INTRODUCTION

Geothermal energy is widely used as a new type of clean energy Homand-Etienne et al.1 The development process of the geothermal energy is cold water injected artificial retention layer, and through fracture network channel heat exchange with high temperature rock mass, and then enter the heating or power of circulation system. In the cycle process of geothermal exploration, when the cold water from the surface into artificial retention layer, high temperature hot dry rock temperature will drop sharply, due to the heat bilges cold shrink effect, hot dry rock a severe cold cracking phenomenon occurs. On the one hand, new cracks will be generated, and on the other hand, the original cracks will be extended or penetrated. As a result, the pore structure, micro-morphology, physical and mechanical properties, and permeability of the dry hot rock will be greatly changed, which will eventually affect the heat exchange efficiency of the artificial reservoir. In order to improve the heat exchange efficiency of the artificial reservoir, it is necessary to carry out the experimental study on the changes of macroscopic and microscopic physical and mechanical properties and fracture properties of the dry hot...
rock during the heat exchange process, that is, the dry hot rock in the process of water cooling.

There are many scholars who have done researches on rock influenced by high temperature. Rathnaweera et al.\(^2\) study is to investigate the influence of extreme temperatures (from 25 to 1000°C) followed by two cooling methods (both rapid and slow) on the mechanical behaviour of clay-rich Hawkesbury sandstone under uniaxial conditions. In the research of Yang et al.,\(^3\) uniaxial compression tests were first carried out to evaluate the effect of high-temperature treatments (200, 300, 400, 500, 600, 700, and 800°C) on the crack damage, strength, and deformation failure behavior of a granite. Feng et al.\(^4,5\) analyzed the change characteristics of fracture mechanical behavior of sandstone with temperature and obtained the rule that the high temperature above 500°C causes a significant reduction of fracture toughness and revealed the macro-micro fracture mechanism and its correlation of granite in different temperature gradients. Zhang et al.\(^6\) studied the thermal effect (from 25 to 500°C) on physical and mechanical properties (such as mass, density, porosity, P-wave velocity, compressive strength, peak strain, and elastic modulus of rock). Brotòns et al.\(^7\) discussed from tests which were performed in order to study the effect of high temperatures in the physical and mechanical properties of a calcarenite (San Julian’s stone). Peng et al.\(^8\) studied the physical and mechanical behaviors of a thermal-damaged coarse marble in uniaxial compression tests. The α-β transition of quartz at 573°C also damaged the mineral stability Glover et al.\(^9\) In the study from Rong et al.,\(^10\) microscopic observation and uniaxial compression tests with acoustic emission (AE) monitoring were conducted on two bedrocks after treatment with different thermal cycles at high temperature. With an increase of initial rock temperature, the number of thermal cracks increases, and a more complex crack-network is formed in each specimen. Zhang et al.\(^11\) and Shao et al.\(^12\) investigated the effect of temperature on the mechanical behavior of Strathbogie granite, and their results showed that the stress-strain curves of this granite showed plastic and post-peak behavior for temperatures above 800°C and the brittle-plastic transition was observed to occur between 600 and 800°C under uniaxial compression. Breede et al.\(^13\) studied the temperature range selected spans the 150-350°C range generally currently used in enhanced geothermal systems (EGS), where there is little thermal damage, and includes the 350-600°C range to provide scientific knowledge relevant to extreme scenarios.

Most of the above scholars focused on the study of rocks in the natural cooling state, fewer comparative analysis and research on the water-cooled state. In this paper, the macroscopic and microscopic deformation and mechanical properties of high-temperature granite after natural cooling and rapid cooling in water were studied, and comparative discussed the mechanical behavior and microscopic mechanism of granite under two different cooling methods. The research results in this paper can provide technical parameter values that are useful for the stable mining of enhanced geothermal heat.

## 2 | SAMPLE PREPARATION AND TEST PROCESSES

### 2.1 | Sample preparation

The diameter of the test specimens is 50 mm and the length is 100 mm, which resulted in an aspect ratio of 2 for mechanical tests, this being in accordance with the ISRM (International Society for Rock Mechanics) suggested method Fairhurst and Hudson.\(^14\) The test specimens were divided into seven groups to be heated to different temperatures. Meng et al.\(^15\) except for one group kept at room temperature, which comprised four specimens, the other groups each comprised eight specimens, four of which were subjected to natural mechanical cooling to room temperature (20°C) and the other four of which were subjected to water cooling, giving a total of 52 test specimens. According to the results of X-ray diffraction (XRD), the mineral composition of granite is shown in Table 1.

### 2.2 | Experimental methods

Instrument for rock Nondestructive testing: An NM-4B non-metal ultrasonic detector (Figure 1) was used to measure ultrasonic wave velocity of granite samples before and after heat treatment.

### Table 1 | Main mineral components and content of granite

| Mineral components     | Content (%) |
|------------------------|-------------|
| Quartz                 | 40.6        |
| Potassium feldspar     | 16.0        |
| Plagioclase            | 23.0        |
| Mica                   | 5.5         |
| Other minerals         | 8.0         |
Granite heat treatments were conducted using a smart muffle furnace (Figure 1), having a maximum temperature of 1200°C, and a stable and easily controlled heating rate. In order to reduce the impact of thermal shock, a heating rate of 4°C/min was selected for the experiment, six temperature gradients (100, 200, 300, 400, 500, and 600°C) were used. The granite samples were placed in the smart muffle, heated to the corresponding temperature, and then kept at this temperature for 8 hours to ensure adequate reaction. After 8 hours, the temperature was turned off and the furnace was left to cool down to room temperature naturally. In order to explore the influence of different cooling methods on the physical and mechanical properties of rock, we also used a water-cooling method. In this method, samples were heated as per the natural cooling method. However, after heating for 8 hours, samples were immediately removed from the furnace and placed into water which was already at room temperature until the samples had cooled to room temperature.

A full uniaxial stress-strain test was carried out on each test specimen using a rock testing machine (Figure 1). Wu et al. The loading mode was a displacement control, with a loading rate of 0.02 mm/min. Shao et al., Yang et al., and Wu et al. belonging to a static load mode. Test results were automatically recorded using a computer.

Macroscopic observation of the fracture morphology of specimens was undertaken, and cross-sectional morphology (SMART-POL) was analyzed using a rock microscope. Equipment used in this analysis (Figure 1) was characterized by having a high resolution and ease of operation.

### 3 TEST RESULTS

“High temperatures resulted in a variety of complex physical and chemical changes in the granite, and the types of physical and chemical reactions differed under different temperatures. In general, higher temperatures resulted in more intense chemical and physical reactions. Heat treatment at different temperatures was directly observed, and it was noted that appearance color in the samples changed (Figure 2).” Moreover, it was also observed that there were significant differences between water-cooled and naturally cooled granite color at the same temperature (Figure 2).

#### 3.1 Longitudinal wave velocity

Longitudinal wave velocity is an index that characterizes the compactness and integrity of rock and can be used to
assess the degree of damage and heterogeneity in a sample. Pore fissures do not generally develop during the formation of granite. The damage can be evaluated by the changes in the P-wave and S-wave velocities of the sample before and after the heating/cooling treatments Weng et al.20 and Yin et al.21 However, exposure of granite to high temperature will cause it to suffer internal dehydration, crystal phase transformation, crystal melting, and pore fissure initiation, expansion, and evolution, and the P-wave velocity within it will change.

A coupling agent (Vaseline) was applied to both ends of the sample before testing to reduce attenuation of the wave velocity during propagation and hence obtain more accurate results from the specimens. The wave velocity through granite after cooling via different modes from different temperatures was calculated with Formula (1).

\[ V_{mp} = \frac{l}{t-t_0} \]  

Where \( V_{mp} \) is the longitudinal wave velocity of an acoustic wave propagating inside the specimen, m/s; \( l \) is the length of the test specimen, mm; \( t \) is the ultrasonic signal excitation time, s; \( t_0 \) is the ultrasonic signal reception time, s. The calculated results are shown in Table 2.

The lines in Figure 3 indicate the average wave velocity through granites heated to different temperatures under the two cooling modes. Liu et al.22 and Chaki et al.23 It can be seen that the average wave velocity decreases with an increase in the heating temperature under both cooling modes. For water cooling, the wave velocity after heating to 600°C is 1080 m/s, which is 72% lower than the value of 3846 m/s for the granite at room temperature (20°C). Granite that is heated to temperatures of <400°C is cooled rapidly, with no micro-cracks being generated, and so the wave velocity drops relatively slowly with an increase in heating temperature. When heated to within the temperature range of 400-600°C, cracks form due to thermal expansion and contraction, resulting in loss of water, increased porosity, and a rapid decrease in the longitudinal wave velocity.

Figure 3B shows that the longitudinal wave velocity under natural cooling is lower than under water cooling and that the amplitude of the decrease is different at different temperature points. This is mainly because the samples were naturally cooled within the furnace, making the cooling rate relatively uniform and slow. The less displaced cracks were generated in this process than in water cooling, and the internal continuity was better, resulting in a relatively slower drop in the longitudinal wave velocity.

In short, the wave propagation speed through high-temperature granite is different depending on cooling mode. The longitudinal wave velocity through a sample that experienced natural cooling is greater than through a sample subjected to water cooling. This shows that more serious internal damage occurs in a water-cooled sample, as water cooling causes the formation and development of pore cracks inside the rock, leading to a decrease in the wave velocity.

### 3.2 | Mechanical properties

#### 3.2.1 | Stress-strain curve characteristics

Test load curves can be used to characterize the process of rock failure (Zhang et al.24; Chen et al.25 and Feng et al.).5 Figures 4 and 5 show the stress-strain curves of granite. Macroscopically, the specimens experienced four typical stages: the compaction stage, elastic stage, elastoplastic deformation stage, and complete failure stage. However, the elastoplastic or plastic section is small, the behavior was on the whole brittle, and some curves exhibit a double-peak phenomenon. For specimens heated to 400°C, the strain generated in the compaction stage under water cooling is generally larger than when naturally cooled, and the strain in the compaction

![Figure 3](image-url)
section does not change between 400 and 500°C. When the heating temperature is 600°C, the strain in the compaction section is larger under natural cooling than in the case of water cooling, which is consistent with the results David et al.26

It can be seen from the Figures 4 and 5 that the stress-strain curves for heated rock samples cooled via the two modes have basically the same form as in the room temperature state, but the strains (or deformation) corresponding to each stage are not only related to heating temperature but also to cooling mode. The following focuses on the characteristics of initial strain, ultimate strain, and the stress-strain curve near ultimate strain. The other characteristics are similar to those of conventional stress-strain curves.

The general trend is as follows. (a) With heating to the same temperature, the peak strain after water cooling is greater than that after natural cooling. This is for the same reason as for the differences in initial strain increase described above. (b) Under the same cooling mode, the overall trend is toward an increase in the peak strain with an increase in heating temperature. This is also for the same reason as for the increase in the initial strain. However, for natural cooling, in the experimental temperature range used in this paper, the peak strain corresponding to each temperature point is lower than the peak strain at room temperature (20°C). The peak strain is highest at room temperature because no thermal cracking has occurred in a specimen kept at room temperature, so its uniaxial compressive strength is relatively high and its elastic deformation ability is strong, resulting in it reaching a large strain value before breaking.

As for natural cooling, when the heating temperature is 100-300°C, the strain in the initial section (compaction) increases with an increase in temperature but is less than the strain at room temperature. With heating to over 300°C, the strain in the initial section continues to increase with an increase in temperature and is greater than the initial strain at room temperature. The reason for this phenomenon is that below 300°C, the degree of thermal cracking in the specimen will increase with an increase in temperature, and some volatile substances inside the test specimen will volatilize, especially water. After natural cooling, on the one hand, some new cracks will have been generated due to the rise and then fall in temperature, and on the other hand, friction under the action of load will have been increased within the test specimen due to the loss of gas and water. An increase in the number and size of cracks results in an increase in strain, and an increase in friction at fracture surfaces results in a decrease in strain. The final overall strain is determined by the temperature experienced by the test specimen. At room temperature, due to the presence of gas and water inside the test specimen, the frictional force at crack surfaces is relatively small, and cracks are easily closed when force is applied, corresponding to an initial increase in strain. When the temperature is 100-300°C, there will be both a decrease in initial strain due to the increase in friction at crack surfaces and an increase in initial strain due to thermal cracking. The degree of initial strain reduction is greater than the degree of its increase, and thus the strain is lower than that at room temperature. With heating to more than 300°C, the thermal cracking phenomenon is intensified with the increase of temperature, and the initial strain is correspondingly increased, causing the overall strain value to be greater than that where there has been no sample heating.

As for water cooling, it can be clearly seen from Figure 12 that as the temperature increases, the initial strain gradually increases. On the one hand, the specimen is ruptured due to rapid cooling by the water. The higher the temperature, the more severe the rupturing, which causes the specimen to be subjected to force. As the temperature increases, the initial strain increases accordingly. After the test specimen encounters water, the friction at the fracture surface

| T (°C) | 20   | 100  | 200  | 300  | 400  | 500  | 600  |
|--------|------|------|------|------|------|------|------|
| Water  |      |      |      |      |      |      |      |
| 1#     | 3846 | 3636 | 3205 | 2551 | 2293 | 1295 | 1079 |
| 2#     | 3831 | 3623 | 3300 | 2564 | 2227 | 1605 | 1497 |
| 3#     | 3717 | 3597 | 3076 | 2747 | 2666 | 1485 | 1066 |
| 4#     | 3436 | 3278 | 3105 | 2949 | 2217 | 1222 | 1035 |
| Average| 3707.86 | 3533.83 | 3171.99 | 2703.05 | 2351.17 | 1402.2 | 1169.54 |
| Natural|      |      |      |      |      |      |      |
| 1#     | 3846 | 3426 | 3141 | 2692 | 2500 | 1960 | 1308 |
| 2#     | 3831 | 3367 | 3277 | 2865 | 2865 | 2028 | 1340 |
| 3#     | 3717 | 3629 | 3192 | 2951 | 2538 | 2247 | 1349 |
| 4#     | 3436 | 3213 | 3181 | 2558 | 2493 | 1614 | 1304 |
| Average| 3707.5 | 3408.75 | 3197.75 | 2766.5 | 2599 | 1962.25 | 1325.25 |
decreases, which also causes the initial strain to increase. On the other hand, the high-temperature test specimen will also undergo chemical changes after it encounters water, and reaction products partially fill the cracks. The compaction of the filling will also lead to an increase in the initial strain. The strain resulting from the comprehensive effects of the water will rise with an increase in temperature, and the initial strain after cooling will increase.

### 3.2.2 Elastic modulus

The elastic modulus values shown in Table 3 are the tangent modulus, which corresponds to the slope of the tangent to the stress-strain curve at half the ultimate strength. Figure 6 shows the change in elastic modulus with heating temperature under different cooling modes.

As can be seen from Figure 6, in the case of water cooling, the elastic modulus is lowered as the temperature is increased. The drop from 7.21 GPa at room temperature to 0.19 GPa at 600°C constitutes a 97.36% decrease. Under natural cooling, the elastic modulus of granite increases when heated from room temperature (20°C) to 100°C. This rise from 7.21 to 8.31 GPa is an increase of 15%. When heated to temperatures in excess of 100°C, there is a tendency to decrease gradually with increased heating temperature, but the magnitude of the decrease is small. It can be seen that the granite is slowly cooled to room
temperature, the elastic modulus first increases and then decreases with an increase in the applied temperature.

Overall, the elastic modulus gradually decreases with an increase in the heating temperature, but the trend is different under different cooling modes. In the natural cooling state, the elastic modulus increases from room temperature to 100°C and then decreases slowly with an increase in temperature beyond 100°C, which is basically consistent with the experimental conclusions in the literature Xu.27

3.2.3 | Uniaxial compressive strength

Figure 7 plots the variation in uniaxial compressive strength with heating temperature under the two cooling modes. The uniaxial compressive strength of granite under the two cooling modes can generally be seen to decrease with an increase in heating temperature. Both curves show a downward trend, but the magnitudes of the decline are different. In addition, naturally cooled granite shows an increase in uniaxial compressive strength after heating to 100°C to 2% higher than at room temperature. When the heating temperature exceeds 100°C, the uniaxial compressive strength shows a slow downward trend. In contrast, the uniaxial compressive strength in the case of water cooling decreases rapidly throughout the temperature range, from 144 MPa at room temperature to 36 MPa at 600°C, a decrease of 75%.

3.2.4 | Peak strain

Figure 8 shows the peak strain of granite under different cooling modes as a function of heating temperature.

It can be seen from the figure that after heating to the same temperature, the peak strain under water cooling is significantly larger than that under natural cooling. The peak strain increases with an increase in heating temperature under water cooling, but under natural cooling conditions, the peak strain reaches a minimum after heating to 100°C, and only at greater temperatures does it increase with an increase in temperature.

3.3 | Microscopic cracks analysis

Figures 9 and 10 are images of micro-flakes from granites heated to different temperatures after cooling via the two modes. Figure 9 shows changes observed after heating then water cooling. The micrograph of granite kept at 20°C shows it to be broadly clean, colorless, and transparent (magnification 300 times). Some variation in the grain structure of the quartz can be seen under cross-polarized light. There are also minor brownish-black minerals and pleochroic flaky black mica. There are no obvious cracks. When the specimen has been heated to 100°C, fine micro-cracks appear. With heating to 200-300°C, obvious macroscopic cracks appear throughout the sample. When the heating temperature is 400°C, more serious damage is seen across the surface. At 500-600°C, the surface features both large macroscopic cracks and accompanying pit erosion. Figure 9G shows that when the heating temperature is 600°C, trans-granular cracks expand and evolve in the direction of grain boundaries until the grains are broken up. Inserra et al.28 studied the edge of the crack seen in the image is blurred, and an off-white filling has been produced. The particles on the surface of the sample have become crisp and easy to peel off.

Figure 10 shows the microscopic changes in the case of natural cooling. It can be seen from the surface micro-structure that different degrees of damage have occurred to the granite after natural cooling from different temperatures. Figure 10B-F shows that some mineral grains have experienced bending. Light gray and black-gray hornblende were
seen occasionally and takes the form of a biaxial crystal, a sheet, or an aggregate. The surface micro-structure of the granite remains basically unchanged for heating temperatures between 20 and 200°C. When the heating temperature is between 300 and 600°C, tiny cracks appear on the surface, gradually expanding with increasing temperature. The cracks are less than when the granite is subjected to water cooling. On the whole, the damage to granite with an increase in heating temperature is more significant under water cooling than with natural cooling, especially when the temperature is higher than 400°C.

4 | DISCUSSION

Gautam et al. have studied the temperature on the physical and mechanical properties of granite after natural cooling. Brotons et al. and Rathnaweera et al. have considered the effect of rapid cooling with water. In this section, the changes in the physical and mechanical properties after natural cooling and water cooling are analyzed from the macroscopic and microscopic perspectives, and the mechanisms by which the physical and mechanical properties of granite are affected by the two cooling methods is revealed. This fully demonstrates that the damage in granite after exposure to high temperature is not only closely related to the temperature reached but to the cooling method.

4.1 | Physical and mechanical properties change with cooling mode

4.1.1 | Longitudinal wave velocity

In order to explore the law of wave velocity changing with heat treatment temperature under different cooling modes, Figure 11 is drawn.
When the heating temperature is 20-200°C, the wave velocity is greater under water cooling than under natural cooling from the same temperature. In the rock micrographs, although micro-cracks are produced under both cooling methods, the density of cracks in the water-cooled test specimen is greater than with natural cooling (Figures 9 and 10). According to the results of previous scholars, Fan et al. wave velocity is negatively correlated with the density of pore fractures. This would mean that the wave velocity under water cooling would be lower than under natural cooling, but the experimental results in this paper are the opposite. The reason for this phenomenon is that only a relatively small number of micro-cracks are generated in the temperature range of 200°C. When the heating temperature is between 200 and 600°C, the wave velocity under natural cooling is greater than that under water cooling. Water cooling from this temperature range, the width, and number of cracks are greater and the degree of damage is significantly greater than under natural cooling, which will result in the wave speed being higher in the case of natural cooling than with water cooling.

### 4.1.2 Stress-strain curve characteristics

Figure 12 is a comparison of the stress-strain curves under the two cooling modes.

It can be seen from Figure 12 that with natural cooling, when the heating temperature is 200-300°C, a double-peak phenomenon appears in the stress-strain curve as it approaches the peak value, with it undergoing a stage of rapid decline then slow rise. This may occur because, in this temperature range, some relatively large micro-cracks resulting from thermal cracking undergo shear displacement when pressure is applied, and the displacement is discontinuous. The stress does not reach the cracking shear strength initially, and the crack experiences a small amount of uniform deformation. When the stress reaches the shear strength, the crack suddenly fails and causes damage, but it is only partial damage relative to the whole test specimen and is not sufficient to cause it to failure overall. The rest of the specimen can continue to be stressed until full failure. Above 300°C, the degree of thermal cracking is larger and many cracks form. Both the cracks and the overall deformation of the test specimen are relatively uniform. There will be large shear displacements, so there will be no double peaks.

For water cooling, the double-peak phenomenon does not appear to over 400°C, there are not only physical and mechanical effects but also chemical effects on the rock, especially the hydration reaction that not only produces precipitates but also repairs primary cracks and defects, which leads to friction between crack faces. When the force applied is increased, the specimen will start to undergo relatively uniform deformation. When the stress rises to a certain extent, the relatively high-friction crack surfaces will change from being in a state of static friction to one of dynamic friction, cracks will suddenly fail, and the stress will suddenly decline, but not enough to cause overall failure in the test specimen. After that, the stress will rise slowly until the test specimen is completely destroyed. It can be seen from the stress-strain curves that the stress sometimes falls suddenly and then quickly returns to a state of increase or decrease before the fall, which is called a “stress drop.” Each “stress drop” commonly corresponds to the formation of a macroscopic fracture surface that is visible to the naked eye.

### 4.1.3 Elastic modulus

For natural cooling below 100°C, the specimen is thermally cracked, and the thermal expansion of mineral particles causes gradual closure in the primary fractures in the granite, resulting in a gradual increase in the elastic modulus. Above 100°C, the inter-granular or intra-granular stresses have increased further and are sufficient to cause the formation of micro-cracks or to cause the expansion and widening of primary micro-cracks. The thermal cracking is intensified, eventually leading to a gradual decrease in the elastic modulus. The experimental result in the literature Chen et al. is that as the temperature increases, the elastic modulus decreases and that there is no temperature point at which it is elevated. This is because the composition of each granite sample and its content of each component are different, resulting in different trends in the elastic modulus. As the temperature continues to rise, thermal cracking gradually increases, resulting in a gradual decline in the elastic modulus.

The elastic modulus of the sample under water cooling decreases gradually with an increase in heating temperature, and water cooling is lesser than under natural cooling. This is because the sample cools rapidly during the cooling process, which makes the temperature difference between the inside
Figure 12 Stress-strain diagram for the two cooling modes
and the outside of the sample increasingly large with an increase in temperature and the uneven shrinkage deformation that occurs causes micro-crack formation inside the rock. The micro-cracks expand and penetrate, and the water content increases, eventually causing the elastic modulus to decrease as the temperature applied increases.

4.1.4 | Uniaxial compressive strength (UCS)

As for natural cooling, the overall law governing uniaxial compressive strength under natural cooling is also one of decrease with an increase in temperature, the main reason for this is that thermal cracking causes the strength to decrease due to the increase then decrease in temperature. In addition, at the temperature points used in this experiment, the uniaxial compressive strength is highest at 100°C. This can be attributed to the fact that at about 100°C, the evaporation of water in some micro-cracks inside the test specimen will increase the friction between the micro-crack surfaces. As for water cooling, below 300°C, the overall decrease in uniaxial compressive strength occurs because the thermal damage caused by cold shock after water contact is higher when the temperature is higher, and this causes an overall reduction in uniaxial compressive strength. Above 300°C, chemical reactions occur when the test specimen meets water, as mentioned above with regards to the double peak in the stress-strain curve. On the one hand, as the temperature increases, the degree of thermal cracking is increased, which manifests as a decrease in strength. On the other hand, due to the chemical reactions that occur, the friction between crack surfaces is increased, and the strength is prevented from decreasing. The combination of the two mechanisms causes the rate of strength decline to reduce.

4.2 | Influence of cooling modes on physical and mechanical properties

Under the influence of temperature, mineral particles inside the rock will undergo heat-expansion and cold-contraction. Different cooling methods for high-temperature granite are essentially cooling treatments with different cooling rates. Due to the different thermal expansion coefficients of different minerals, the degree of grain deformation caused by different decreasing rates of temperature is inconsistent. The different cooling rate of different mineral particles inside high-temperature granite results in uncoordinated shrinkage, resulting in cracks. The faster the temperature changes, the more obvious is the dissonance. Since the cooling rate due to water cooling is higher than that of natural cooling, the uncoordinated shrinkage of mineral particles is more obvious. As a result, more cracks are distributed due to water cooled than naturally cooled. This result was confirmed by optical microscopy of the granite specimens. As cracks are the direct cause of the change of rock mechanical properties, UCS of water cooling rock is therefore lower than that of natural cooling. Study on mechanical properties Ding et al.30, Chen et al.25; Fan et al.29; Huang et al.31; Changbing et al32 and Weng et al.33

Different internal micro-structure caused by different cooling methods are also the reason for different physical properties of granite. The propagation rate of wave velocity in different integrity rocks is inconsistent. In general, the more integrity the rock has, the higher will be the wave velocity Fan et al.34,35; Liu et al.36; Wang et al.37. It can be seen that the integrity of the rock interior caused by water cooling is lower than that of natural cooling. Therefore, the velocity of wave propagation in water-cooled granite is lower than that due to natural cooling. Physical property study Brotóns et al7; Zhang et al8; Gautam et al.38

Due to different cooling rates, different cooling methods can significantly influence rock mechanical properties. The elastic modulus and uniaxial compressive strength of granite under the two cooling modes from room temperature (20°C) to 600°C show a monotonically decreasing trend, while the peak strain shows a monotonically increasing trend. With an increase in temperature, the mechanical strength of granite gradually weakens, gradually transforming from brittleness to ductility. This result fully indicates that damage to granite under high temperature is closely related to temperature and to the cooling mode.

5 | CONCLUSIONS

In this study, granite samples were exposed to heat treatment at 100, 200, 300, 400, 500, and 600°C. Samples were cooled after these treatments using water cooling and natural cooling methods. By testing the physical and mechanical properties of granite before and after heat treatment, we examined the effects of different temperatures and cooling methods on the acoustic wave velocity, uniaxial compression strength, elastic modulus, and microscopic cracks in granite.

1. The wave velocity, elastic modulus, and uniaxial compressive strength of the test specimen decrease with an increase in its heating temperature under both cooling modes. The reductions in these values are greater under water cooling than with natural cooling.
2. Under different temperatures, after cooling via both modes, the uniaxial compressive strength and elastic modulus of the test specimen decrease with an increase in temperature. After heating to the same temperature, the reduction in the axial compressive strength and elastic modulus is greater for a test specimen subjected to water cooling than
one undergoing natural cooling. As the heating temperature increases, the elastic modulus decreases. The drop in elastic modulus under water cooling is greater than under natural cooling. The elastic modulus is strengthened if the sample is heated to 100°C and then allowed to cool naturally.

3. The characteristics of the stress-strain curve of granite are different after heating to different temperatures and cooling via different modes. For the natural cooling state, the stress-strain curve exhibits double peaks when heated to within the range of 200-300°C. For water cooling, the double peak appears at temperatures above 300°C. Through this experiment, the influence range of the cooling method on the sample can be roughly judged.

ACKNOWLEDGMENTS
This study was supported by the National Natural Science Foundation of China (Grant No. 51574173), the Natural Science Funds for Young Scholar (51904195), Shanxi Province Science Foundation for Youths (201901D211300).

CONFLICT OF INTEREST
The authors declare no conflicts of interest.

ORCID
Yaoqing Hu https://orcid.org/0000-0001-9254-0407

REFERENCES
1. Homand-Etienne F, Houpert R. Thermally induced microcracking in granites: characterization and analysis. Int J Rock Mech Min Sci. 1989;26(2):125-134.
2. Rathnaweera TD, Ranjith PG, Gu X, et al. Experimental investigation of thermomechanical behaviour of clay-rich sandstone at extreme temperatures followed by cooling treatments. Int J Rock Mech Min Sci. 2018;107:208-223.
3. Yang S, Ranjith PG, Jing H, et al. An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments. Geothermics. 2017;65:180-197.
4. Feng G, Kang Y, Meng T, Li YHX. The influence of temperature on mode I fracture toughness and fracture characteristics of sandstone. Rock Mech Rock Eng. 2017;50(8):2007-2019.
5. Feng G, Kang Y, Sun Z, et al. Effects of supercritical CO₂ adsorption on the mechanical. Energy. 2019;173:870-882.
6. Zhang W, Sun Q, Hao S, et al. Experimental study on the variation of physical and mechanical properties of rock after high temperature treatment. Appl Therm Eng. 2016;98:1297-1304.
7. Brotoños V, Tomás R, Ivorra S, Alarcón JC. Temperature influence on the physical and mechanical properties of a porous rock: San Julian’s calcarenite. Eng Geol. 2013;167:117-127.
8. Peng J, Rong G, Cai M, et al. Physical and mechanical behaviors of a thermal-damaged coarse marble under uniaxial compression. Eng Geol. 2016;200:88-93.
9. Glover PWJ, Baud P, Darot M, et al. A/B phase transition in quartz monitored using acoustic emissions. Geophys J Int. 1995;120:775-782.
10. Rong G, Peng J, Cai M, et al. Experimental investigation of thermal cycling effect on physical and mechanical properties of bedrocks in geothermal fields. Appl Therm Eng. 2018;141:174-185.
11. Zhang S, Huang Z, Wang H, et al. Experimental study on the rock-breaking characteristics of abrasive liquid nitrogen jet for hot dry rock. J Petrol Sci Eng. 2019;181:106166.
12. Shao S, Ranjith PG, Wasantha PLP, Chen BK. Experimental and numerical studies on the mechanical behaviour of Australian Strathbogie granite at high temperatures: an application to geothermal energy. Geothermics. 2015;54:96-108.
13. Adams WW, Stewart JJ, Cohn CM, Muller O, Demmig-Adams B. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geotherm Energy. 2013;1(1):4.
14. Fan LF, Wu ZJ, Wan Z, Gao JW. Experimental investigation of thermal effects on dynamic behavior of granite. Appl Therm Eng. 2017;125:94-103.
15. Meng T, Zhang DH, Hu Y, et al. Study of the deformation characteristics and fracture criterion of the mixed mode fracture toughness of gypsum interlayers from Yunying salt cavern under a confining pressure. J Nat Gas Sci Eng. 2018;58:1-14.
16. Gautam PK, Verma AK, Jha MK, et al. Effect of high temperature on physical and mechanical properties of Jalore granite. J Appl Geophys. 2018;159:460-474.
17. Meng T, Liu R, Meng X, et al. Evolution of the permeability and pore structure of transversely isotropic calcareous sediments subjected to triaxial pressure and high temperature. Eng Geol. 2019;253:27-35.
18. Gautam PK, Verma AK, Jha MK, et al. Study of strain rate and thermal damage of Dholpur sandstone at elevated temperature. Rock Mech Rock Eng. 2016;49(9):3805-3815.
19. Wu X, Huang Z, Cheng Z, et al. Effects of cyclic heating and LN₂-cooling on the physical and mechanical properties of granite. Appl Therm Eng. 2019;156:99-110.
20. Wu Q, Weng L, Zhao Y, et al. On the tensile mechanical characteristics of fine-grained granite after heating/cooling treatments with different cooling rates. Eng Geol. 2019;253:94-110.
21. Yin T, Shu R, Li X, et al. Combined effects of temperature and axial pressure on dynamic mechanical properties of granite. Trans Nonferr Metal Soc China. 2016;26(8):2209-2219.
22. Liu S, Xu J. Mechanical properties of Qinling biotite granite after high temperature treatment. Int J Rock Mech Min Sci. 2014;100(71):188-193.
23. Chaki S, Takarli M, Agbodjan WP. Influence of thermal damage on physical properties of a granite rock: porosity, permeability and ultrasonic wave evolutions. Constr Build Mater. 2008;22(7):1456-1461.
24. Chai S, Mao X, Liu R, et al. The mechanical properties of mudstone at high temperatures: an experimental study. Rock Mech Rock Eng. 2014;47(4):1479-1484.
25. Chen S, Yang C, Wang G. Evolution of thermal damage and permeability of Beishan granite. Appl Therm Eng. 2017;110:1533-1542.
26. David EC, Brantut N, Schubnel A, et al. Sliding crack model for nonlinearity and hysteresis in the uniaxial stress-strain curve of rock. Int J Rock Mech Min Sci. 2012;52:9-17.
27. Xichang BX. Study on the characteristics of thermal damage for granite. Rock Soil Mech. 2003;24(12):194-198.
28. Inserra C, Biwa S, Chen Y. Influence of thermal damage on linear and nonlinear acoustic properties of granite. Int J Rock Mech Min Sci. 2013;62:96-104.
29. Fan LF, Wu ZJ, Wan Z, et al. Experimental investigation of thermal effects on dynamic behavior of granite. *Appl Therm Eng*. 2017;125:94-103.

30. Ding Q-L, Ju F, Mao XB, et al. Experimental investigation of the mechanical behavior in unloading conditions of sandstone after high-temperature treatment. *Rock Mech Rock Eng*. 2016;49:2641-2653.

31. Huang Y, Yang S, Tian W, Zhao J. Physical and mechanical behavior of granite containing pre-existing holes after high temperature treatment. *Arch Civ Mech Eng*. 2017;17:912-925.

32. Changbing Z, Zhijun W, Yuan Z, Bin G. Experimental study on hydraulic fracturing of granite under thermal shock. *Geothermics*. 2018;71:146-155.

33. Weng L, Huang L, Taheri A, Li X. Rockburst characteristics and numerical simulation based on a strain energy density index: a case study of a roadway in Linglong gold mine, China. *Tunn Undergr Sp Tech*. 2017;69:223-232.

34. Fan J, Xie H, Chen J, et al. Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. *Applied Energy*. 2020;258:114007.

35. Fan J, Chen J, Jiang D, et al. A stress model reflecting the effect of the friction angle on rockbursts in coal mines. *Geomechanics and Engineering*. 2019;18(1):21–27.

36. Liu W, Zhang Z, Chen J, et al. Physical simulation of construction and control of two butted-well horizontal cavern energy storage using large molded rock salt specimens. *Energy*. 2019;185:682–694.

37. Wang T, Li J, Jing G, et al. Determination of the maximum allowable gas pressure for an underground gas storage salt cavern—A case study of Jintan, China. *Journal of Rock Mechanics and Geotechnical Engineering*. 2019;11(2):251–262.

38. Gautam PK, Verma AK, Sharma P, et al. Evolution of thermal damage threshold of Jalore granite. *Rock Mech Rock Eng*. 2018;51(9):2949–2956.

**How to cite this article:** Li C, Hu Y, Meng T, Jin P, Zhao Z, Zhang C. Experimental study of the influence of temperature and cooling method on mechanical properties of granite: Implication for geothermal mining. *Energy Sci Eng*. 2020;8:1716–1728. [https://doi.org/10.1002/ese3.627](https://doi.org/10.1002/ese3.627)