Experimental study of the influence of temperature and cooling method on dynamic mechanical properties and damage of granite

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Abstract
The change in mechanical properties of high-temperature rock after cooling treatments is getting increasing attention. However, only a few studies have been conducted on the dynamic characteristic parameters. Therefore, this study aims to perform a dynamic damage analysis of high-temperature rocks subjected to different thermal shocks. Accordingly, the specimens were grouped and heated to 200°C, 400°C, 600°C, and 800°C, and they were cooled by natural, water, and liquid nitrogen cooling. Ultrasonic detector tests, the split Hopkinson pressure bar experiments, and scanning electron microscope tests of the high-temperature granite specimens were conducted using different cooling methods. Subsequently, the change rules of dynamic stress–strain curves and properties were calculated, and the morphology and micromorphology of fragments were compared. Based on the outcomes, the thermal shock damage and impact damage evolution were evaluated and quantified. The findings revealed that when the treatment temperature increases, the dynamic peak stress and elastic modulus decrease, while the peak strain increases, and the effect of rapid cooling was more significant in the influence of rock dynamic characteristics. Moreover, when the damage factor is more than 0.51, the change of dynamic stress-strain is accelerated, leading to the instability of the structure under the impact load. The research results are expected to provide an adequate theoretical basis for the development and utilization of geothermal resources and underground engineering applications.

KEYWORDS
damage evolution, granite, rock dynamics, thermal and cooling treatment

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1 | INTRODUCTION

Recently, with the development and utilization of geothermal energy, such as the hot dry rock (HDR), an increasing number of researchers have focused on comprehending and evaluating the impact of high temperature on the mechanical behavior of rocks. In certain circumstances, the reservoir rocks or surrounding rocks were initially in a high-temperature environment or heated to extremely high temperatures before being subjected to rapid cooling treatment; for instance, in the process of the exploitation of HDR, cold drilling fluid is pumped into the wellbore to assist in rock breaking, and the liquid nitrogen is used in fracturing engineering, or when a conflagration occurs in the rock tunnel, and water-based fire extinguishing agents are used to extinguish the fire. In such cases, when relatively low-temperature fluids (such as water and liquid nitrogen) make contact with high-temperature rocks, the drastic temperature changes are accompanied by the generation of thermal stress which deteriorates the mechanical properties of rock. Consequently, it is imperative to understand the change in mechanical properties of high-temperature rock after cooling treatments. It can lay a solid theoretical foundation for increasing the production efficiency of geothermal well engineering applications or estimating the stability of the surrounding rock of tunnel postfire.

Two aspects of the research were conducted in previous studies, including the effect of thermal and cooling treatments. The previous research results indicated that both thermal and cooling treatments could result in changes in rock properties and damage the rock. Among them, the effect of heating on the rock properties and microstructures has been thoroughly studied. With the increase in the heating temperature, some mechanical parameters of rock, such as porosity, and permeability, increased, while other properties, such as the wave velocity and thermal conductivity, decreased. Simultaneously, a considerable number of research results indicate that the improvement of the heating problem will also decrease some mechanical parameters, including compressive strength, tensile strength, and Young’s modulus. Following the heat treatment, the brittleness of the rock will be reduced and the ductility will be enhanced. Numerous scholars have investigated the changes in the rock microstructure after heating treatment using scanning electron microscopy (SEM) and X-ray microcomputed tomography (CT) tests. The results show that the number of pores in the rock increases significantly, and some small pores aggregate into macropores or even fractures under the action of thermal stress.

Regarding the cooling treatments for high-temperature rock, numerous theoretical studies and experimental investigations have been performed. However, previous studies have primarily focused on natural and water cooling methods, particularly the latter method was extensively applied as a cooling method by Shao et al. and Siratovich et al. It was pointed out that visible thermal microcracks in granite specimens appeared after water cooling treatment, the permeability of granite specimens was enhanced, and was four orders of magnitude higher than the untreated specimens. Kumari et al. investigated the generation and propagation of microcracks, and it was pointed out that compared with the microcracks caused by high temperature, the specimens subjected to preheating and water cooling treatment revealed complex patterns based on combined shear and splitting. In Zhu et al., the mechanical behavior of granite after water cooling was explored via uniaxial compression tests. They indicated that the deterioration mechanism of granite and its physical and mechanical properties primarily originated from the generation and propagation of microcracks. An acoustic emission (AE) system was also employed to study the changes in mechanical properties at different temperatures after water cooling treatment. Besides, the impacts of natural and water cooling on the physical and mechanical properties of granite under varying temperature treatments have also been compared. Compared with natural cooling, the wave velocity decreased more extensively, and the strength and elastic modulus were lower after water cooling. Based on the above research results, it could be stated that the present research focuses on the changes in static mechanical properties of high-temperature rock after cooling treatment, including the density, acoustic velocity, elastic modulus, and compressive strength.

However, it is crucial to pay more attention to the dynamic characteristics of high-temperature rock after cooling, which is critical for many engineering operations. For example, in underground projects such as geothermal energy exploitation, percussive rock breaking tools were used to drill geothermal wells, the cold drilling fluid flew out from the water hole of the bit and instantly cool the high-temperature rock in contact. Subsequently, a high-frequency impact load was applied to the cooled rocks. Under such circumstances, the rock dynamic characteristics of the high-temperature rock after cooling treatment have a more significant impact on drilling efficiency and bit selection. In addition, the high-temperature rock after cooling is faced with the influence of earthquakes, explosions, construction vibrations, and other dynamic loads, which is different from static loading. Under the action of dynamic load, it involves the short-term mechanical behavior of rock. Therefore, from the perspective of rock breaking efficiency or the safety, reliability, and durability of rock engineering, it is necessary to comprehend the dynamic performance of...
high-temperature rock after cooling. Consequently, it is imperative to further investigate the dynamic characteristics of the rock at high temperatures after cooling treatment. Meanwhile, previous studies have not fully considered the influence of cooling methods on high-temperature rocks. In addition to natural and water cooling, the effect of liquid nitrogen (LN\textsubscript{2}) cooling on the change of the rock dynamic characteristic should also be considered. Moreover, there is little comparative analysis of the influence of three cooling methods on a high-temperature rock.

Considering the above, granite, the main reservoir matrix of geothermal wells was selected and made into standard specimens. Subsequently, the specimens were grouped and heated to 200°C, 400°C, 600°C, and 800°C, then they were cooled by natural, water, and LN\textsubscript{2} cooling. Ultrasonic detector tests, the split Hopkinson pressure bar (SHPB) experiments, and SEM tests of the high-temperature granite specimens were conducted under different cooling approaches. The impact of heating temperature and different cooling ways on the P-wave velocity was quantified, and the dynamic stress-strain and properties under different heating temperatures and cooling methods were analyzed. Moreover, thermal shock damage evolution and the damage mechanism of high-temperature rock under different cooling methods are discussed. It is expected that the experimental results will provide an adequate theoretical basis for the development and utilization of geothermal resources and underground engineering applications.

2 | EXPERIMENTAL METHODS

2.1 | Specimen preparation

It is well known that granite was the main reservoir matrix of hot dry rock, of which the temperature can be 150–650°C, which makes granite a critical reservoir material for improved geothermal systems (EGSs).\textsuperscript{7,30,40} Generally, the drilling and fracturing fluid would cool the high-temperature granite during drilling and fracturing operations. Besides, granite is a vital type of rock for nuclear self-storage, where temperatures can reach 1500°C.\textsuperscript{26,30,41} Therefore, granite specimens were chosen as the research object in this study.

Before the experiment, all the granite specimens were processed into standard rock specimens with a diameter of 50 mm and a height of 25 mm. Moreover, the length-diameter ratio was 0.5 to satisfy the hypothesis of stress uniformity,\textsuperscript{22,42–44} as shown in Figure 1. An acoustic test was performed to ensure that all samples' acoustic velocity difference was slight, and select pieces with similar mechanical properties while minimizing the error caused by rock heterogeneity.

Owing to the influence of the composition of granite on its mechanical properties, an X-ray diffraction (XRD) experiment was conducted before heating the granite specimens. The results illustrate that the granite primarily comprises 31.0% quartz, 27.7% K-Feldspar, 22.6% plagioclase, 11.0% mica, 7.6% clay minerals, and 0.1% clay minerals calcite (Figure 2).

2.2 | Thermal and cooling treatment

The primary aim of the research is to investigate the effect of different cooling methods on granite specimens at various high temperatures. The preparatory work consisted of three stages.

In the first stage, a high-temperature furnace (Figure 3) with a maximum temperature of 1200°C and an accuracy of 1.0°C was used to heat the rock
samples. All the pieces were divided into five main categories, of which the target temperature levels were set as 25°C, 200°C, 400°C, 600°C, and 800°C. During the heat treatment process, 2.5°C/min was chosen as the heating rate to avoid the influence of drastic temperature gradient, and it was considered sufficiently low to reduce the effect of the thermal gradient inside the specimens. After attaining the target temperature, the constant temperature was maintained for 2 h to ensure that the temperature inside and outside the rock was consistent. Subsequently, the specimens were removed from the furnace. Each category was divided into three groups; each group contained three samples and was treated by natural cooling, water cooling, and LN₂ cooling. Finally, after the samples cooled to room temperature, the samples were placed into a heating furnace and dried at 60°C for 3 h to reduce the impact of moisture, and then cooled to room temperature again for further testing.

2.3 | Experimental procedures

2.3.1 | Ultrasonic velocity measurement

After the thermal and cooling treatment, the HS-YS2A rock acoustic velocimeter was used to measure the P-wave velocity of the specimens. During the ultrasonic measurement, the sample was placed between the transmitter and the receiver and was always centered, and both ends were spread with the vaseline to reduce the attenuation of the wave velocity, as shown in Figure 4. Moreover, a specific force was applied to ensure that the sensors made close contact with the specimen. Since each group contained three treated samples, the average value of wave velocities was chosen to ensure the reliability of the result.

2.3.2 | SHPB experiment

To measure the change of dynamic characteristics of rock at different temperatures after different cooling methods, the SHPB testing system was used to measure the dynamic stress–strain curves of the specimens. The experimental device and measurement mechanism are illustrated in Figure 5. The experimental device primarily includes impact loading, speed test, waveform collection, and bar system, the diameter of which is 50 mm. The length of both the incident and transmission bar is 2500 mm, the striker bar is spindle-shaped, and the length is 400 mm. The shape of the striker bar can be used to obtain a semi-sine wave in the process of impact. The material of the bar system is 35CrMn steel with an elastic modulus of 206 GPa and a density of 7800 kg/m³, the bar system is a rigid body.
that is always within the range of elastic deformation during the test.\textsuperscript{45}

According to the one-dimensional (1D) wave propagation theory, different parameters can be calculated using the following equation:

\[
\begin{align*}
\sigma(t) &= \frac{A}{2A_s} E(\varepsilon_t + \varepsilon_R + \varepsilon_I) \\
\varepsilon(t) &= \frac{C}{L_s} \int_0^t (\varepsilon_t - \varepsilon_R - \varepsilon_I) dt \\
\dot{\varepsilon}(t) &= \frac{C}{L_s} (\varepsilon_t - \varepsilon_R - \varepsilon_I)
\end{align*}
\]

where \( A \) and \( A_s \) denote the cross-sectional area of the bar and specimen (m\(^2\)), respectively, \( L_s \) refers to the length of the specimen (m), and \( E \) and \( C \) represent the elastic modulus (GPa) and elastic wave speed (m/s), respectively.

Figure 6A presents a typical SHPB test recording of the waveform, and Figure 6B reveals the stress balance diagram in the test. It can be observed that the summary between the incident wave (In) and reflected wave (RE) approximately equals to the transmitted wave (TR) suggesting, which proves that the dynamic stress could reach equilibrium.

2.3.3 | SEM investigation

After the SHPB experiments, the specimens were broken into different fragments, the fracture morphology was affected by the high temperature and cooling treatments.
However, the difference between fragments was too small to be observed by the naked eye. Therefore, the Hitachi SU8010 cold field emission SEM was employed to observe and analyze fragments’ microstructure. During the experiments, four pieces of fragments were selected from each specimen to reduce the error caused by the inhomogeneity of rock by averaging, considering all the samples at different temperatures and under different cooling treatments.

3 EXPERIMENTAL RESULTS

3.1 Variation of ultrasonic velocity and decay rate

3.1.1 External crack development

Before the ultrasonic velocity measurement was performed, the specimens were compared after thermal and cooling treatment according to different heating temperatures and cooling methods. When the temperature of rock specimens was heated from room temperature (25°C) to 400°C, it is evident that granite does not exhibit significant physical changes in terms of thermal cracking and retains integrity up to 400°C. It indicates that although granite is subjected to heating and cooling treatments, the resulting thermal stress does not exceed the tensile strength of granite, as shown in Figure 7.

When the thermal treatment temperature reached 600°C, some visible microcracks can be observed in the granite specimens after water and LN₂ cooling treatment. However, these cracks were limited to the surface of the specimen. When the thermal treatment was 800°C (Figures 8 and 9), apparent cracks appeared in all the granite specimens cooled in all three methods. It is worth mentioning that the cracks of naturally cooled granite specimens are relatively small, while those of water-cooled and LN₂ cooled rocks are rather large. In particular, for the latter, cracks had extended deeper inside the specimens, and large rock fragments tend to peel off from the sample. It demonstrated that higher heating temperature and rapid cooling could generate more thermal shock damage to the granite specimens.

3.1.2 Ultrasonic velocity measurement results

The velocity of the wave in the medium could indirectly reflect a change in the mechanical properties of the medium or the development of microcracks. As mentioned above, the P-wave velocity of all the samples at different temperatures and under different cooling methods were computed, and the measured results are presented in Figure 10A. Indeed, the velocity of granite specimens decreases as the thermal treatment temperature increases under the same cooling method. When the thermal treatment temperatures are the same, the P-wave velocity of the specimens treated by water and LN₂ cooling was lower compared with that of natural cooling.

Figure 10B presents the decay rate of P-wave velocities of all the specimens at varying temperatures under different cooling methods. When the treatment temperatures were 400°C, 600°C, and 800°C, compared with the granite at room temperature (25°C), the decay
The rate of P-wave velocities of specimens under natural cooling, water cooling, and LN$_2$ cooling decreased by 35.8%, 39.8%, and 41.0%; 64.5%, 68.9%, and 68.4%; 82.8%, 84.5%, and 85.5%, respectively.

Previous studies have shown that the generation of microcracks primarily reduces the P-wave velocity in the rock specimens during the thermal and cooling treatments. Based on the test results, it is evident that a higher
treatment temperature can bring more significant damage. Besides, with the application of a higher cooling rate, a more noticeable reduction in P-wave velocity is induced in the sample, and thereby, it leads to more severe damage.

3.2 | **SHPB experiment results**

3.2.1 | **Effect on the dynamic stress–strain curve**

SHPB experiments were conducted on the specimens that experienced the different thermal treatments at different temperatures and cooling treatments. Subsequently, the dynamic stress-strain curves of the specimens were calculated and compared, as shown in Figure 11. From the figures, it is evident that:

(a) Under different cooling methods, the dynamic stress–strain trends of the granite samples at different high temperatures were roughly the same, which can be divided into three stages. Considering the stress–strain curve under the condition of heating at 400°C and natural cooling as an example (Figure 11B), with the continuous increase of strain, the growth of stress is approximately linear (stage

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**FIGURE 9** Microcracks after heating and cooling (600°C and 800°C).

**FIGURE 10** Effect of different cooling treatments on wave velocity
A–B); then the stress increases nonlinearly as the strain reaches the peak, which indicated that microcracks appeared and developed to a certain extent (stage B–C); finally, the stress reduces with the further enhancement in strain and the rock breaks at this stage (stage C–D).

(b) When the cooling methods were the same, it can be observed from the figure that the peak stress decreases as the temperature increases, which means that the dynamic compressive strength of rock decreases, mostly resulting from the generation and development of microcracks. The peak strain, particularly the plastic strain of rock increases, indicating that the temperature rise could generate an enhancement in plasticity and a reduction in the brittleness of rock. The results are consistent with previous findings.\textsuperscript{35,46}

### 3.2.2 Effect on dynamic properties

Figure 12 illustrates the variations of dynamic peak stress with the treatment temperature under the three cooling methods. Under the three cooling methods, the peak value of dynamic stress exhibits a downward trend as the heat treatment temperature increases. However, there are some differences in the law of variation.

Under natural cooling conditions, the dynamic peak stress decreases slightly before the treatment temperature of 600°C and drops sharply when the temperature is in the interval of 600–800°C. It is primarily due to two reasons: (a) In the interval of 25–400°C, the rise in temperature leads to an uneven expansion of minerals, resulting in decreased peak stress. At this stage, the peak stress decreases from 207.1 to 177.2 MPa. (b) In the interval of 600–800°C, the thermal stress was higher than
that at 400°C, and the quartz in the specimen undergoes an irreversible phase transition at 573°C, which is accompanied by an increase in cracks in the rock due to volume expansion. Simultaneously, the phase transition will also lead to changes in the structure and physical properties of quartz, resulting in a sharp decrease in the peak stress (from 177.2 to 97.5 MPa).\textsuperscript{11,47}

For the rapid cooling methods of water and LN\textsubscript{2}, the dynamic peak stress decreases as the temperature increases, which is more obvious than natural cooling. As the figure reveals: (a) In the interval of 25–400°C, the change of the dynamic peak stress under the two cooling methods exhibits a law of approximately linear decline (from 207.1 to 178.9 MPa). However, the peak stress of the two cases began to differ at 600°C (167.3 MPa for water cooling treatment and 164.4 MPa for LN\textsubscript{2} cooling treatment); (b) When the thermal temperature is 800°C, the dynamic peak stress decreases to 75.9 and 49.0 MPa for water and LN\textsubscript{2} cooling treatment, respectively. Compared to the room temperature, the dynamic peak stress can be reduced by 63.4\% and 76.3\%, respectively.

From the above analysis, it can be concluded that the dynamic peak stress is always lowest under the LN\textsubscript{2} cooling treatment, indicating that after the same high-temperature treatment, LN\textsubscript{2} cooling has the most obvious effect on the dynamic peak stress of the granite.

Figure 13 illustrates the peak strain of the granite with thermal treatment under the three different cooling treatments. The peak strain under the three cooling treatments exhibits a similar pattern, representing a growing trend as the thermal treatment temperature increases.

When the temperature is lower than 200°C, the peak strain changes slightly under the three cooling treatments, slightly increasing with the rising temperature. When the temperature reached 400°C, the peak strains under the three cooling treatments appeared different. The most significant strain was of the specimen cooled by LN\textsubscript{2}, followed by water and natural cooling. With the increase in temperature, the peak strain increases, and the difference between the three cooling methods is more prominent. When the temperature was 600°C and 800°C, the peak strains under natural, water, and LN\textsubscript{2} cooling treatment were 1.23\%, 1.32\%, and 1.46\%; and 2.67\%, 2.84, and 3.36\%, respectively.

It is primarily because with the increasing temperature the thermal expansion of mineral components in the specimen results in microcracks, especially when the temperature reaches 400°C or even higher, these microcracks lead to the more considerable plastic strain of rock mass. Compared with natural cooling, rapid cooling (water and LN\textsubscript{2} cooling) makes the high-temperature specimen bear more thermal stress, produce more cracks, and exhibit higher peak plastic strain. When the treatment temperature exceeds 600°C, the peak strain of the rock is tremendous due to the extended metamorphism of the rock.

Based on the rising trend of the stress–strain curve, the secant slope of the two-point with the peak stress of 40\% and 60\% was selected as the elastic modulus of the sample. The calculation formula is as follows:

$$E_S = \frac{\sigma_1 - \sigma_2}{\varepsilon_1 - \varepsilon_2}$$

(2)

where $E_S$ represents the secant modulus of elasticity, GPa; $\sigma_1, \sigma_2$ indicates the 40\% and 60\% of the peak stress,
MPa, respectively; \( \varepsilon_1, \varepsilon_2 \) denote the corresponding strains, dimensionless.

Figure 14 shows the variation of elastic modulus at different high-temperature and under different cooling treatments. It can be observed from the trend of the curves before 200°C that the elastic modulus slightly reduces with the increasing temperature, and the amplitude is rather small. When the treatment temperature reaches or is higher than 400°C, the decreasing rate of elastic modulus starts increasing significantly. Compared with the three cooling methods, the LN2 cooling method has the most significant effect on the elastic modulus, followed by water and natural cooling.

When the treatment temperature is 400°C, the elastic modulus based on the three cooling methods was 30.5, 29.2, and 27.4 GPa, respectively. It indicates that the elastic modulus has been significantly reduced compared with the original condition (42.8 GPa). In particular, when the temperature is 800°C, the size of fragments is the smallest, and the peripheral powder increases. It is worth mentioning that when the treatment temperature is the same in the interval of 600–800°C, the degree of fragmentation of water-cooled specimens is obviously more significant than that of natural and LN2 cooling samples.

### 3.3 Crushing morphology of granite fragments

#### 3.3.1 Comparison of the morphology of fragments

The rock fragments after SHPB experiments were collected and compared, as displayed in Figure 15. It shows that the fragmentation of granite fragments increases significantly with increasing heat treatment temperature when the cooling method is the same. When the heat treatment temperature reaches 800°C, the fragments are similar to the state of powder.

At room temperature (25°C), the granite sample is impacted into several large pieces of rock fragments and accompanied by apparent characteristics of axial splitting. When the thermal treatment temperatures are 200°C and 400°C, the characteristic mentioned above still exists. The fragments of high-temperature rock specimens cooled by LN2 are the smallest, followed by those treated by natural and water cooling methods. It comprehensively illustrates that the thermal stress generated in the process of rapid cooling induced has led to the formation of many cracks in the interior of the rock specimens, resulting in a higher degree of fragmentation of the rock.

As the temperature continues to rise to 600°C, it was found that with the increasing treatment temperature, the fragmentation degree of the sample progressively intensifies and the process broke numerous small pieces under three cooling treatments, accompanied by the generation of powder. As the temperature continues to rise to 800°C, the size of fragments is the smallest, and the peripheral powder increases. It is worth mentioning that when the treatment temperature is the same in the interval of 600–800°C, the degree of fragmentation of water-cooled specimens is obviously more significant than that of natural and LN2 cooling samples.

#### 3.3.2 Comparison of micromorphology of fragments

The microstructure of the broken fragments was observed via an SEM test, and the comparison results are presented in Figure 16. Evidently, for the broken rock fragments, before the thermal and cooling treatment, the surface of granite is smooth without any microcracks. After the thermal and cooling treatment, the surface of the fragments becomes increasingly uneven, and a large number of microcracks begin to appear, particularly when the heat treatment temperature exceeds 400°C.

Within the range of 400°C and 600°C, when the cooling methods are the same, the number of microcracks increases significantly with the increase in temperature, and the cracks become increasingly significant. When the heat treatment temperature is the same, the cooling methods are different, the microcracks produced by LN2 cooling are the most obvious, which is followed by water and natural cooling treatment.
4 | DISCUSSIONS

In the current work, the damage to granite specimens is quantified by considering the effects of cooling treatment on heated granite. As mentioned above, the damage process can be classified into two stages: (a) In the first stage, the damage was caused by the thermal and cooling treatment. The expansion of original cracks and cavities, the generation and development of new microcracks, and the phase transformation of rock components will affect rock damage. (b) In the second stage, the main reason is the impact damage. It is well known that impact damage is dynamic, and the macrodynamic failure corresponds to the most damage accumulation process. Mesoscale damage includes the generation of microcracks, microholes, and shear bands, which appear in the form of multisource under impact load. It is rather complex to define damage variables and observe damage from the macroperspective for rock materials based on the above. In this study, the macrocontinuous damage evolution method is adopted. For the first stage, the measurement results are quantified based on wave velocity, and for the latter, the attenuation of elastic modulus is used to measure the damage to granite specimens.

| Natural cooling | Water cooling | LN$_2$ cooling |
|-----------------|---------------|----------------|
| 200°C           |               |                |
| 400°C           |               |                |
| 600°C           |               |                |
| 800°C           |               |                |

**FIGURE 15** Effect of different cooling methods on crushing morphology characteristics.
Thermal shock damage evolution

4.1 Damage mechanism

Granite is composed of different minerals, including quartz, mica, feldspar, and so on, these minerals have significant heterogeneity, and their thermal conductivity and thermal expansion coefficient are different. During the cooling process of high-temperature granite, the internal mineral particles will inevitably produce shrinkage deformation. The microelements are selected as the research objects, and when the temperature changes to $\Delta T$ (°C), the strain produced without restraint is as follows:

$$\varepsilon_T = \alpha \Delta T,$$  \hspace{1cm} (3)

where $\alpha$ represents the thermal expansion, °C$^{-1}$.

The corresponding tensile stress can be expressed as follows:

$$\sigma_T = E \varepsilon_T = E \alpha \Delta T,$$ \hspace{1cm} (4)

where $E$ represents the elastic modulus, GPa.

In the rock mass, the microelement will not shrink freely with the change of temperature because of the influence of internal and external constraints. In this case, the microelement will produce an actual strain ($\varepsilon'$, dimensionless) with the overall shrinkage of the rock.
mass, as shown in Figure 17. At this time, the tensile stress of the microelement is as follows:

$$\sigma'_{\text{tensile}} = \sigma_T - E\varepsilon' = E\varepsilon + E\alpha\Delta T - E\varepsilon'. \quad (5)$$

Microcracks will appear when the tensile stress due to binding is greater than the tensile strength of granite ($\sigma_{\text{tensile}}$).

$$\sigma'_{\text{tensile}} > \sigma_{\text{tensile}} \quad (6)$$

Indeed, if there are natural cracks between the original rocks, the tensile stress caused by shrinkage will further aggravate this situation.

Considering the specimen treated at 600°C as an example, when the water (25°C) and LN₂ (−196°C) were used to cool the specimens, the temperature difference on the rock surface can reach 625°C, and 796°C, respectively, and the coefficient of thermal expansion of granite is $3 \times 10^{-6} \, \text{°C}^{-1}$, the elastic modulus is 36 GPa. It is assumed that the strain produced by the microelement is $1.5 \times 10^{-3}$. The tensile stresses under this condition can reach 13.5 and 31.9 MPa, which have exceeded the tensile strength of granite.

Furthermore, the damage caused by the temperature gradient is also significant. The thermal conductivity of granite is low (2.6–3.6 w/(m k)). Consequently, there will be a very narrow heat transfer transition zone on the surface of granite during the rapid cooling process. The rock in the inner layer of the transition zone is limited by temperature and produces less strain. The outer layer of the transition zone is significantly affected by temperature, and the strain produced is more significant. When the outer layer of the transition zone needs to maintain its actual deformation, the thermal stress restricting its deformation will occur. When the thermal stress value is greater than the tensile strength of granite, cracks will occur outside the transition zone, as shown in Figure 18.

There are two other factors leading to rock damage under the joint action of heat treatment and cooling method: (a) The difference in the thermodynamic characteristics of the cooling medium affects thermal distribution, including the specific heat capacity and thermal conductivity. For instance, the thermal conductivity of water is better than air, which can achieve a better and faster heat transfer effect. (b) The flow characteristics of the cooling medium and the expansion characteristics after phase transformation will damage the rock, when water contacts high-temperature rocks, it will be transformed into water vapor with volume expansion, which will cause further damage to the rock.

4.1.2 Damage evolution

Different heating temperatures and cooling methods produce significant thermal shock damage to rock samples, which will lead to the deterioration of rock mechanical properties. Therefore, a damage factor related to P-wave velocity was defined to assess the damage degree of rock. The formula is as follows:

$$D_v(T) = 1 - \left(\frac{v_{\text{post}}}{v_{\text{pre}}}\right)^2, \quad (7)$$

where $D_v(T)$ indicates the damage factor calculated by P-wave velocity, dimensionless; $v_{\text{post}}, v_{\text{pre}}$ represent the

**FIGURE 17** Mechanism of thermal stress
P-wave velocity of heated and cooled samples and untreated samples, respectively, m/s.

The evolution of damage factors of thermal-treated granite subjected to different cooling treatments is presented in Figure 19. The results indicate that different cooling treatments have a considerable effect on granite damage. The damage factor is enhanced with the rising temperature. Under the three cooling treatments, the difference in the rock damage factor first rises before decreasing. The difference is most significant at 200°C and almost disappears at 800°C.

When the treatment temperature is 200°C, the damage factor of samples after natural, water, and LN$_2$ cooling are 0.29, 0.38, and 0.42, respectively. Previous studies reported that there are almost no microcracks after natural cooling, which is consistent with the SEM results in this section. However, there is a significant difference in the damage factor under the three cooling methods, which is primarily due to the thermal stress caused by the drastic temperature change in the process of rapid cooling (water and LN$_2$ cooling), which can result in the expansion of primary cracks and pores. Hence, the wave velocity and damage factor are further affected.

As the temperature increases, the difference of damage factor decreases. When the treatment temperature is 400°C, the damage factors of granite specimens under water and LN$_2$ cooling are almost equal, and it is different from that under natural cooling. It is principally because the bound water is evaporated, the initial microcracks induced by uneven deformation of mineral particles developed, the effect of high temperature is more apparent, and the drastic change of temperature caused by water and LN$_2$ cooling is getting smaller.

When the temperature reaches or exceeds 600°C, the damage factors under the three cooling methods were essentially identical. The main reason for this was that the quartz transforms from α to β, and the minerals in the granite undergo irreversible chemical changes when the temperature reaches 573°C. Concurrently, the microstructure of rock exhibits thermal expansion imbalance that can be ascribed to the anisotropy of mineral particles and different expansibility at high temperatures, leading to a significant increase in microcracks of sandstone samples. Under this condition, the effect of cooling treatment is negligible.

FIGURE 18 Effect of temperature gradient

FIGURE 19 Damage factor of granite based on P-wave velocity.
4.2 Impact damage evolution

As mentioned above, the attenuation of elastic modulus is used to measure the damage to granite specimens. The damage factor of impact failure can be represented as follows:

\[ D_{E}(T) = 1 - \frac{E_{\text{post}}}{E_{\text{pre}}} \]

where \( D_{E}(T) \) indicates the damage factor calculated by the elastic modulus, dimensionless; \( E_{\text{post}}, E_{\text{pre}} \) represent the elastic modulus of the heated and cooled samples and untreated samples, GPa.

The experiment results demonstrated that the thermal and cooling treatment could cause more severe damage to the granite, manifesting the obvious deterioration of physical and mechanical properties. The damage factor of impact failure was computed to analyze the effect on the dynamic failure of rock, as displayed in Figure 20. Indeed, the damage factors enhance when heat treatment temperature increases. Under the same temperature condition, the rock damage factor is highest after LN\(_2\) cooling, followed by water and natural cooling. It provides solid evidence that the high-temperature rock after heat treatment is more likely to be damaged under the action of liquid nitrogen cooling.

\[ \sigma_{dy} = aD_{E}^{2} + bD_{E} + C, \]  
\[ \varepsilon_{dy} = aD_{E}^{2} + bD_{E} + C. \]

As shown in Figure 21, the relationships between the damage factor and dynamic stress (\( \sigma_{dy} \)) and strain (\( \varepsilon_{dy} \)) are calculated to further quantify the dynamic damage process of rock. The experimental results match well with the fitting results, and a high correlation coefficient \( R^2 \) of the fighting formula was obtained (\( R^2 \geq 0.99 \)), which better fitted the dynamic damage evolution of the granite specimen after thermal and cooling treatment, which can be found in Equations (9) and (10) and Table 1.

When the damage factor is 0.51, the minimum dynamic peak stress under the three cooling methods is 164.4 MPa, which is 79.4% of the value before the thermal
TABLE 1 Coefficient values of different cooling methods

| Fit coefficient | Natural cooling | Water cooling | LN₂ cooling |
|-----------------|-----------------|---------------|-------------|
| σ<sub>dy</sub>  | -132.81922      | -158.61803    | -201.70888  |
| a               | -11.2758        | -8.52653      | 21.06626    |
| b               | 203.90953       | 200.82728     | 200.06426   |
| c               | 0.02824         | 0.03308       | 0.03847     |
| ε<sub>dy</sub>  | -0.00196        | -0.00463      | -0.00738    |
| a               | 0.00786         | 0.00803       | 0.00812     |

and cooling treatment (207.1 MPa). Correspondingly, under this condition, the minimum dynamic peak strain is 1.46%, which is 92.1% more than it was treated (0.76%). When the damage factor is more than 0.51, the change of stress and strain is accelerated, meaning that the damage speed will be accelerated, leading to the instability of the structure under the impact load.

5 | CONCLUSIONS

The granite specimens were grouped and heated to 200°C, 400°C, 600°C, and 800°C, respectively, before they were cooled using different cooling methods: natural, water, and LN₂ cooling. Subsequently, ultrasonic detector tests, SHPB experiments, and SEM tests were conducted. The thermal shock and impact damage evolutions were discussed. The following conclusions are obtained:

(1) Under the same heat treatment temperature, different cooling methods have significant differences in the hardness of wave velocity. Under the three cooling treatments, all the P-wave velocities show a linearly reducing trend with the increasing temperature. At each temperature level, the P-wave velocity of the LN₂-cooled specimen remains the lowest, followed by water cooling and natural cooling.

(2) When the treatment temperature increases, the dynamic peak stress, and elastic modulus decrease, and the peak strain increases. In particular, the mechanical properties of the specimen significantly decreased when the treatment temperature exceeded 600°C. The strength of LN₂-cooled high-temperature specimens is lower when compared with that of natural and water-cooled granite.

(3) With the rise of the thermal treatment temperature, the impact fragmentation degree of granite increases, changing from large blocks to small blocks even powder. When the thermal treatment temperatures are in the range of 200°C and 400°C, the fragments of high-temperature rock specimens cooled by LN₂ are the smallest, followed by those treated by natural and water cooling methods, caused by the thermal stress generated in the process of rapid cooling. As the temperature continues to increase further, the degree of fragmentation of water-cooled specimens is greater than that of natural and LN₂ cooling samples for the invasion of water weakens the connection between mineral particles.

(4) The damage factor resulting from the thermal and cooling treatment has an increasing impact when the treatment temperature increases. When the damage factor is more than 0.51, the change of stress and strain is accelerated, meaning that the damage speed will be accelerated, leading to the instability of the structure under the impact load.

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