Research Article

Thermal Property of Granite in Deep Strata and Its Effect on Thermal Zone of Surrounding Rock

Peng Xiang ^{1,2} Hui-Ci Xu ¹ Hong-Guang Ji,^{1,2} Qi Li ¹ and Huan Wang¹

¹University of Science and Technology Beijing, School of Civil and Resource Engineering, Beijing 10083, China

²Beijing Key Laboratory of Urban Underground Space Engineering, USTB, Beijing 10083, China

Correspondence should be addressed to Hui-Ci Xu; 1136707530@qq.com

Received 1 November 2021; Accepted 31 December 2021; Published 21 January 2022

Academic Editor: Xing-Dong Zhao

Copyright © 2022 Peng Xiang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In order to clarify the changes in the thermophysical properties of rocks in deep high-temperature strata and their influence on the temperature field of the surrounding rocks, thermal property tests were conducted on rock samples taken from 1,500 to 2,000 m depth in the Xiling well construction area of Sanshandao gold mine. According to the difference equation based on the principle of heat balance, the numerical solution of unsteady heat conduction of surrounding rock can be deduced. In addition, we can explore the dynamic process of the heat-regulating ring that under ventilation measures in deep high geothermal strata and analyze its influence on the dynamic process based on the equation. The result of the research shows that the thermal conductivity of rock is mainly determined by the mineral composition and is influenced by factors such as mesostructure. Calcite and muscovite of granite have a great impact on lithology, even they just account for a relatively small percent. As the ground temperature increases step by step, the variation of the thermal conductivity of rock is less and the thermal diffusion coefficient of rock and its ability to transmit temperature changes both decrease. On the contrary, as the specific heat capacity of rock increases, its heat storage capability enhanced. Therefore, the expansion range of the heat-regulating ring of surrounding rock is influenced by mineral composition and the temperature of the environment, and the influence of the former is much greater than the latter.

1. Introduction

At present, a large number of metal mines in China have entered the stage of deep mining, and the mining of resources at a depth of -1,000 meters is gradually becoming the new normal [1–3]. With the increase in mining depth, the stratum temperature is increasing, and the heat damage problem of the mine is becoming more and more serious. The temperature of the thermostatic zone in the direct mining area of Sanshandao is 14–15°C, and the normal geothermal gradient is about 2.2×10^{-2} °C/m [4]. From this, it can be predicted that the temperature of the original rock will reach 60°C at the depth of 2,000 m. The rock body has internally changed a lot, showing the characteristics of fractured granite, most of the existing studies [5–7] are on the changes in rock mechanical properties, PENG K et al. [8] studied the effect of temperature on the mechanical properties of granite under different fracture modes, Chen et al.

[9] investigated the effect of temperature on the mechanical properties of granite by uniaxial compression and fatigue loading, and some studies [10–14] are on the thermal effects of rocks under high temperature. There are also some studies on the thermal effects of rocks at high temperatures, but there are fewer studies on the changes in thermophysical properties of surrounding rocks affected by temperature. So it is necessary to study the influence of temperature on the thermal properties of the rock and eventually on the temperature distribution of the surrounding rock.

The occurrence of heat damage in metal mines in deep high ground temperature strata is the result of heat dissipation from a variety of heat sources, including heat dissipation from surrounding rocks, heat dissipation from mechanical equipment, heat dissipation from groundwater gushing, heat dissipation from ore oxidation, and heat dissipation from the human body. But for the working face, it is mainly heat dissipation from surrounding rocks [15].

Thermal conductivity is one of the controlling factors of heat dissipation in the surrounding rock, and it is important for the calculation of heat dissipation in the surrounding rock. The thermal conductivity of rocks is affected by various factors such as temperature, pressure, mineral composition, porosity, water content, and joints and fractures [16]. For dense and hard rocks, water content has little influence on thermal conductivity. In the dry state, the thermal conductivity of rock decreases with the increase in porosity; in the wet state, the thermal conductivity of rock increases with the increase in porosity. In addition, the thermal conductivity of rock decreases with the increase in temperature [17, 18]. The thermal conductivity is the basis for the study of heat release from surrounding rocks, and it is necessary to explore the variation of thermal conductivity of rocks at plateau rock temperature. In addition, the nonstationary heat transfer process is related to the thermal conductivity, specific heat capacity, and density of rocks, and the thermal diffusion coefficient can comprehensively characterize the ability of objects to transfer temperature changes. Therefore, the variation of thermal conductivity, thermal diffusion coefficient and specific heat capacity with depth, and temperature of deep stratigraphic fractured granite are also investigated in this study.

After excavation, convective heat exchange between the surrounding rock and wind flow, the temperature of the surrounding rock near the wall of the tunnel decreases, while the surrounding rock at the original rock temperature in the deep part continuously transfers heat to the surrounding rock near the wall, thus forming a temperature change area around the tunnel, which is called heat-regulating ring. At present, the calculation of the heat-regulating ring mainly uses empirical formulas, finite differences, and numerical simulations. Among the previous studies, MA Ling [19] proposed an analytical solution that couples transient heat transfer in the surrounding rock with steady-state heat transfer in the borehole and solved it by MATLAB platform; CHEN Liu [20] used the numerical simulation software COMSOL to explore the coupling problem of heat transfer and seepage in the fractured surrounding rock in deep underground space; BIAN Menglong [21] derived the temperature distribution inside the surrounding rock under steady-state heat conduction from the classical theory of heat transfer. Predecessors to the distribution of temperature field of surrounding rock and development conducted in-depth research, and we derive a heat conduction equation for the surrounding rock applicable to deep metal mines. It can be more accurate to calculate the change in the internal heat-regulating ring of surrounding rock, and the influence of temperature on the thermophysical properties of surrounding rock is considered.

In summary, based on previous studies, we first investigate the heat transfer characteristics of fractured granite under high ground temperature environment and analyze the expansion characteristics of the heat-regulating ring of deep perimeter rocks and the influence of rock thermal property changes on them by deriving the difference equation of unsteady heat conduction applicable to metal mine perimeter rocks in this study.

2. Materials and Methods

2.1. Thermophysical Experiment of Deep Granite

2.1.1. Experimental Design. The specimens used in the thermal property test were taken from the depth of 1,500 to 2,000 m in the Xiling construction area of Sanshandao gold mine, all of which are granites, among which the biotite monzonitic granites at the depths of 1,500, 1,600, 1,800, 1,900, and 2,000 m are mainly composed of potassium feldspar, plagioclase, quartz, black mica, and chlorite, and the calcite sericite granite at the depth of 1,700 m is mainly composed of potassium feldspar, plagioclase, quartz, and muscovite. The particle size of rock minerals ranges from 0.8 to 7.5 mm, showing the characteristics of cleavage. The specimens were processed into a 50 mm diameter and 25 mm height round cake according to the test standard. The test apparatus used was a Hot Disk Thermal Constants Analyzer and an electric heating blast drying oven.

The thermophysical properties of rocks at room temperature and real-time high-temperature thermophysical properties under the condition of gradual temperature increase were carried out, respectively.

When conducting the thermal property test of the rock at room temperature, the probe was first fixed on the sample holder, and then, the probe was clamped with two pieces of the sample to be tested, and the thermal property test was conducted, and the data were analyzed to obtain the thermophysical parameters of the sample; when conducting the incremental thermal property test, according to the requirements of Metal and Nonmetal Mine Safety Regulations, the starting temperature is set at 30 °C. Since the ground temperature at the depth of 2,000 m in the Sanshandao area reaches nearly 60 °C, the end temperature is set at 60 °C, and the rock sample was first put into the oven together with the Hot Disk probe, and the temperature gradient was entered in the control software, and the temperature gradient designed for this test was 10°C. The thermal properties of the specimens were measured at 30, 40, 50, and 60°C respectively. After the oven reaches the predetermined temperature, the heating power is adjusted and the specimen is continuously heated. When the temperature of the rock sample always differs from the oven temperature within 1°C within one hour, the instrument automatically starts the thermal property test. The physical test equipment is shown in Figure 1, and the test flow design is shown in Figure 2.

2.2. Deep Stratigraphic Granite Thermal Property Test

2.2.1. Thermophysical Parameters of Deep Granite. The results of the thermophysical parameters of the rocks at various depths obtained by the Hot Disk thermal property test are shown in Table 1, the thermal conductivity of granite at depths of 1,500–2,000 m in the Sanshandao area is between 2.27 and 3.15 W/(m·K), the thermal diffusion coefficient is between 1.09 and 1.57 mm²/s, the specific heat capacity is between 1.55 and 2.46 MJ/(m³·K), among which the parameter values measured in the rock sample at 1,700 m

FIGURE 1: Physical drawing of the thermal constant analyzer.

FIGURE 2: Test process design.

TABLE 1: Thermophysical parameters of rock samples from 1,500–2,000m in the Xiling well construction area of Sanshandao gold mine.

Depth m	1500	1600	1700	1800	1900	2000
Thermal conductivity W/(m·K)	2.2754	2.3731	3.1501	2.4600	2.9549	2.8666
Thermal diffusion coefficient mm ² /s	1.4672	1.0972	1.5658	1.2335	1.2011	1.3181
Specific heat capacity MJ/m ³ K	1.5510	2.1645	2.0119	2.0003	2.4602	2.1748

depth are large, the stratum is calcite sericite granite, and the rest of the depth stratum is biotite adamellite.

2.2.2. Relationship between the Thermophysical Characteristics of Granite and Its Mesostructure and Mineral Composition. Regarding the relationship between the thermal conductivity of a rock and its mineral composition, a geometric mean model has been proposed, and where the thermal conductivity of the rock skeleton is the product of the thermal conductivity of the mineral components, it makes up the rock [22]:

$$\lambda_s = \prod_{i=1}^n \lambda_i^{\text{vol}_i}, \quad (1)$$

where λ_s is thermal conductivity of rock skeleton; λ_i is thermal conductivity of the i_{th} mineral in the rock; and Vol_i is the content of the i_{th} mineral in the rock.

This formula only considers the composition of the mineral composition. If the porosity is introduced into the formula, then

$$\lambda_d = \lambda_s^{1-\varnothing} \lambda_f^{\varnothing}, \quad (2)$$

where λ_d is thermal conductivity of rocks after considering voids; λ_f is thermal conductivity of air; and Φ is porosity of the rock.

According to the available research results, the thermal conductivity of various mineral components is shown in Table 2 [23–25]:

The distribution of mineral composition and the proportion of each group of rock samples under polarized light microscopy are shown in Table 3, which shows that potassium feldspar, plagioclase, and quartz are higher than 90% in each group of rock samples and constitute the main part of the rocks. The proportion of potassium feldspar, plagioclase, and quartz is between 23% and 30%, 36% and 43%, and 24% and 33%, respectively. Biotite chlorite is present in all samples except 1,700 m, with a percentage of 4% to 8%. Muscovite and calcite are only found in the 1,700 m deep rock samples, accounting for 3%. Muscovite and calcite contents are small, but they have a great influence on the properties of the rocks.

The thermal conductivity of the rock specimens at each depth was obtained by Hot Disk thermal property test and calculation. The results are shown in Table 4.

According to the above results, the calculated and measured values of thermal conductivity of the three groups of samples at 1,800–2,000 m have the same variation pattern and are close to each other; The difference between calculated values and measured values of thermal conductivity of the three groups of rock samples is 0.159, -0.2969, and 0.0594 W/(m·K), respectively, which are 6.46%, -10.05%, and 2.07% higher than the measured values, respectively. But the test results of the three groups of samples at 1,500–1,700 m are somewhat different from the theoretically calculated values. The rock samples at 1,700 m depth are calcitized sericite granite, containing a certain amount of calcite, and its measured value was 0.5441 W/(m·K) larger than the calculated value or approximately 17.27% higher; the calculated thermal conductivity values of 1,500 and 1,600 m rock samples are greater than the measured values, with differences of 0.6566 W/(m·K) and 0.4439 W/(m·K), respectively. The calculated values are 28.86% and 18.71% higher than the measured values, respectively.

In conclusion, as all factors affecting thermal conductivity cannot be taken into account in formula calculation, and there are also certain errors in test instrument measurement, and there are certain numerical differences between the thermal conductivity calculated by a formula and that measured by the instrument, but they can also be mutually verified.

2.2.3. Thermophysical Characteristics of Granite under Increased Temperature Environment. The deep stratigraphic rocks are at high temperatures and present the characteristics of cataclastic granites. The microfabric and mineral properties will change to a certain extent, and their thermophysical properties will also change. In order to better understand the thermophysical parameters of granite at high ground temperature and to explore its real-time thermophysical characteristics at different

temperatures, a stepwise incremental thermophysical test was carried out and the results are shown in the following.

The changes in thermal conductivity of granites with increasing temperature are related to lithology, among which calcitized sericite granites are more obviously affected by temperature, and the thermal conductivity decreases by 0.07453 W/(m·K) during the warming process from 30 to 60°C, which is about 2.34% lower compared with that at 30°C, while the thermal conductivity of the biotite monzonitic granite hardly changes. The specific situation is shown in Figure 3.

The thermal diffusion coefficient of granite gradually decreases with the increase in temperature, and the specific heat capacity gradually increases with the increase in temperature, both showing a linear relationship with temperature, as shown in Figure 4.

After fitting thermal diffusion coefficient and specific heat capacity with temperature, we get Table 5.

The decreasing gradient of thermal diffusion coefficient with increasing temperature of the biotite monzonitic granite is about 0.003 (mm²/s)/°C to 0.0046 (mm²/s)/°C, and the thermal diffusion coefficient of calcite sericite granite is not only large but also has a large decreasing gradient with increasing temperature, which can reach 0.0066 (mm²/s)/°C. During the temperature increase from 30°C to 60°C, the thermal diffusion coefficients of each depth specimen decreased by 9.59%, 7.46%, 10.73%, 8.81%, 7.36%, and 8.88% respectively, compared with that at 30°C. The incremental gradients of specific heat capacity with increasing temperature were concentrated between 0.005 and 0.006 (MJ/m³·K)/°C for all groups of granite specimens. Compared with 30°C, the specific heat capacity of rock samples at depths of 1500–2000 m increases by 10.47%, 7.85%, 9.40%, 9.77%, 7.40%, and 6.90%, respectively.

From the above test results, we can know that the thermophysical properties of fractured granite more obviously change at high temperatures, and its ability to transmit temperature changes decreases and its thermal storage capacity increases. The change in thermophysical properties of calcitized sericite granite at 60°C temperature is greater than that of black cloud monzonitic granite.

3. Numerical Calculation

3.1. Analytical Solution of Temperature Distribution of Surrounding Rock in Deep Strata

3.1.1. The Basic Law of Heat Conduction and Its Solution. Fourier expressed the basic law of thermal conductivity in the mathematical form on the basis of comparing the theoretical solution with experimental studies, Fourier's law [26], the mathematical expression of which is as follows:

$$q = -\lambda \frac{\partial t}{\partial x} = -\lambda \text{grad}t. \quad (3)$$

The general form of the three-dimensional unsteady differential equation of thermal conductivity in the right-angle coordinate system is as follows:

TABLE 2: Thermal conductivity of different mineral compositions.

Thermal conductivity W/(m·K)	Quartz 7.69	Potassium feldspar 2.37	Plagioclase 1.87	Black mica 2.51
Thermal conductivity W/(m·K)	Calcite 3.59	Dolomite 4.70	White mica 2.05	Hornblende 2.54
Thermal conductivity W/(m·K)	Alkali feldspar 2.30	Rock salt 5.60		

TABLE 3: The proportion of mineral composition of each group of rock samples.

Depth m	Potassium feldspar%	Plagioclase%	Quartz%	Biotite chlorite%	Epidote%	Muscovite%	Calcite%	Other%
1500	23	36	33	7	Trace			Trace
1600	23	41	30	6				Trace
1700	28	42	24			3	3	
1800	23	43	25	8				1
1900	30	37	25	7				1
2000	28	36	32	4				Trace

TABLE 4: Thermal conductivity of 1,500–2,000 m deep rock samples in the Xiling well construction area of Sanshandao gold mine.

Depth m	1500	1600	1700	1800	1900	2000
Calculated value W/(m·K)	2.932	2.817	2.606	2.619	2.658	2.926
Measured value W/(m·K)	2.2754	2.3731	3.1501	2.4600	2.9549	2.8666

FIGURE 3: Variation of thermal conductivity with temperature for rock samples from 1,500 to 2,000 m depth in the Xiling construction project area of Sanshandao gold mine.

$$\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) + \frac{q_v}{\rho c}. \quad (4)$$

In the absence of an external heat source, the differential equation for thermal conductivity can be transformed as

$$\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right), \quad (5)$$

where λ is the thermal conductivity, W/(m·K); ρ is the density of the surrounding rock, kg/m³; c is the specific

FIGURE 4: The thermal diffusion coefficient and specific heat capacity of the rock samples from the depth of 1,500–2,000 m in the Xiling well construction project area of Sanshandao gold mine vary with temperature.

TABLE 5: Fitting relationship between thermal diffusivity, specific heat capacity, and temperature of samples at various depths.

Depth m	Thermal diffusion coefficient fitting	Specific heat capacity fitting
1500	$\alpha = -0.0046118t + 1.6018$	$c = 0.005396t + 1.404$
1600	$\alpha = -0.002761t + 1.1903$	$c = 0.005696t + 1.9932$
1700	$\alpha = -0.0066047t + 2.0228$	$c = 0.005573t + 1.5734$
1800	$\alpha = -0.0040375t + 1.4989$	$c = 0.005958t + 1.6508$
1900	$\alpha = -0.0031242t + 1.3786$	$c = 0.005753t + 2.1772$
2000	$\alpha = -0.0029705t + 1.3986$	$c = 0.005126t + 2.0664$

heat capacity of the surrounding rock, $J/(kg \cdot K)$; $a = \lambda/(\rho c)$ is the thermal diffusion coefficient of the surrounding rock, mm^2/s ; t is the temperature, $^{\circ}C$; τ is the time coordinate, s ; x , y , and z are the spatial coordinates, m ; q is the heat flow density, W/m^2 ; and q_v is the internal heat source heat dissipation per unit time, W/s .

The solution of the nonstationary heat conduction problem requires giving the temperature distribution at the initial moment and the temperature or heat transfer on the boundary of the object, and the initial and boundary conditions can be summarized into three categories. When the stope is established in the deep underground plateau rock temperature strata and ventilation measures are taken, the convective heat and mass transfer process between the tunnel wall and the airflow transfers the heat in the surrounding rock to the airflow, so that the temperature of this part of the surrounding rock is reduced, and the surrounding rock far away from the wall of the tunnel continuously transfers heat to the surrounding rock near the wall. Therefore, the wall of the tunnel belongs to the third type of boundary condition, while the remote surrounding rock that is not affected by the ventilation belongs to the first type of boundary condition.

3.1.2. Numerical Solution for Nonstationary Thermal Conductivity. The heat balance expression for the internal node n when using the heat balance method is as follows:

$$Q_x - Q_{x+dx} = Q_E. \quad (6)$$

Q_x and Q_{x+dx} denote the heat imported and exported from x and $x+\Delta x$ positions, respectively, of the microelement, and Q_E is the increment of thermodynamic energy of the microelement.

Thus, the difference equation inside the surrounding rock can be deduced as

$$t_n^{(i+1)} = \frac{a\Delta\tau}{\Delta x^2} (t_{(n+1)}^{(i)} + t_{(n-1)}^{(i)}) + \left(1 - 2\frac{a\Delta\tau}{\Delta x^2}\right) t_n^{(i)}. \quad (7)$$

The boundary nodes are treated according to the third type of boundary conditions, and the difference equation can be obtained after simplifying the heat balance equation as follows:

$$t_1^{(i+1)} = t_1^{(i)} \left(1 - 2\frac{a\Delta\tau}{\Delta x^2} - \frac{2h\Delta\tau}{\rho c \Delta x}\right) + 2\frac{a\Delta\tau}{\Delta x^2} t_2^{(i)} + \frac{2h\Delta\tau}{\rho c \Delta x} t_f, \quad (8)$$

where A is the heat flow area, m^2 ; t_f is the ventilation temperature, $^{\circ}C$; and h is the convective heat transfer coefficient, $W/(m^2 \cdot K)$.

FIGURE 5: Temperature distribution in the heat-regulating circle of surrounding rocks of rock samples of different depths. (a) Room-temperature thermophysical parameters. (b) High-temperature thermophysical parameters.

4. Results and Discussion

4.1. Analysis of the Effect of Rock Thermal Property Changes on the Temperature Field of the Tunnel Surrounding Rock. In general, the temperature distribution of steady-state thermal conductivity depends on the thermal conductivity coefficient, and the temperature distribution of unsteady thermal conductivity is related to thermal conductivity, specific heat capacity, and density [27]. Therefore, the thermal diffusivity can better describe the change in the surrounding rock temperature field with time in deep stope under ventilation conditions.

According to the stratigraphic temperature in the San-shandao area, we can learn that the stratigraphic temperatures at depths of 1,500, 1,600, 1,700, 1,800, 1,900, and 2,000 m are 47, 49.2, 51.4, 53.6, 55.8, and 58°C, respectively, and the original rock temperature reaches close to 60°C after entering the 2,000 m depth level, while China's "Metal and Nonmetal Mine Safety Regulations" stipulates that the wind temperature should not exceed 28°C, so this study defines 60°C as the high-temperature state and 28°C as the normal-temperature state, and the thermal diffusion coefficients of rocks at 60°C raw rock temperature can be derived from Table 5 as 1.3251, 1.0246, 1.6265, 1.2566, 1.1911, and 1.2204 mm²/s, and rock thermal diffusion coefficients of 1.4727, 1.113, 1.8379, 1.3858, 1.2911, and 1.3154 mm²/s at 28°C protolith temperature.

Combining with the engineering background of San-shandao gold mine, the numerical solution of unsteady thermal conductivity derived using the heat balance method is brought into MATLAB calculation, and the surrounding rock is in the original rock temperature state before the

tunnel ventilation, assuming the ventilation air temperature is 28°C and the wind speed is 1 m/s. According to the thermal diffusion coefficients of each group of rock samples at different temperatures derived from Table 5, the thermophysical parameters before and after the occurrence of the change are substituted into the finite difference equation, and the temperature distribution of the surrounding rocks in the range of temperature change after ventilation under the normal-temperature thermophysical parameters and high-temperature thermophysical parameters are calculated respectively, and then, the heat-regulating ring is adjusted at each depth, as shown in Figure 5.

According to the above figure, it can be seen that the temperature of surrounding rock increases with the increase in the distance from the roadway wall, and the temperature gradient gradually decreases. In particular, the radius of the heat-regulating ring of the sample with a depth of 1,800 m is the largest, and the temperature of the surrounding rock decreases the most. In the range of 1 m away from the roadway wall, the temperature of surrounding rock shows a linear increase trend, and there is no significant difference among groups. However, with the increase in the distance from the roadway wall, the temperature distribution of surrounding rock presents a downward parabola form, and the influence of rock samples' thermophysical parameters on the temperature distribution of surrounding rock begins to appear. It can be known that the change in surrounding rock thermophysical parameters simultaneously affects the radius of the surrounding rock heat-regulating ring and the temperature distribution inside the surrounding rock. But the expansion trend of the heat-regulating ring becomes slower under the same ventilation conditions and original rock

FIGURE 6: Comparison of changes in the radius of the heat transfer zone of the surrounding rock in different depths of rock samples.

temperature because the high temperature reduces the thermal diffusion coefficient of the rock. The expansion range of the radius of the heat-regulating circle of the tunnel surrounding rock calculated by the rock thermophysical parameters from 1,500 to 2,000 m depth decreases from 6.466, 5.698, 7.095, 6.263, 5.995, and 6.064 m to 6.094, 5.501, 6.751, 5.945, 5.841, and 5.889 m respectively. In addition, the difference between the maximum and minimum radius of the heat-regulating ring obtained from the calculation of the thermal properties at room temperature and high temperature is 1.397 m and 1.25 m respectively, which shows that the influence of the difference of the rock itself on the temperature field of the surrounding rock is much larger than the influence of the change of the thermophysical properties under the effect of temperature on the temperature field of the surrounding rock, as shown in Figure 6.

In summary, both the plateau rock temperature and rock mineral composition will have an impact on the thermophysical properties of the rock. The expansion of the radius of the heat-regulating circle of the surrounding rock after the tunnel excavation and ventilation is affected by the temperature and the lithology, which produces different ranges of changes and is dominated by the lithology, which needs to be taken into account during calculation and analysis.

5. Conclusions

- (1) With the increase in stope depth and the thermophysical parameters of fractured granite change, there is no obvious law between them, and under the high ground temperature environment, with the accumulation of heat in the rock around the stope, the thermal conductivity of granite insignificantly changes, the thermal diffusion coefficient gradually decreases, and the specific heat capacity gradually increases, all showing a linear relationship with temperature.

- (2) The thermal conductivity of the rock calculated by using the geometric mean model is different from the result obtained by the Hot Disk test indicating that the thermophysical properties of the rocks are not completely determined by the mineral composition, but the results calculated are based on the ratio of the rock-mineral skeleton within the acceptable range.
- (3) According to the heat balance principle, the difference equation of nonstationary thermal conductivity applicable to the metal mine surrounding rocks was derived, and combined with the background of Xiling construction project area of Sanshandao gold mine, the thermophysical parameters of granite measured at room temperature and plateau rock temperature were substituted into the difference equation for calculation, and it was found that the thermophysical parameters of surrounding rock also affect the radius of heat-regulating ring and the temperature distribution inside the surrounding rock. Under the same ventilation conditions and original rock temperature, the thermal diffusion coefficient of the rock decreased due to high temperature, and the thermal conductivity became poor, which led to the expansion of the radius of the heat transfer circle. However, the difference between the rocks themselves has more influence on the heat transfer circle of the surrounding rocks.

Data Availability

All data included in this study are available upon request upon request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant nos. 51774021 and 52074021), the Major Scientific and Technological Innovation Project of Shandong Province (no. 2019SDZY05), the Open Fund of Hubei Key Laboratory for Efficient Utilization and Block Building of Metallurgical Mineral Resources (2021zy003), and the Fundamental Research Funds for the Central University (FRF-GF-20-01B).

References

- [1] H. Xie, "Deep rock mass mechanics and mining theory" research concept and expected results," *Engineering Science and Technology*, vol. 49, no. 2, pp. 1–16, 2017.
- [2] H. Xie, F. Gao, and J. U. Yang, "Research and exploration of deep rock mass mechanics," *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. 11, pp. 2161–2178, 2015.
- [3] H. Xie, "Research progress on deep rock mass mechanics and mining theory," *Journal of China Coal Society*, vol. 44, no. 5, pp. 1283–1305, 2019.
- [4] X. Zhao, X. I. U. Guolin, and Z. Yang, "Surrounding rock temperature gradient test and engineering thermal environment analysis of Sanshandao Gold Mine," *Metal Mine*, vol. 42, no. 6, pp. 109–113, 2013.
- [5] T. Xu, G. L. Zhou, M. J. Heap, W. C. Zhu, C. F. Chen, and P. Baud, "The influence of temperature on time-dependent deformation and failure in granite: a modeling a," *Rock Mechanics and Rock Engineering*, vol. 50, no. 9, pp. 2345–2364, 2017.
- [6] P. K. Gautam, A. K. Verma, M. K. Jha, P. Sharma, and T. M. Singh, "Effect of high temperature on physical and mechanical properties of Jalore granite," *Journal of Applied Geophysics*, vol. 159, pp. 460–474, 2018.
- [7] R. D Dwivedi, R. K Gole, V. V. R Pprasad, and A. Sinha, "Thermo-mechanical properties of Indian and other granites," *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, pp. 303–315, 2008.
- [8] K. Peng, H. Lv, F. Z. Yan, Q. Zou, X. Song, and Z. Liu, "Effects of temperature on mechanical properties of granite under different fracture modes," *Engineering Fracture Mechanics*, vol. 226, 2020.
- [9] Y. L. Chen, J. Ni, W. Shao, and R. Azzam, "Experimental study on the influence of temperature on the mechanical properties of granite under uni-axial compression and fatigue loading," *International Journal of Rock Mechanics and Mining Sciences*, vol. 56, pp. 62–66, 2012.
- [10] L. F. Fan, J. W. Gao, Z. J. Wu, S. Q. Yang, and G. W. Ma, "An investigation of thermal effects on micro-properties of granite by X-ray CT technique," *Applied Thermal Engineering*, vol. 140, pp. 505–519, 2018.
- [11] S. Q. Yang, P. G. Ranjith, H. W. Jing, W. L. Tian, and Y. Ju, "An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments," *Geothermics*, vol. 65, pp. 180–197, 2017.
- [12] L. Griffiths, O. Lengliné, M. J. Heap, P. Baud, and J. Schmittbuhl, "Thermal cracking in westerly granite monitored using direct wave velocity, coda wave interferometry, and acoustic emissions," *Journal of Geophysical Research: Solid Earth*, vol. 123, no. 3, pp. 2246–2261, 2018.
- [13] F. Li, S. You, H.-g. Ji, D. Elmo, and H.-t. Wang, "Strength and energy exchange of deep sandstone under high hydraulic conditions," *Journal of Central South University*, vol. 27, no. 10, pp. 3053–3062, 2020.
- [14] M. Gao, J. Xie, Y. Gao et al., "Mechanical behavior of coal under different mining rates: a case study from laboratory experiments to field testing," *International Journal of Mining Science and Technology*, vol. 31, no. 2021, pp. 825–841, 2021.
- [15] Na Yao, *Numerical Simulation Study on Ventilation and Cooling of Tunnels in High Geothermal Metal mines*, North China University of Technology, Beijing, China, 2016.
- [16] P. Gao, *Analysis of Rock Thermophysical Parameters and Research on Multi-Field thermal Effect Coupling model*, Jilin University, Changchun, China, 2015.
- [17] Z. Chen, W. U. Xu, and H. Wang, "Research on thermal conductivity of granite under high temperature conditions," *Science Technology and Engineering*, vol. 16, no. 24, pp. 193–197, 2016.
- [18] G. Ren, J. Li, and T. Hu, "The effect of temperature on the thermal conductivity of granite," *Journal of Railway Science and Engineering*, vol. 17, no. 8, pp. 1986–1992, 2020.
- [19] M. A. Ling, Y. Zhao, H. Yin, and J. Zhao, "A coupled heat transfer model of medium-depth downhole coaxial heat exchanger based on the piecewise analytical solution," *Energy Conversion and Management*, vol. 204, Article ID 112308, 2020.
- [20] C. Liu, J. Li, Y. Zhang, F. Han, C. Ji, and J. Zhang, "Study on coupled heat transfer and seepage in large sparsely fractured surrounding rocks in deep underground spaces," *Applied Thermal Engineering*, vol. 162, Article ID 114277, 2019.
- [21] M. Bian, *Research on Gas-Solid Heat Transfer Theory and Ventilation Cooling Simulation in Xiadian Gold Mine*, University of Science and Technology Beijing, Beijing, China, 2019.
- [22] S. Fuchs and A. Förster, "Rock thermal conductivity of Mesozoic geothermal aquifers in the Northeast German Basin," *Geochemistry*, vol. 70, pp. 13–22, 2010.
- [23] V. Pasquale, M. Verdoya, and P. Chiozzi, "Measurements of rock thermal conductivity with a transient divided bar," *Geothermics*, vol. 53, pp. 183–189, 2015.
- [24] G. S. Jia, Z. D. Ma, Y. P. Zhang et al., "Series-parallel resistance method based thermal conductivity model for rock-soil with low or high porosity," *Geothermics*, vol. 84, Article ID 101742, 2020.
- [25] A. Tatar, S. Mohammadi, A. Soleymanzadeh, and S. Kord, "Predictive mixing law models of rock thermal conductivity: applicability analysis," *Journal of Petroleum Science and Engineering*, vol. 197, Article ID 107965, 2020.
- [26] F. Jia, *Engineering Heat Transfer*, China Petrochemical Press, Beijing, China, 2017.
- [27] M. Lin, *Rock Thermophysics and its Engineering application*, Chongqing University Press, Chongqing, China, 1991.