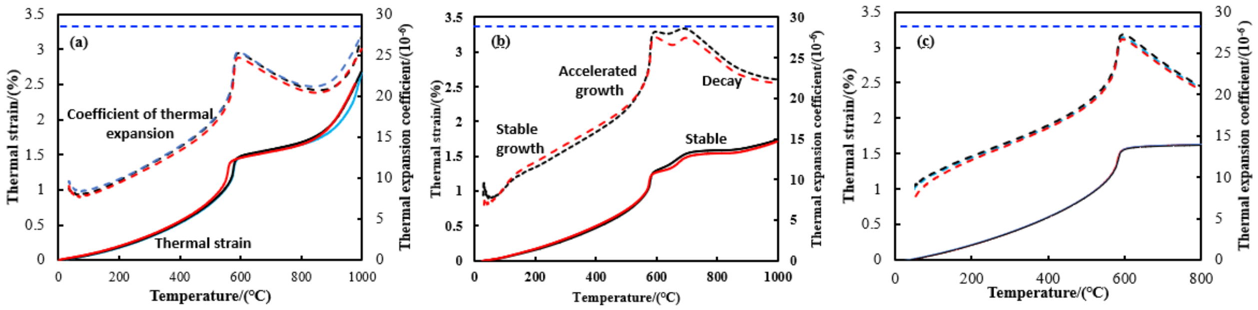


Figure 5: Evolution of thermal strain and thermal expansion coefficient with temperature of rocks (a) Republican granite (b) Kangding granite; (c) Songliao sandstone.

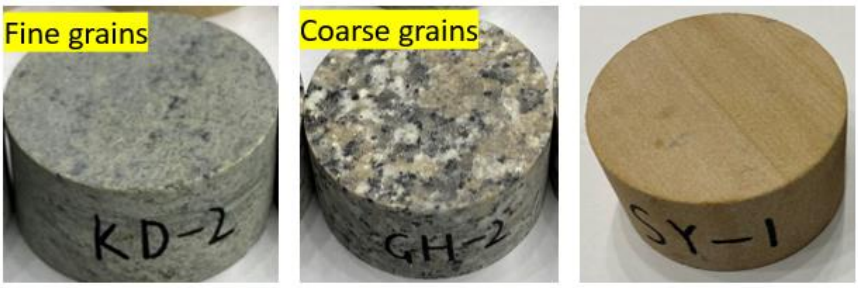


Figure 6: Three types of rock (a) Republican granite; (b) Kangding granite; (c) Songliao sandstone.

3.3 Specific heat capacity

The specific heat capacity of a material is the amount of heat absorbed (or given off) by an increase (or decrease) in temperature of 1°C in a certain process, for an object of mass m, without a phase change or chemical reaction. The temperature interval studied in this paper is 50°C-250°C. In this temperature range, there are only physical reactions within the rock, i.e. volatilization of free and bound water and crack initiation due to thermal cracking, and no chemical processes such as quartz phase change and thermal decomposition of mineral decarbonization.

The reason for the increase in the specific heat capacity of rock materials with increasing temperature is related to the lattice vibrations of the solid. Rocks are composed of a large number of mineral crystals, and the rock components measured are mainly inorganic materials, consisting mainly of ionic and covalent bonds, so that in the temperature range where no phase change occurs, the specific heat capacity of the rock conforms to the medium temperature zone of the Debye model, i.e. the specific heat capacity is positively correlated with temperature; on the other hand, thermal cracking of the rock occurs at high temperatures, and some of the heat energy absorbed makes the rock expand in volume and induces thermal crack sprouting On the other hand, thermal cracking occurs at high temperatures, where some of the heat absorbed expands the volume of the rock and induces the development and expansion of thermal cracks.

The results show that the specific heat capacity of Songliao sandstone increases significantly with increasing temperature, while it already shows a tendency to enter the high-temperature region of the material, with a gradual slowdown in growth. This also indicates that the increase in specific heat capacity with temperature is limited.

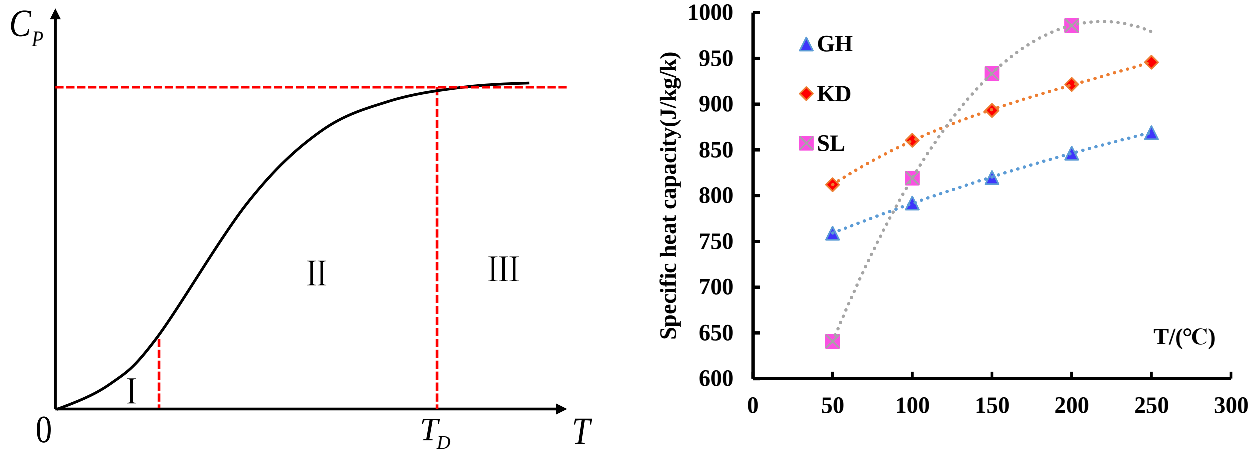


Figure 7: (a) Characteristic curve of mineral crystal heat capacity as a function of temperature (b) Specific heat capacity of three types of rocks and its evolution with temperature.

4. CONCLUSION

(1) There are obvious differences in the thermal conductivity of the three types of rocks under thermal action. The thermal conductivity of all three types of rocks decreases continuously with increasing temperature and increases continuously with increasing pressure, but the difference in porosity of the three types of rocks makes the response of the Songliao sandstone to pressure the most sensitive and the thermal conductivity of the Kangding granite with the lowest porosity the least sensitive to pressure, and it is found that with further increase in stress, the thermal conductivity of the rocks will show a peak point, and when the stress reaches the yield stress point of the rocks The thermal conductivity of the rock will appear to decrease when the stress reaches the yield stress point of the rock.

(2) The thermal expansion coefficients of the three types of rocks show different phases of change with increasing temperatures up to 1000°C. All of them appear at the phase change point of quartz. The peak thermal expansion coefficients of the rocks are obtained near the peak of the phase transition point of the quartz, and there is little difference in the thermal expansion coefficients of the different rocks. The evolution pattern of thermal expansion with temperature is consistent for all three rock types and is on the order of 10-6; the evolution pattern of the coefficient of thermal expansion is due to a combination of thermal expansion of rock minerals, decomposition of rock minerals and the occurrence of thermal cracking.

(3) The specific heat capacity of the rocks increases with increasing temperature. The heating temperature range of all three types of rocks is within the physical range of occurrence, and the increasing specific heat capacity of the rocks with increasing temperature is due to lattice vibrations in the atoms. The higher specific heat capacity of Kangding granite among the granites indicates that Kangding granite has richer thermal resources under the same temperature conditions of thermal storage, which is conducive to dry-heat rock-type geothermal development. The specific heat capacity of the Songliao sandstone varies most significantly with temperature, but the growth trend is gradually slowing down. The specific heat capacity of rocks increases with temperature, indicating that high-temperature rocks will be able to store more thermal energy and release more energy when the rocks are destroyed compared to room-temperature conditions

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