Research Article

Influence of Temperature on Quantification of Mesocracks: Implications for Physical Properties of Fine-Grained Granite

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Thermally induced changes in mesocrack and the physical properties of fine-grained granite may influence their stability, transport characteristics, and performance related to various deep subsurface energy projects. In this study, granite was heat-treated at different temperatures (20°C, 100°C, 200°C, 300°C, 400°C, 500°C, and 600°C). The propagation and evolution of different types of cracks and the physical properties of the granite were quantitatively investigated, using optical observations of petrographic thin sections, P-wave velocity measurements, and permeability tests. The results show that as the temperature increased, the number and length of cracks increased, and the cracks were randomly distributed in all directions. This led to an increase in rock damage ($\lambda(n)$) and an increase in permeability ($K$). In particular, when the temperature was $\geq400°C$, the damage rate significantly increased, and the number and length of intragranular cracks significantly exceeded the number and length of intergranular cracks. This led to changes in the permeation path, causing it to mainly travel through the interior of mineral particles. Using the inverse of P-wave velocity ($V_p$), the dimensionless crack density ($\rho$) of granite was found to increase as the temperature increased, and this result was similar to the change of optical crack density ($P_l$). These analyses laid a reference for understanding the correlation between microcrack characteristics and macrophysical properties of granite.

1. Introduction

In the process of geological evolution, a variety of fossil energy sources (coal, oil, shale gas, etc.) have been formed, which are exist in different depths [1]. When underground mining energy engineering, the rock is affected by the changing temperature, which will induce thermal cracks. Microcracks in rock are typically 0.1 mm long or shorter, and the ratio of their aperture and their length, of less than $10^{-2}$, generally ranges from $10^{-3}$ to $10^{-5}$ [2]. The formation of microcracks is the manifestation of rock damage. When the damage accumulates or the crack extends to a certain point, the rock will fail. Particularly in underground engineering, rocks are often found in complex temperature environments. Because of the influence of temperature field on crack propagation, rock stability can change. Therefore, temperature is an important factor affecting the safety, efficiency, and smooth completion of underground engineering.

For example, in developing an enhanced geothermal system (EGS), the purpose of artificial reservoir modification is to properly propagate and penetrate fractures, to form a fracture network structure that facilitates heat exchange and gas-liquid flow. This improves the efficiency of geothermal energy development and ensures the stable operation of the project. In the geological storage of nuclear waste, reservoir rocks are generally granite. As time passes, the decay of radioactive elements gradually produces thermal radiation, causing temperature increases in the surrounding rock strata. Studies have predicted that the released heat can cause the temperature of granite to rise up to 200~300°C [3, 4]. Because the rock is in a changeable temperature field for a long time, the thermal cracks consistently change. Once these cracks penetrate and form macrocracks, rocks may fail.
This may lead to nuclear waste and radiation leakages, polluting the underground environment. This highlights the importance of studying the influence of temperature on the propagation and evolution of mesocracks in rocks.

Cracks formed in different kinds of rocks in different environments have many characteristics. Most stress-induced cracks in granite are long [5], straight, and narrow with sharp ends. The formation of new initial transgranular cracks relates to the high-angle interface of different minerals. At 100°C to 125°C, the permanent strain of Inada granite can lead to the accumulation of new microcracks and the opening of existing microcracks [6]. The quartz in Zhejiang granite shows brittle and isotropic cracks, whereas feldspar and biotite show anisotropic cracks. The separation of cleavage surface (cracking crack) is a main failure mode of biotite and feldspar [7]. Zhao et al. [8] used a high precision micro-CT system (μCT225kVFCB) to observe the three-dimensional microfracturing of granite at temperature conditions ranging from room temperature to 500°C. They found an irregular spatial structure in granite crystals, with grain sizes of 100-300 μm. At 200°C, a very small number of microcracks appeared. At 300°C, some cracks overlapped to form larger cracks, and the crack length increased by approximately 10 times. At 500°C, the closed polygonal cracks surrounding the granite crystal particles formed, creating a mylonitic crystal grain structure in the granite. More than 90% of the cracks were generated along the periphery of the particles, and approximately 10% of the thermal cracks passed through the mineral particles.

Microscopic cracks of rocks are mainly studied using SEM (Scanning Electron Microscopy) CT, and thin sections of rocks. Quantitative statistics about microcracks are mainly generated using manual identification and automatic identification with computer programming. For example, the stereological techniques of Underwood can be applied to obtain the microcrack density of rock [9]. The technique involves placing a grid on a microscale image and then calculating the number of intersections between the lattice and the crack, thereby calculating the crack density in the region. The artificial quantification of crack statistics is time-consuming, workload intensive, and subjective. However, quantitative statistics about microcracks can also be automatically obtained by special analysis software [2, 10]. Griffiths et al. [2] developed an algorithm to process optical micrographs of rock, automatically creating binary images of the microcrack network. These processed images can be used to calculate the mean microcrack length and the number of microcracks per unit area (and therefore the 2D microcrack density). Subjective factors are not fully avoided using computer recognition method, because different computer recognition methods may produce different results for the same research sample.

High temperatures can affect both the microstructure of rock and the rock's macrophysical and mechanical properties. Chen et al. [10] conducted a uniaxial compression test of granite after a high temperature heat treatment. As the heating temperature increased, the peak strain of the granite increased, and the peak stress and elastic modulus decreased. When the temperature was lower than 400°C, the effect of heating on the peak stress, elastic modulus, and peak strain of granite was small. When temperature is lower than 500°C, the change in fracture toughness of sandstone occurs more slowly [11, 12]. When the temperature exceeded 500°C, the fracture toughness of sandstone significantly decreased [11, 12]. Feng et al. [11] studied the permeability of granite at real-time high temperatures. The results showed that 300°C is the threshold temperature for changes in the permeability of granite. Thermomechanics coupling can more significantly affect the permeability of granite. Generally, heating decreases the compressive and tensile strength of granite. This is due to the increase of thermal stress and the formation of tensile microcracks [13]. The mechanical properties of rock decrease in the heat-cooling cycles, because of the increase in the density of tensile microcracks caused by thermal action. The existence of a thermal gradient causes macrocracks to form. Hu et al. [14, 15] studied the mechanical and thermodynamic properties of granite after high temperature treatment. Chen et al. [16] studied the thermal damage and permeability evolution of Beishan granite at different heating rates (1-5°C/min). They found that the physical and mechanical properties of the granite weakened as the temperature increased. The intergranular cracks were the main microcracks induced by thermal action at 100-573°C.

The research described above helps explain the effect of temperature on cracks and the physical and mechanical properties of rock, which are related to their mesocracks. Generally, microcracks are divided into transgranular cracks, intergranular cracks, and intragranular cracks according to their formation mechanism. Rock is a complex structure, composed of different mineral particles. As the temperature changes, mineral particles swell, changing the structure and generating different microfracture mechanisms in the rock. As such, the temperature affects different types of cracks and consequently changes the corresponding physical properties of cracks. As a porous medium, rock provides channels for gas diffusion and liquid flow. Therefore, the evolution of microcracks in rocks relates to the ability of the rock to resist fracture failure and relates to the changing characteristics of channels. Quantitatively studying the propagation and evolution of different types of mesocracks and the changes of rock physical properties helps establish a meso-macro correlation. This enables a deeper understanding of the effects of high temperatures on rocks and further informs engineering practices. Fine-grained dense granite is generally stronger, and the mineral particles are relatively small. The generation and propagation of cracks relate to the size and density of mineral particles in rocks.

Quantitative studies are needed to understand microcracks in fine-grained granite and the relationships between these cracks and its physical properties. Therefore, this study evaluated the impact of heat treating rocks at different temperatures. The study quantified the propagation and evolution of different types of cracks using petrographic thin sections. The mesostructure characteristics were observed using SEM. The physical properties of granite were also tested. Thus, we explored the relationship between the
microstructure of fine-grained granite and its macrophysical properties under the influence of different temperature gradients.

### 2. Mesocrack Characteristics of Granite in Heat Treatment Experiment

#### 2.1. Heat Treatment Experiment of Granite

The granite samples were placed into a muffle furnace for heat treatment at different temperatures. Seven temperature measuring points were established for this experiment: room temperature (20°C), 100°C, 200°C, 300°C, 400°C, 500°C, and 600°C. The temperature was increased at a constant rate of 5°C/min. After reaching each preestablished temperature, the sample was kept warm for 10 hours. Then, stop heating, and the samples were allowed to cooling to room temperature naturally.

#### 2.2. Mesocrack of Granite

After heat treatment, the granite was then observed under a polarizing microscope, and many mesoscopic pictures were collected. Figure 1 shows some of these pictures.

The granite grains are relatively integrity at 20°C, and there are few cracks, showing very compact characteristics. Above 100°C, a few cracks were seen, with some cracks in the mineral particles and with some cracks between mineral particles. The cracks in quartz and feldspar grains significantly increased when the temperature rose to 400°C. When the temperature continues to rise to 500°C or above, the cracks in the mineral particles and the cracks between the particles became very clear, with significantly larger cracks. Many cracks intersected, dividing quartz particles and feldspar particles into several small pieces and forming a very fragmented structure. This is due to different physical and chemical reactions of rocks at different temperatures. The dehydration reaction of adsorbed water and crystalline water, the isomorphic transformation of quartz, the expansion of mineral particles caused by thermal stress, and other factors cause new cracks to form and existing cracks to expand.

#### 2.3. Size and Density of Cracks

The orthogonal polarization and single polarization imaging of rock slices was performed under a microscope. The types of cracks were carefully observed and identified, and the trajectory of cracks was depicted. We carefully measured the number and length of these cracks. Because of the complexities of rock formation and structure, the shape, size, and direction of cracks appear somewhat disorderly. As such, for ease of study, we developed some simplifications [17, 18]: (1) A crack approximating a straight-line segment is expressed as one crack. Bending and broken-line cracks are identified separately, i.e., multiple cracks are identified at each bending or broken-line connection. (2) The transgranular crack is considered to be an intragranular crack connected at the head and the tail of the grain. That is, the transgranular crack and the intragranular crack are unified as an intragranular crack.

Several scholars [5, 19–22] have used crack density to quantitatively describe the crack characteristics in rocks. Two methods are generally used to calculate crack density. The first method is to draw the observation datum line on the mesoscopic picture. Then, researchers count the number of intersections between the base line and the crack and obtain the crack density by dividing the number by the total length of all the baselines, as shown in Equation (1).

\[
P_1 = \frac{N_i}{L_b}.
\]

In this expression, \(P_1\) is the crack density; \(N_i\) is the number of intersections between the crack and the baseline; \(L_b\) is the total length of the baseline.
The second method involves delineating a part of the area in the microimage, counting the length of the crack in the area, and dividing the length of the crack by the area. This generates the crack density, as shown in Equation (2).

$$P_i = \frac{L_i}{A_r}$$  

where $L_i$ is the total length of cracks in the study area and $A_r$ is the area of the study area.

This study applied the first method to calculate the crack density, because optical means were used to collect mesoscopic pictures. Therefore, $P_i$ is called the optical crack density in this paper. For each temperature, five pictures were taken at the same magnification factor and the statistics of crack characteristics were generated. Figure 2 shows the statistical results for the number and length of cracks in granite after heat treatments at different temperatures from 20°C to 600°C.

The number of cracks in granite increased with the increase of temperature (Figure 2(a)). As the temperature increased from 20 to 300°C, the number of intragranular cracks increased from 176 to 334, and the number of intergranular cracks increased from 115 to 462. As the temperature increased to 400°C, the number of intragranular cracks increased to 638 and the number of intergranular cracks increased to 473. From 400 to 600°C, the number of cracks significantly increased. The number of intragranular cracks was 7.06 times greater at 600°C compared to 20°C. The intergranular cracks at 600°C were 4.23 times longer compared to at 20°C. Therefore, high temperatures are more likely to increase the generation and propagation of cracks.

The thermal crack conditions of rocks caused by high temperatures can be quantitatively described by analyzing the number, length, aspect ratio, crack density, and other factors. Equation (1) was used to calculate the optical crack density of granite under different temperatures. The crack density increased as the temperature increased (Figure 3). The crack density was 0.26 mm⁻¹ at 20°C, and the crack density was 3.37 mm⁻¹ at 600°C. The temperature at 600°C was about 13 times higher than 20°C. The crack density of granite increased rapidly when the temperature exceeded 300°C. High temperatures had a very significant effect on the generation and propagation of cracks.

2.4. Crack Propagation Direction. Studying the propagation direction of mesocracks in rock helps predict the potential macrocrack growth trends. For this study, angle intervals were set at incremental values 20° apart, at 0-20°, 20-40°, 40-60°, 60-80°, 80-100°, 100-120°, 120-140°, 140-160°, and 160-180°. The number of cracks within each angle section was counted. Counts were completed for five pictures at each temperature. The difference between the crack head and the crack tail is 180°; as such, the overall statistic for 360° plane cracks can be completed by counting the cracks in the range of 0-180°. This involved drawing the number of cracks in each direction, as shown in Figure 4. In all
directions, the number of cracks is a closed curve with a different radius. The figure shows the changes in the number of curves after the heat treatment at different temperatures. The closed curve was a polygon shape at 20-200°C, with a small number of cracks in different directions. This is because the number of cracks was relatively small when the temperature was relatively low. However, when the temperature exceeded 300°C, the closed curve became increasingly circular. These results show that temperature was not associated with a particular orientation for crack propagation in a certain direction. For the fine-grained dense granite from Suizhou, the direction of crack propagation appeared to be random when subjected to high temperatures.

3. Physical Properties (P-Wave Velocity and Permeability)

3.1. P-Wave Velocity of Granite. In underground energy development project, the relative magnitude of P-wave velocity can be used to infer the integrity in rock. Temperature impacts change in the internal structure of rock, leading to changes in the P-wave velocity. Figure 5 shows the P-wave velocity for granite after heat treatment at different temperatures in this study.

Figure 5 shows that the P-wave velocity decreased as the temperature increased between 20°C and 300°C. When the temperature ranged from 300°C to 400°C, the velocity sharply decreased. The P-wave velocity continued to decrease above 400°C. The P-wave velocity after the high temperature treatment at 600°C was 20.52% the velocity at 20°C. It is assumed that the high temperature caused more weak elastic properties and integrity in the rock. Some scholars [23] have applied an elastic modulus as the damage variable to describe the effect of temperature on the mechanical properties of rock and have proposed the concept of thermal damage (Thermal Damage). Similar to this idea, this study used the P-wave velocity to measure the rate or gradient of damage (λ(3)) to granite at different temperatures. For this study, Equation (3) shows the specific calculation.

\[ \lambda(3) = \left(1 - \frac{X(T)}{X(20)}\right) \times 100\%. \]  

In Equation (3), \( X(T) \) is the P-wave velocity at different temperatures, and \( X(20) \) is the wave velocity at 20°C. The experimental data were substituted into Equation (3) to calculate the damage rate after heat treatment at different temperatures, as shown in Table 1.

The damage rate of granite is 5.13% at 100°C. As the temperature increased, the damage rate gradually increased. The damage rate of granite was less than 30% when the temperature was below 300°C. The damage rate of granite was 27.49% more at 400°C than at 300°C; 400°C was the temperature range at which the rate of damage increased the most. As the temperature continued to rise, the damage rate increased at a more gentle rate until reaching 79.48% at 600°C. The damage rate reflects the degree of damage to the granite and reflects an accumulation of damage. Therefore, high temperatures above 400°C significantly damage rocks.

3.2. Determination of Crack Density Using P-Wave Velocity. From an experimental perspective, optical and electronic microscopy methods have been widely used to study the microcrack structure of rocks. From a theoretical perspective, the theoretical evolution in the elastic properties of damaged materials can be predicted using effective medium theory (EMT) [24–30]. EMT predicts material properties as a function of a single dimensionless damage parameter. Some scholars have studied the elastic wave velocity of materials and have used that measure to estimate crack density of materials [24–30].

Cracks in rocks cause internal damage. Assuming that the elastic properties of rocks are related to their damage, according to Effective medium theories (EMTs), we can obtain the dimensionless crack density of rocks with cracks [30, 31]. This is expressed in Equation (4).

\[ p = \frac{1}{V} \sum_{i=1}^{N} \frac{C_i}{r_i^3}. \]  

In this expression, \( C_i \) is the radius of the \( i \)th crack and \( N \) the total number of cracks embedded in the representative elementary volume \( V \). Three facts are important here [30, 31]. First, real fractures are not generally uniformly spatially distributed—a fractal-type description may be more realistic (e.g., in some crystalline rocks, cracks can be very highly spatially concentrated, with large intact rock between these zones). Second, real fractures have intersections. Third, real fractures do have shapes, which are complex in detail. Despite these facts, most EMTs assume there are nonintersecting cracks, uniform distributions of crack centers, and simple crack geometries.

Although those three important simplifications can be discussed from a theoretical point of view, they have led to considerable insights [30, 31]. The simplest EMT reflects the theory of noninteractivity, because it does not address the problem of stress interactions between cracks. It is therefore independent of crack center distribution [31]. To address a random crack center and orientation distribution (isotropic), stress interactions are partially geometrically compensated for. The effective Young’s modulus \((E^*)\) and...
The shear modulus ($G^*$) of a dry rock can be written as Equations (5) and (6) [30, 31].

$$\frac{E_0}{E^*} = 1 + \frac{16(1 - \mu_0^2)(1 - 3\mu_0/10)}{9(1 + \mu_0/2)} \rho, \quad (5)$$

$$\frac{G_0}{G^*} = 1 + \frac{16(1 - \mu_0^2)(1 - 3\mu_0/10)}{9(1 - \mu_0/2)} \rho, \quad (6)$$

**Figure 4:** Distribution of cracks in different directions.

**Figure 5:** $P$-wave velocity vs. temperature.

**Table 1:** The damage rate of granite (%).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>20</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{(a)}$ (%)</td>
<td>0.0</td>
<td>5.13</td>
<td>14.83</td>
<td>29.32</td>
<td>56.81</td>
<td>65.17</td>
<td>79.48</td>
</tr>
</tbody>
</table>
\[ V_p = \sqrt{\frac{K^* + 4/3G^*}{\rho_d}}. \] (7)

In these equations, \( E_0 \) is Young’s modulus, \( G_0 \) is the shear modulus, and \( \mu_0 \) is Poisson ratio of the uncracked rock. Equation (7) was used to determine the \( P \)-wave velocity of rock. Using this approach, \( V_p \) is the \( P \)-wave velocity, \( K^* \) is the bulk modulus, \( G^* \) is the shear modulus, and \( \rho_d \) is the bulk mass density. Formulas (5)–(7) are used to calculate the dimensionless crack density (\( \rho \)). The inversion was performed using a simple least-square technique, best described in Schubnel et al. [31].

The initial parameters were set as \( E_0 = 50 \, \text{GPa}, \mu_0 = 0.28, \) and \( \rho_d = 2.7 \, \text{g/cm}^3 \). Figure 6 and Table 2 plot the dimensionless crack density (\( \rho \)) and optical crack density (\( P_l \)) as the temperature varied. As the temperature increased, both \( \rho \) and \( P_l \) decreased.

The dimensionless crack density increased with temperature (Figure 6). The curve has clear three stage changes. In the first stage, the dimensionless crack density increased slowly, which was consistent with the increase in the optical crack density in the temperature range of 20°C–300°C. In the second stage, the increasing rate of dimensionless crack density increased, as the temperature ranged from 300°C to 500°C. The increasing rate of optical crack density increased at 300°C–400°C. In the third stage, the increasing rate of dimensionless crack density increased sharply from 500°C to 600°C. The optical crack density increased from 400°C to 600°C; however, the rate of increase did not change much. Overall, the optical crack density and dimensionless crack density increased slowly when the temperature was lower than 300°C. The theoretical results align with the experimental results using optical microscopy. Once the temperature exceeded 400°C, their values increased, but their increasing rates varied inconsistently. Therefore, when the temperature exceeded 400°C, there was a difference between the theorized and the experimental results obtained by optics. This may be due to the significant cracking of rocks caused by the high temperature and the complex network of cracks.

### 3.3. Permeability of Granite

Permeability is a basic physical property of rock and reflects a certain degree of fracture penetration. The heat transfer medium (\( \text{H}_2\text{O} \) or \( \text{CO}_2 \)) exchanges heat in the geothermal reservoir. The better the permeability of reservoir rock is, the more favorable the heat transfer medium flow in the reservoir. This not only determines the heat exchange efficiency, but also directly affects the effective extraction of geothermal energy output value. This study assessed granite permeability after heat treatments at different temperatures. The results were then averaged and plotted as a curve, shown in Figure 7.

The permeability of granite was \( 0.51 \times 10^{-18} \, \text{m}^2 \) at 20°C, indicating that Suizhou granite is a low permeability compact granite. As the temperature increased, the permeability of granite gradually increased. The permeability at 200°C was four times as high as the permeability at 20°C. When the temperature rose to 300°C, the permeability abruptly increased, six times the level seen at 200°C. The permeability of granite at 400°C increased more significantly than at 300°C. It can be concluded that the degree of crack penetration in the rock increased. First, there was an increase of the length and width of the original crack; further, there is the generation and development of new cracks. When the temperature reached 500°C, the permeability of granite exceeded the measuring range of the permeability (≤10 mD). Therefore, its permeability is at least over \( 10000 \times 10^{-18} \, \text{m}^2 \). This was due to the intense movement of molecules in rocks caused by the high temperature, the frequent and deeper
thermal action, and the more active penetration of internal cracks. Overall, the permeability increased with temperature, first slowly and then more sharply. Therefore, the high temperature can advance the formation of internal channels in rocks.

4. Discussion

4.1. Mesostructure of Granite. High temperatures cause the decomposition of some substances in rocks, reduce the amount of the original substances, and generate new substances. This changes the mineral composition. The physical changes occurring in rocks at high temperatures, including the expansion of mineral particles and the propagation of microcracks, can lead to structural changes. A previous study [32] found that even if the change in mineral composition is not significant, a high temperature can still cause significant changes in the internal structure of rocks. This changes the ability of rocks to resist fracture failure. SEM is used to observe the microscopic structure of rocks in experimental research [32, 33]. Therefore, this study applied SEM to observe the granite under different temperatures. Selected pictures are shown in Figure 8.

Some cracks and pores were observed until temperature reaches 300°C; these were caused by the main crack propagating along larger and harder mineral particles, as shown in Figure 8(b). When the temperature exceeded 400°C, transgranular fractures occurred easily, because thermal stress weakened the mineral particles. At the same time, the inconsistency of thermal expansion also facilitated intergranular fractures. Figures 8(c)–8(f) make it clear that there are many transgranular and intergranular cracks on the fracture surface, as well as coupling cracks. These cracks penetrate each other, resulting in a fragmented and loose structure. The surface of the fracture is disorderly and rough.

4.2. Change of Mineral Composition of Granite. Granite mainly contains sodium (calcium) feldspar, quartz, and potassium feldspar. It also contains a small amount of other materials, which barely decompose at 600°C. The homogeneous polymorphism of quartz occurs at different temperatures. At atmospheric pressure, quartz has seven isomorphic forms [34]: α-quartz, α-tridymite, α-cristobalite, β-quartz, β-tridymite, β1-tridymite, and β-cristobalite. The alpha-crystalline form is stable at a low temperature, while the beta-crystalline form is stable at a high temperature. These seven crystals will undergo some transformation at different temperatures, as shown in Figure 9.

There are two modes of SiO₂ transformation: the reconstruction type and displacement type [35]. (1) Reconstructive-type transformation is the transformation between different β-types, including β-quartz, β-tridymite, and β-cristobalite. Reconstructive transformation involves bond destruction and reconstruction, leading to a comparatively slow transformation. In addition, when the temperature is lowered, the transition does not occur due to supercooling, and it will continue to exist in a metastable state until it finally transforms into its own cryogenic variant. (2) Displacement-type transformation is the mutual transformation between high-temperature and low-temperature types of the same crystal type. Examples include the transformation between α-quartz and β-quartz; the transformation between α-tridymite, β1-tridymite, and β-tridymite; and the transformation between α-cristobalite and β-cristobalite. This structural transformation does not involve bond breakdown and reconstruction. As such, the transformation process is rapid and reversible. The transformation of quartz crystal types, whether reversible or not, causes a change in the granite structure. The isomorphic transformation of quartz becomes more prominent as quartz content increases. The transformation between crystal forms of quartz results in a volume change of quartz particles.
The quantitative results of properties with temperature. Properties of microcrack as a function of temperature. In microcrack, and the formation of large voids and cracks at the macroscale. This makes the physical and mechanical properties of microcrack a function of temperature.

4.3. Evolution of Mesocrack Characteristics and Physical Properties with Temperature. The quantitative results of mesothermal cracks in granite show that the number and length of intragranular cracks increased more gently at 20°C-300°C and increased more substantially at temperatures exceeding 300°C. Therefore, high temperatures clearly advanced crack development. The intergranular cracks dominated crack propagation at temperatures less than 400°C. However, when the temperature exceeded 400°C, the cracks in the grains gradually became dominant. This is because at lower temperatures of 20°C-300°C, the rock was heated and the free water evaporated first. The thermal expansion coefficient of mineral particles differed at different temperatures, with inconsistent deformation. The degree of connection between mineral particles was lower compared to the mineral particles themselves; as such, thermal cracks mainly occurred between mineral particles. When the temperature reached 400°C, the thermal stress of mineral particles clearly increased. High temperature made the softening effect of mineral particles more clear. Thermal stress caused the cracking of mineral particles to form new cracks, which gradually expanded. The length of the cracks also increased. Therefore, thermal cracks gradually appeared in the mineral particles. This demonstrates that cracks in the particles gradually became dominant at high temperatures. Thermal cracks occur in both quartz and feldspar. Statistical results of all cracks (with no distinction between intragranular and intergranular cracks) show that cracks did not propagate in a particular direction but propagated randomly in all directions.

Increasing the number, length, and density of cracks may cause corresponding changes in the physical properties of rocks. The development of intergranular and intragranular cracks results in rock damage and voids. Therefore, the P-wave velocity is expected to decrease with the increase of temperature. In this study, the P-wave velocity decreased gradually at 20°C-300°C; however, when the temperature reached 400°C, the velocity decreased suddenly and sharply, followed by further decreases. This is consistent with the variations in the number, length, and density of cracks. The SEM images showed that a high temperature above 400°C caused the granite to produce significant and serious cracking, large pore and more fissures, and a loose and fragmented structure. The propagation rate of P-wave was lower in air compared to in the solid rock medium. Therefore, the rock damage caused by the evolution of mesocracks aligns well with the change in P-wave velocity.

The permeability gradually increased at temperatures ≤ 400°C and significantly increased at temperatures ≥ 400°C. In particular, at a temperature of 500°C, rock permeability exceeded 10 md. Permeability reflected the degree of penetration in the internal passages in the rocks. Therefore, it appears that the high temperature led to a significant increase in the degree of penetration in the rock. This is due to an increase in the crack width in the rock, the development of cracks along the length direction, and the interconnection and penetration of cracks, forming larger cracks. The number of cracks increased; in particular, the cracks in the particles occurred more readily at high temperatures. This shows that the permeability path in the rock largely passed through particle interiors. However, when the temperature is higher than 400°C, the permeation channel along the particles was no longer dominant.

The SEM images also showed that the intergranular and transgranular cracks increased as the temperature increases, and they intersected with each other. The type of crack was determined by the fracture mechanism. As such, this outcome was due to the transition from a low temperature intergranular fracture mechanism to a transgranular-intergranular coupling fracture mechanism and then to a transgranular fracture. Although 573°C is the phase transition temperature point of quartz in rocks, no significant change in the cracks was observed from 500°C to 600°C. This may be because the dense fine-grained granite was already significantly cracked due to the high temperature effect above 400°C. In addition, this study adopted a 10-hour thermal insulation period. Therefore, the internal cracking of granite had more time to proceed, because of the high
temperature above 400°C. Most research results have found a sudden change in temperature between 500°C and 600°C. For example, Griffiths et al. [2] found that when the granite was heated to 550°C and 600°C, the porosity greatly increased, whereas $V_p$ and UCS significantly decreased. The transformation of the α-β phase in quartz near 573°C appears to have been accompanied by a large volume expansion, increasing the intergranular thermal stress [38–41].

A study [2] has shown that porosity, wave velocity, and UCS of rocks continue to change when the temperature exceeds 600°C, while the measured microcrack density remains almost constant. This has been attributed to the presence of microcracks in crystals, which are usually much smaller than the size of crystals [42]. At high temperatures, microcracks grow with each other and generate microcrack grids. In their algorithm, they are considered to be many microcracks, leading to a reduction in the length of the crack. In addition, the wave velocity decreased and the porosity increased when the temperature changed from 600°C to 900°C. The thermal microcrack aperture of westerly granite was found to significantly increase when the temperature exceeded the quartz alpha-beta transition temperature [5, 38]. These studies also found that the microcrack aperture increased when the temperature increased to 600°C or above. It was assumed that the increase in the crack aperture may be the cause, not the number of cracks. To clearly explain the relationship between crack density change and rock physical properties, it was necessary to quantitatively study the number and length of intragranular and intergranular cracks.

This study’s results show that the crack density increased gradually at 20°C-300°C. At 400°C, the density suddenly significantly increased to 2.15 mm$^{-1}$. After that, the crack density continued to increase to 3.37 mm$^{-1}$ until the high temperature of 600°C was reached. The crack density was consistent with the growth and evolution of the number and length of cracks. As the number of cracks increased, the crack density represented by the number of cracks correspondingly increased. Crack density can better explain the change in the rock’s physical properties. With the increase of crack density, P-wave velocity and permeability of rock decreased. The crack density obtained by the inversion of P-wave velocity also shows that the dimensionless crack density increased as the temperature increased. However, the change rate of crack density and dimensionless crack density obtained using optical methods differed when the temperature exceeded 400°C. Under the action of high temperature, the number, length and width of any type of crack appeared to change. The crack density was a function of the physical properties of rocks in the temperature range of 20°C–600°C.

5. Conclusion

In this study, fine-grained dense granite was heat treated at different temperatures, ranging from 20°C to 600°C. The evolution of intragranular and intergranular cracks in granite with temperature was quantitatively studied using an optical microscope. The rock’s physical properties were studied using P-wave and permeability measurements. The dimensionless crack density was inverted based on the effective medium theory. The mesostructure characteristics were investigated using SEM. The results and analysis led to a clearer understanding of the correlation between microcrack characteristics and macrophysical properties of granite. The study’s main conclusions are as follows:

(1) Microcracks appeared in fine-grained dense granite after heat treatment at 100°C. As the temperature increases, the crack density increased, showing that the number of internal cracks increased and the length of the cracks increased. At lower temperatures (≤300°C), thermal action mainly induced intergranular cracks in granite. At higher temperatures (above 400°C), intragranular crack propagation dominated. Moreover, when the temperature reaches 400°C, the crack density of granite suddenly increased. When granite was heated at different temperatures, the evolution direction of crack propagation in granite was generally random.

(2) The P-wave velocity of granite decreased with temperature. The damage rate increased as the temperature increased. The degree of damage was particularly aggravated at a temperature above 400°C. Based on the effective medium theory, the dimensionless crack density curve of granite plotted against temperature was obtained, using P-wave velocity inversion. The dimensionless crack density and crack density increased as the temperature increased. When the temperature was lower than 500°C, the densities experienced similar rates of change. The dimensionless crack density changed rapidly when the temperature exceeded 500°C.

(3) The permeability of granite increased with the increased temperature. The permeability of granite was low between 20°C and 200°C, ranging from $0.511 \times 10^{-18} \text{ m}^2$ to $2.077 \times 10^{-18} \text{ m}^2$, showing a relatively compact property. When the temperature reached 300°C, the permeability of granite suddenly increased to $12.949 \times 10^{-18} \text{ m}^2$, which was about 6 times higher than the permeability at 200°C and 25 times higher than the permeability at 20°C. When the temperature continued to rise to 400°C, the permeability increased sharply. In particular, when the temperature exceeded 500°C, the permeability increased sharply. Therefore, high temperatures significantly facilitated fracture connectivity in rocks. At high temperatures of 400°C and above, the permeation path of fine-grained dense granite was mainly through the internal path of particles.

(4) As the temperature increased, cracks gradually appeared in the granite, and the number and length of intergranular cracks and intragranular cracks increased. This led to an increase in crack density. In particular, high temperatures above 400°C facilitated the formation of clear cracks in the rock.
The crack size of granite significantly increased after heat treatments at a temperature of 400°C or above. As the crack length increased, the crack expanded and they gradually connected. Further, the crack width increased, leading to the gradual separation of mineral particles. Thus, the mineral particles were divided into several small pieces. This led to a loose granite structure and penetration between cracks, leading to an increase in permeability. The evolution and accumulation of cracks in different types and directions caused the internal structure of rock to be fragmented, affecting its physical properties.

Data Availability

All the data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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References


G. Q. Zhang, Structural Transformation of SiO₂ with Different Initial States under High Temperature and High Pressure. [Ph. D. Thesis], Jilin University, Changchun, 2009.


