Effect of meso-structure on thermal conductivity of deep granite

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Abstract. In order to study the correlation between meso-structure and thermal conductivity of deep rocks at high geo-temperature, the thermal physical tests were carried out on the granite samples in the depth of 1500m to 2000m in Sanshandao, firstly, the polarizing microscope was used to test the micro characteristics, the nuclear magnetic resonance was used to test the distribution of pore structure, finally, the heat transfer characteristics of dry and wet rock in medium and high temperature environment are obtained by using transient plane source method. The influence of external environment and meso-structure of rocks on thermal conductivity was discussed. The results show that the denseness, porosity, pore size distribution, the way of connection, quartz content between mineral particles and the degree of claying directly will affect the thermal conductivity of rock, among which the denseness and claying have the greatest influence on the thermal conductivity compared to other factors. The results of drying and watering cycle at 60°C test show that the damage of rock internal structure caused by temperature cyclic load can not to be ignored, which can change the thermal conductivity of rock, the increase of pore water content after water saturation treatment enhances the heat transfer performance of rock. The research results provide a data basis and new insights on the thermal conductivity of deep fragmented granite under high geo-temperature and high hydraulic conditions.

1. Introduction

Deep rocks are in a high geo-temperature environment, and the mesoscopic characteristics and thermal conductivity have obvious differences compared with shallow strata [1]. Thermal conductivity can not only cause changes in the temperature field of the wall rock, but is also an important cause of many engineering disasters. Therefore, it is of great significance for the stability of rock mass engineering to study the evolution characteristics of meso-structure and thermophysical parameters of deep rock under the high geo-temperature [2-3].

The research on thermal conductivity of rock mainly included the characteristics of rock and the external environment. P.K.Gautam [4,5] pointed out that mineral composition and water content will cause changes thermophysical properties in rock. Kaemmlein [6] studied the influence of mineral particle size range on thermal conductivity. Song et al. [7] found that the thermal conductivity of rock

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is related to the mineral composition and structure. Li et al. [8] conducted an experimental study on the influence of granite thermal conductivity and thermal damage. Katharina Albert et al. [9] obtained the relationship between the change of thermal conductivity and rock joints. Jean et al. [10] pointed out the influence of depth and temperature on the change of rock thermal conductivity. Li et al. [11] revealed the evolution characteristics of thermal conductivity and temperature through thermal damage model. Gabova a et al. [12] explored the influence of high temperature on the thermal conductivity of sandstone. Guo [13] and Sun et al [14] developed an effective thermal conductivity calculation model. JieHan et al. [15] studied the relationship between the thermophysical properties of clay in rock and temperature. The relationship between the microstructure and thermal conductivity of rocks under high geo temperature cannot be ignored in the evaluation for rock stability, and there are few related studies at present.

In order to study the correlation between meso-structure and thermal conductivity of deep rocks at high geo-temperature, the polarizing microscope, NMR and thermal physical tests were carried out to measure the meso-structure and thermal properties of granite from the depth of 1500m to 2000m in Sanshandao. The coupling relationship among rock meso-structures and the thermal conductivity was analyzed. The results would provide a database and new insights on the thermal conductivity of deep fragmented granite.

2. Experimental process
The maximum geo-temperature is close to 55~60 ℃ in the depth of 1500m to 2000m in Sanshandao, Shandong province. The granite samples were prepared into Ф50mm×25mm. This experiment was carried out according to the three steps: (i) The polarizing microscope, acoustic-waves-monitor, NMR and thermal constant analyzer were used to test the meso-structure and thermal properties of granite samples. (ii) Putting the specimens into heating device, and then the temperature was increased to 60℃ by 2℃/min, keeping the temperature for two hours and natural cooling to the 20℃ in the heating device, after which specimens were subjected to thermal constant experiments, NMR and water saturation experiments. The thermal cycling tests were repeated until the pore diameter curve did not change or was less than 0.01 mm. The test process and equipment are shown in Fig. 1. (iii) Putting the specimens into heating device and raise it from 20℃ to 30℃, 40℃, 50℃ and 60℃ at 2℃/min. After keeping the temperature in each stage for two hours, measure the thermal conductivity by thermal constant analyzer.

![Figure 1. Flow chart of heating test.](image)

3. Meso-structure characteristics of deep granite
3.1 Meso-structure of deep granite
The micro-structure in the depth of 1500m to 2000m of cataclastic granite was observed and photographed by polarizing microscope (Fig.2). Fig.3 is the cumulative histogram of mineral composition of six groups of granite from which it can be concluded that Sanshandao granite is mainly composed of plagioclase, potash feldspar and quartz, which account for more than 90% of granite.
The rest of the minerals are less than 10% in total and consist of biotite, chlorite and opaque minerals. In addition, K-feldspar and plagioclase minerals in group D with severe clayization include 3% muscovite and 3% calcite. The average content of K-feldspar is 25.8%. The proportion of group A and B is the smallest, about 23%. The proportion of group C is the largest, about 28%. The floating range is small. The average content of plagioclase is 39.2%, and the floating range is 36% - 43%. The average content of quartz particles is 28.1%, and the floating range is 24% - 33%. The range of biotite and chlorite is 1% - 6%.

Digital image processing technology is used to scan the particle section, and the geometric information of the image is extracted and processed by Photoshop and python software. Equivalent radius of the particle is used to characterize the particle size, and the calculation formula is as follows:

\[ r = R \sqrt{\frac{A_p}{\pi}} \]  

(1)

R is equivalent radius. R is conversion coefficient between pixel length and actual length. Ap is the number of pixels occupied by the cross-section of the particle.

It can be seen from Figure 4 that the particle size distribution of each group of samples has obvious differences. Samples A and B have the largest particle size and the widest range, ranging from 2-8mm, 1.2-7.5mm, and the average particle size exceeds 4mm. The median particle size is consistent with the average particle size, indicating that the particle size distribution is more uniform. The average particle size of D sample is distributed in the interval of 1-7mm. Samples C, E, F box diagram area is small, the average particle size is 0.5-5.5mm, the particle size distribution is relatively concentrated and the particle size is small, the median particle size is higher than the average, indicating larger proportion of small particle size. In addition, the distribution of abnormal values in the box chart reflects the degree of dispersion of particle size. The maximum particle size of the A sample is more than 10mm, and the fluctuation range of the abnormal value of the E and F samples is relatively small, and the maximum abnormal value is only 7.5 mm.

3.2 Relationship between thermal conductivity and meso-structure of granite

The samples are tested by acoustic-waves-monitor, NMR and thermal constant analyzer, and the test results are shown in Table 1. The longitudinal wave velocity can reflect the compactness of rock [16], Sort the wave speed of the specimens from the largest to the smallest: F>E>D>C>B>A, it can be obtained that, except for the clayed specimens, the wave speed is positively correlated with the thermal conductivity, indicating that compactness of the rock is an important factor affecting the thermal conductivity.

In addition to the denseness of the specimen, its porosity and composition also affect the thermal conductivity. The granites of group E and F have low porosity (2.09% and 1.88%), fluids with low thermal conductivity have a low proportion, and solids with high thermal conductivity have a high proportion, which leads to an increase in the thermal conductivity of rocks, in addition, there is intercalation between the rock crystals of groups E and F, which is conducive to heat propagation. Secondly, the thermal conductivity of quartz is three times that of potassium feldspar and four times
that of plagioclase [17], and the high percentage of quartz in the specimens of group F results in a much larger thermal conductivity than that of group E.

Comparing the three groups of specimens A, B and C, found that thermal conductivity is different from the pattern of specimens in groups E and F. For further study, the pore size distribution was examined by NMR as shown in Figure 5. 24.5% of the pore size less than 0.5 μm in specimen C, 21.4% in specimen B and 19.5% in specimen A. Combining polarizing microscope and ultrasonic detector, it is found that when the porosity is similar, the smaller the pore diameter, the greater the connection between the particles, thus improving the thermal conductivity.

The D group granite is seriously clayed, and the clay exists in the pores between particles, which improves the thermal conductivity. The above factors show that the clay of rock will increase the thermal conductivity of rock, and the density of rock has the greatest influence on the thermal conductivity compared with other factors.

| Category | porosity % | quartz % | P-wave velocity cm/s | thermal conductivity W/mK |
|----------|------------|----------|----------------------|---------------------------|
| A        | 2.145      | 33       | 2.232                | 2.284                     |
| B        | 2.152      | 30       | 2.500                | 2.386                     |
| C        | 2.181      | 25       | 2.604                | 2.482                     |
| D        | 2.555      | 24       | 2.976                | 3.196                     |
| E        | 2.092      | 25       | 3.472                | 2.706                     |
| F        | 1.876      | 32       | 3.676                | 3.024                     |

4. Variation characteristics of granite microstructure under high geo-temperature

4.1 Effect of cycling temperature on porosity of granite

The NMR signal of known porosity standard specimens was detected by NMR instrument, and the corresponding relationship between porosity and NMR signal was established. The calibration curve is shown in Figure 6. The porosity change of different specimens under temperature cycle is shown in Figure 7. Table 2 shows the water loss scale after saturated water and temperature cycling.

From the test results, the porosity of coarse-grained granite of A and B groups varies greatly under the cyclic load of 60 °C. The porosity increases by 5% at the first heating, and then varies in the range of 2.2% ~ 2.3%. After the fourth temperature cycle, it tends to be stable, and the overall porosity increases by about 4%. The water loss of medium and group B is larger (about 0.275 ml). With the increase of temperature cycles times, the water loss tends to increase gradually, but the increment decreases. This indicates that the internal structure of rock can be slightly damaged by temperature cycling at 60 °C, and the porosity and pore connectivity are improved correspondingly, but the effect is more slowly with the increase of cycling time.

The specimen of group C is least affected by temperature cycle, its porosity changes in a small range, and water loss does not show regularity. This is due to the local generation of detritus caused by the effect of temperature and water in the minerals inside rock after temperature cycle, and then the detached detritus either fills the micro fractures or is carried away by water.

After the first two high temperatures, the porosity and water loss of group D specimen only changes slightly. After the third high temperature, the water loss increased by 45.2%, after stabilizing. The main reason is that the mineral clay of the specimen is serious. When the thermal load produces a strong thermal stress on the mineral boundary, the surrounding clay material will play a role in buffering the stress, so as to maintain the stability of the rock microstructure. As the number of saturation-drying cycles increases, some of the clay minerals gradually dissolve in water and transfer their positions, resulting in the increase of porosity and connectivity.
Group E specimen porosity increased by 1% each time during the previous 3 temperature cycles, and then decreased. In the second temperature cycle, the porosity of the group F specimen decreased by about 4%. The reason may be that under the continuous influence of hydrothermal effect, a small amount of particle exfoliation occurred in the rock sample, resulting in the reduction of residual mass of the rock specimen, and then led to the decrease of porosity. There is no change in the water loss between the two groups of rocks, indicating that the temperature cycle at 60 °C has little effect on the pore connectivity of the rocks.

![Figure 6. NMR calibration curve](image)

| Group | Water loss volume/ml |
|-------|----------------------|
|       | 1        | 2        | 3        | 4        | 5        |
| A     | 0.179    | 0.236    | 0.258    | 0.272    | 0.281    |
| B     | 0.169    | 0.221    | 0.255    | 0.265    | 0.272    |
| C     | 0.169    | 0.160    | 0.140    | 0.137    | 0.142    |
| D     | 0.250    | 0.250    | 0.363    | 0.368    | 0.353    |
| E     | 0.083    | 0.096    | 0.074    | 0.069    | 0.088    |
| F     | 0.071    | 0.081    | 0.088    | 0.091    | 0.088    |

4.2. Effect of cycling temperature on pore size distribution of rock

In order to further explore the damage degree of 60 °C to the meso-structure of the rock, the T2 relaxation time spectrum of each specimen was detected by NMR technology. There is a one-to-one corresponding relationship between NMR T2 value and rock pore size. Through conversion, the proportion of pores with different pore sizes in the total pores could be obtained, as shown in Figure 8. For convenience, the radius of the hole $r < 0.1 \mu m$ was defined as a small hole, $0.1 \mu m < r < 1 \mu m$ as a mesopore, $1 \mu m < r < 10 \mu m$ as a macropore, and $10 \mu m < r < 100 \mu m$ as a super large hole.

In group A, B, C and E, the proportion of mesopores and macropores accounts for more than 90% of the total, and the proportion of macropores is approximately twice that of mesopores. That is $1 \mu m < r < 10 \mu m$ pore size is dominant, pore size distribution is relatively concentrated. The pore type is single, and the pore size sorting is good. With the increase of temperature cycling time, the variation trend of pore distribution proportion in each pore size range is different, showing no regularity. Among them, the proportion of small holes in the groups A and B increases the most, while the proportion of small holes in group C decreases seriously, which may be caused by local debris generation, which will not be described here.

The granite pore size distribution range of the group D specimen is large, mainly small pore size, up to 50%, which is attributed to the severe clayization of the rock. The clayization of rock will lead to the increase of internal fractures in the rock, and part of the clay will fill the macropores, resulting in
the increase of the proportion of small pore size. With the increase of temperature cycling time, the change trend of the pore size of rock shows that the proportion of small pores increases, (from 46% to 51%), decreasing proportion of medium pores and large pores. There are two possible reasons: one is that clay material will expand when it meets water; the other is that clay is difficult to crack when it is heated, and thermal stress will be generated between mineral particles, both of which will lead to smaller pore size.

The pore size difference of sample F is small and the connectivity is poor. However, under the effect of thermal load, due to the small particle size, the number of microcracks produced is significantly larger than that of coarse-grained granite, resulting in a significant increment in the number of small holes. It indicates that the damage of fine-grained granite is more obvious, and it is more sensitive to temperature cycling. The damage of granite grows rapidly in the first few temperature cycles, and becomes stable after about four cycles. This is mainly due to the void between inter-mineral cracks and intra-mineral cracks in granite will be increased with the increase of cycling times. The larger void can provide buffer space for mineral expansion and enhance the ability to adapt to thermal deformation of rock, so that the damage of granite will not further increase in the subsequent cycles.

The above results show that: 60 °C will change the pore distribution ratio of each pore size range, and the dense granite with small particle size is more sensitive to temperature cycle. With the increase of the number of cycles at 60 °C, the variation trend of pore distribution proportion in each pore size range is different, which makes the pores develop and expand, and the pores are connected with each other. On the whole, the proportion of small holes increases, while the proportion of mesopores and macropores decreases. The pore structure of rock specimen changes, resulting in stronger permeability, and then changes its physical properties.

![Figure 8. Pore size distribution of granite samples under cycling temperature](image)

5. Variation characteristics of thermal conductivity of granite under different temperature

5.1 Thermal conductivity evolution as temperature cycled

Take three groups of specimen, B, D and E, and draw the thermal conductivity diagram of each sample in different states according to the one-time temperature cycle process. As shown in Figure 9, specimen after drying, the thermal conductivity of group B and group E specimen increases slightly. It indicates that the high temperature of 60 °C causes irreversible expansion of rocks minerals, which makes the contact between particles more density and the thermal conductivity increase. However, the
thermal conductivity of the specimen D decreases significantly, with a decrease of 6.3%. It is speculated that the loss of water of clay minerals after high temperature leads to volume shrinkage, increased gap between minerals and decreased thermal conductivity. After saturated, the thermal conductivity of specimens B, D and E increases by 10.1%, 10.3% and 2.0%, respectively. The test results show that the improvement of thermal conductivity of rock by water saturation treatment is considerable, which can be attributed to the fact that water enters into the rock mass and occupies the space of air, and the thermal conductivity of water is stronger than that of gas, which leads to the larger increment of saturated rock with larger porosity. Compared with specimens B and D, the porosity of specimen D is much larger than that of specimen B, but the increment of thermal conductivity is almost the same. This is mainly due to the partial dissolution of clays in water, which weakens the thermal conductivity of rock. Compared with the first drying, the thermal conductivity of specimens B, D and E decreased by 3.0%, 2.6% and 4.4% respectively after the second drying. Besides the influence of water, the microcracks produced by the joint action of temperature and water in the meso-structure of rock are also an important factor for the decrease of thermal conductivity.

Figure 10 shows the evolution of thermal conductivity of specimens in wet and dry environments under repeated temperature cycles, among them, the thermal conductivity of specimen B varies from 2.37 to 2.73 W/mK, specimen D is from 2.92 to 3.45 W/mK, specimen E is from 2.62 to 2.97 W/mK. The thermal conductivity tends to increase after drying with the increase of the number of temperature cycles. Observing the specimens in group D, the amount of change in their thermal conductivity after wet-dry is large and unstable, which is attributed to the clay minerals dissolved in water. The floating clay particles started to settle during the evaporation of water and their position changed, one is that the porosity is further increased; the other is that clay particles may settle on the surface of minerals with high thermal conductivity (such as quartz), both of phenomena can cause a reduction in thermal conductivity.

5.2 Thermal conductivity change at full geo-temperature

Figure 11 shows the variation diagram of thermal conductivity of granite during heating. The results show that the increase of temperature from 30°C to 60°C has little effect on the thermal conductivity of deep granite. The thermal conductivity of the three groups of granite specimens A, B, and C gradually increases with the increase of temperature, reaching the peak at 50°C, the increase is about 0.3% of the initial point, and it shows a downward trend when it exceeds 50°C. It can be considered that after being heated, mineral particles begin to expand and gradually fill the internal pores, making the rock specimen dense, so the thermal conductivity increases. When the temperature reaches 50°C, the pores of granite are filled with expansive minerals, and part of the thermal stress accumulates on
the mineral boundary, which leads to the development of microcracks and the decrease of thermal conductivity.

The thermal conductivity of the specimens in groups D, E and F gradually decreases with the increase of temperature, this is a result of the clay is hydrophilic. and the decrease in thermal conductivity of specimen D is the largest, decline of 2.2% of the initial value, this is a result of the clay is hydrophilicity. On the one hand, high temperature will lead to the evaporation of water, on the other hand, the loss of water in clay will lead to its volume contraction and the gap between mineral particles becomes larger. The internal structure of group E and F specimens is dense, so there is no thermal expansion stage of minerals in these groups of specimens. High temperature causes water evaporation, and the space occupied by internal air becomes larger, resulting in the decrease of thermal conductivity with the increase of temperature. In conclusion, it can be concluded that the influence of temperature on the thermal conductivity of the specimen is mainly due to the internal meso-crack growth and the change of water content.

![Figure 11. Variation diagram of thermal conductivity of granite during heating](image)

6. Discussion

The thermal conductivity of deep cataclastic granite is related to a variety of mesoscopic features, such as the expansion of rock porosity and cracks will reduce the thermal conductivity, the increase of quartz and water content in rock will increase the thermal conductivity and the mineral clayization and mineral particle size can significantly affect the thermal conductivity. The 60 °C temperature cycle damages the internal structure of the rock and reduces the water content, these are the two main reasons for the decrease of thermal conductivity of rocks due to high temperature. This article starts from the mesoscopic characteristics of the rock, the correlation between the grain fabric characteristics of cataclastic granite and its thermal conductivity is analyzed, with the rise of geo-temperature, the change characteristics of rock mesostructure and the influence of dry and wet environment on its thermal conductivity are studied. Because the state of the rock sample in the laboratory experiment is still different from the rock in the reservoir and the experiment involves many variables, at present, it is only used to provide a data basis and new insights on the thermal conductivity of deep fragmented granite under high geo-temperature. How to further study the correlation between meso-structure and thermal conductivity and put forward the evaluation standard of deep rock thermal conductivity, which is the research content that the author will carry out in the next step.

7. Conclusion

1) Deep rocks mesoscopic characteristics and thermal conductivity show obvious differences. The increase of mineral clayization and water content can significantly reduce the thermal conductivity. In addition, porosity, quartz content, inter-crystal intercalation and cracks have a certain impact on thermal conductivity.
2) The damage to the internal structure of the rock caused by 60°C temperature cycling cannot be ignored, especially, the meso-structure of the rock significantly affected in the first cycle of heating at 60°C, which enhances meso fissures connectivity in the granite and causes a decrease in thermal conductivity. In addition, the thermal conductivity of fine-grained granite is more sensitive to temperature.  
3) During the temperature increase process from 30°C to 60°C, the thermal conductivity of coarse-grained and fine-grained granites changes little, and the granites with severe clayization have a significant decrease. It shows that the influence of temperature increase on the deep granite is mainly attributed to the internal mesoscopic crack growth and the change of water content.

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