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Characteristics of Acoustic Emission Response during Granite Splitting after High Temperature-Water Cooling Cycles

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Abstract: In order to investigate the effect of a high temperature-water cooling cycle on the acoustic emission characteristics of the granite splitting process, Brazilian splitting tests were conducted on granite disc specimens treated with high temperature–water cooling (cycle times 1, 5, 10, 15, 20) from 250 to 650 °C. The relationship between the acoustic emission count, cumulative acoustic emission number, amplitude distribution, and the maximum energy of the specimens and temperature as well as the number of hot and cold cycles were investigated, and the relationship between the acoustic emission changes and specimen damage during the splitting of the granite specimens after the high temperature-water cooling cycle was discussed and analyzed. The test results show that the acoustic emission changes in the splitting process of granite disc specimens have obvious hot and cold shock effects, and that the acoustic emission value and amplitude density of the specimens at the initial stage of splitting show an increasing trend with an increasing number of hot and cold cycles, and the amplitude distribution is more obviously affected by temperature. When the temperature is low and the number of hot and cold cycles is small, the maximum energy value at the peak stress point is larger, and the maximum energy value tends to decrease gradually as the temperature increases and the number of cycles increases.

Keywords: high temperature-water cooling; cyclic action; granite; Brazilian split test; acoustic emission characteristics

1. Introduction

As industrialization continues to accelerate, the use of fossil fuels such as oil and coal for incineration is gradually increasing, which is one of the major causes of global warming [1,2]. Therefore, seeking to develop and utilize efficient, clean, and green new energy is an important issue that humankind is tasked with. As an alternative to traditional energy sources, geothermal resources are clean and widely distributed, with abundant thermal reserves that can be steadily developed over a long period of time, and have broad prospects for development and application [3,4]. Many geothermal mining solutions have been proposed by scholars and experts around the world, among which enhanced geothermal systems (EGS) are recognized and effective [5,6]. In the process of geothermal resource exploitation, dry hot rock needs to undergo several high temperature–water cooling processes, which greatly change the pore structure and mineral composition of dry hot rock [7–11], thus further affecting the physical and mechanical properties of dry hot rock [12,13]. In order to exploit and utilize geothermal resources in a sustainable, safe and stable way, an in-depth study of the macro-mechanical change characteristics of dry hot rock.
rock in the mining process is an important scientific guide for the design of the mining plan of deep geothermal resources and a safety evaluation of the mining process.

In recent years, the physical and mechanical characteristics of high-temperature granites have received increasing attention from related scholars, and there are more studies on the microstructure of rocks under pressure after high-temperature action, from macroscopic cracks to microcracks, and from qualitative description to quantitative description—the research results are more abundant [14–17]. Yang et al. [18] analyzed the evolution of internal cracks in granite after high temperature at 800 °C by uniaxial compression tests, using AE monitoring and X-ray micro-CT. Al-Shayea [19] studied the heating damage process of Westerly granite using the acoustic emission technique and measured its fracture toughness at 20–50 °C. Chen et al. [20] analyzed the effect of high temperature on the mechanical parameters and fracture toughness of granite and explained the mechanical damage mechanism from the microstructural and mineral perspectives. Kumari et al. [21,22] treated EGS reservoir rocks (Strathbogie granite, Australia) at high temperatures and adopted different cooling rates and showed that quenching can lead to the development of microcracks within the rock and also that the cooling rate has an effect on the brittleness of the rock. Siratovich et al. [23] carried out heat treatment followed by both the rapid and slow cooling of three typical rocks to cool them down and showed that the thermal stress caused significant changes in the physical properties of the material, resulting in the increased permeability of the samples, with the rapidly quenched samples showing the most damage. Currently, the mechanical characteristics of granite after high temperature–water cooling cycles have received attention from related scholars [24,25]. Rong and Yu et al. [26,27] conducted uniaxial compression tests on marble and granite after the action of hot and cold cycles and analyzed the physical and mechanical properties of rocks affected by hot and cold cycles by means of microscopic and acoustic emission monitoring results. Zhu et al. [28,29] studied the damage characteristics of granite after hot and cold cycles, and on the basis of acoustic emission, the concepts of mechanical damage, high-temperature impact damage and cold water impact damage during uniaxial compression of specimens were proposed, and damage equations were established, respectively.

In the process of geothermal resource development, dry hot rock may be in tension in addition to being in compression, however, there are few studies reported on the damage during the tension of granite specimens under the action of high temperature–cold water circulation. The tensile strength measured by Brazilian splitting is closer to the direct tensile method and can be used to measure the tensile strength, modulus of elasticity and fracture toughness of rocks, etc. This method is often used to determine the tensile strength of rocks [30–32]. Therefore, in this paper, Brazilian splitting tests were conducted on granite specimens treated with different high temperature (250, 350, 450, 550, 650 °C)–water cooling cycles (number of cycles: 1, 5, 10, 15, 20) to investigate the effects of temperature and number of cycles on the mechanical changes in the splitting process of granite according to the acoustic emission counts, cumulative acoustic emission counts, amplitude and distribution, and the change of the maximum energy of acoustic emission, and the results of scanning electron microscopy are also used to explore the mechanism of cold and thermal impact damage of granite. The research results provide ideas for rock stability monitoring during EGS mining and enrich the basic mechanics of rocks during geothermal resource mining.

2. Specimen Preparation and Test Program

2.1. Specimen Preparation

The granite specimens used in this study were collected from the territory of Quanzhou City, Fujian Province, China. In order to reduce the dispersion of the physical and mechanical properties of the specimens and to ensure the comparability of the tests, all the rock samples were taken out on the same granite. According to the XRD diffraction analysis, the mineral composition of this granite is mainly quartz, feldspar, common hornblende, and black mica, and the contents of the four mineral components are 60%, 32%, 5%, and 3%, respectively, and their diffraction patterns are shown in Figure 1. The average ultrasonic
sound velocity of the specimens reached 2.79 km/s, indicating that the rocks are relatively dense and hard, with small internal porosity and no obvious defects and an average density of 2807 kg/m³.

![Diffraction pattern of granite specimens.](image1)

**Figure 1.** Diffraction pattern of granite specimens.

According to the rock mechanics test method of ISRM [33], granite specimens were processed into discs with a diameter $2R$ of 50 mm and a thickness $t$ of 25 mm by high-pressure water jet cutting, section grinding, and polishing (Figure 2).

![Granite disc specimen.](image2)

**Figure 2.** Granite disc specimen.

### 2.2. Specimen Handling and Loading Scheme

Granite disc specimens were heated by the MXQ1700 high-temperature furnace of the State Key Laboratory of Deep Geotechnics and Underground Engineering, China University of Mining and Technology, which has high-precision temperature control and small high-temperature shock, and can reach a maximum temperature of 1300 °C. The processed granite disc specimens were put into the high-temperature furnace and heated slowly to the set temperature according to the heating rate of 10 °C/min. The temperatures were set to 250, 350, 450, 550, and 650 °C, and the constant temperature was maintained for 2 h after heating to the set temperature to ensure the uniform heating of the specimen as a whole. After the completion of the constant temperature, the high-temperature furnace rock
samples were quickly and steadily transferred into the cold water which the test process maintained at 20 °C so it was completely cooled; the specimen was then withdrawn from the water, and the specimen’s surface was wiped clean of water stains. After undergoing simple drying, the first heating–water cooling process was complete. After simple drying, the granite was cycled according to the first heating–cooling process with the number of cycles set to 1, 5, 10, 15, and 20. The high temperature–cold water circulation treatment specimens and high-temperature equipment are shown in Figure 3a,b.

![Figure 3. High temperature–cold water circulation specimen, heating device, and loading system. (a) Granite disc specimens; (b) MXQ1700 high-temperature furnace; (c) Compression machine and acoustic emission test detector.](image)

Because of the small vertical load required to perform Brazilian splitting, all the disc specimens were tested with the MTS816 electro-hydraulic servo rock testing machine at the China University of Mining and Technology in order to ensure sufficient loading servo accuracy, which has a maximum axial load of 1459KN and a maximum axial stroke of 100 mm. The loading adopts displacement control mode, the loading rate is 0.05 mm/min, and the vertical load and displacement values are automatically collected by computer. During the test, the PCI-Express8 acoustic emission system made by Physical Acoustics, Inc. was used to collect the acoustic emission signal during the splitting of the specimen in real time. The sampling frequency of the external parameters of the device was 30 Hz and the input signal range was ±10 V (Figure 3c).
3. Analysis of Test Results

3.1. Tensile Load, Acoustic Emission Count, and Amplitude Variation Characteristics

In the interest of space, only the tensile load, acoustic emission counts, cumulative acoustic emission counts, and amplitude variation characteristics of the specimens with time after the hot and cold cycles at 350 °C were analyzed in this paper. As shown in Figure 4, it can be clearly seen that the tensile load and the acoustic emission parameters (acoustic emission number, cumulative acoustic emission number, and amplitude) show a clear hot and cold shock effect with time.

![Figure 4](image-url)

Figure 4. Curves of stress, acoustic emission counts, cumulative acoustic emission counts and amplitude with time under hot and cold cycles.
(1) With the increase in the number of hot and cold impact cycles, the overall trend of the specimen peak load decreases, and the damage time will be extended accordingly, which means that the brittle characteristics of the specimen gradually weaken and the ductile characteristics gradually increase in the process. When the number of cycles was 1, 5, 10, 15, and 20, the peak load reduction in the specimens was 35.13%, 47.25%, 47.36%, 44.47%, and 55.63% compared with the peak load of the specimens at 20 °C, respectively, as shown in Figure 4a–f. It can be seen that when the number of hot and cold cycles is in the range of 5–15 times, the number of hot and cold cycles impacts on the internal damage of the specimen is not significant. When the number of cycles reaches 20, the peak strength of the specimens shows a significant decrease again, and the decrease increased by 11.16% compared with the 15th hot and cold cycle.

(2) Define $\alpha$ as the ratio of cumulative acoustic emission counts to total cumulative acoustic emission at the initial splitting stage (before the cumulative acoustic emission mutation point $a$) of the specimen, and the value of $\alpha$ gradually increases with the number of hot and cold cycles. The $\alpha$ value of 1.32% is for the 20 °C specimen, as shown in Figure 4a. When the number of hot and cold cycles reached 1 and 5, the $\alpha$ values were 4.92% and 6.63%, respectively, and the acoustic emission counts and amplitudes were mainly concentrated near the yielding stage and the peak point, and the cumulative acoustic emission count curves changed abruptly near the peak stress, as shown in Figure 4b,c, which means that after five hot and cold cycle treatments, the internal structure of the specimens is relatively dense and there are only a few scales of mechanical damage in the initial cleavage stage. However, when the number of cycles was 10 and 15, the $\alpha$ values reached 15.74% and 22.59%, respectively (Figure 4d,e), indicating that 10 and 15 cycles of hot and cold impact had caused significant damage inside the specimen and cracks mainly occurred at this stage. After 20 hot and cold cycles, the acoustic emission counts and amplitudes of the specimens were significantly reduced during the splitting process, and the accumulated acoustic emission was significantly reduced, however, the $\alpha$ value reached 34.62%, and the acoustic emission counts and amplitudes at the peak point were significantly reduced (Figure 4f).

Figure 5 shows the cumulative acoustic emission characteristics of the disc specimens after different high-temperature hot and cold cycles. It can be seen that with the increase in temperature and the increase in the number of hot and cold cycles, the cumulative acoustic emission counting curve of the granite disc specimens in the splitting process shows an overall decreasing trend. Compared with the 20 °C disc specimen, there was no significant change in the cumulative acoustic emission count after experiencing high-temperature heating at 250 °C for one cooling, but the cumulative acoustic emission count showed a significant decrease from 86.06 $\times$ 102 to 57.30 $\times$ 102 after experiencing the effect of five hot and cold cycles, with a decrease of 33.42%, and the decrease in the cumulative acoustic emission count showed a decreasing trend after experiencing 10–20 hot and cold cycles (Figure 5a,b). The cumulative acoustic emission counts after the specimens underwent one water cooling at 450 °C and did not significantly change from that after one water cooling at 350 °C, which was related to the pore closure inside the fractures due to the expansion of mineral particles inside the granite specimens at this temperature (Figure 5c,d). The cumulative acoustic emission counts at both high temperatures of 550 °C and 650 °C showed a significant decrease (Figure 5e,f), and the acoustic emission of the specimen was 0 after the number of cold and hot cycles reached 15 at 650 °C, indicating that after 15 cold and hot impacts at this temperature, the specimen underwent toughness damage, the internal structure of the specimen was almost completely destroyed, and the released elastic energy and cumulative acoustic emission counts significantly decreased.
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Figure 5. Curve of the accumulated acoustic emission number of specimens with time under the action of high-temperature hot and cold cycles.
3.2. Magnitude Distribution Characteristics

In order to quantitatively analyze the effect of the number of hot and cold cycles on the change of the acoustic emission amplitude of granite specimens at different temperatures, five amplitude intervals of 40–50, 50–60, 60–70, 70–80, and 80–90 dB were set, and Figure 6 shows the distribution of the acoustic emission amplitude of granite specimens in the splitting process under the action of high-temperature hot and cold cycles. Previous studies have shown that smaller amplitudes correspond to small-scale cracks and larger amplitudes correspond to large-scale cracks [34].

Figure 6. Magnitude distribution of granite after the action of cold and heat cycles at different temperatures.
It can be seen from Figure 6 that the amplitudes are mostly distributed in the intervals of 40–50 dB and 50–60 dB after the action of hot and cold cycles at all temperatures, which means that most of the cracks generated inside the specimens during the Brazilian splitting test were small-scale cracks. The treatment of hot and cold cycles at different temperatures has a great influence on the amplitude distribution of granite disc specimens. As the temperature increases and the number of hot and cold cycles increases, the amplitude distribution of the specimens transforms from smaller to larger, indicating that the smaller cracks inside the specimens transform into larger cracks.

At room temperature, the acoustic emission amplitudes of granite disc specimens during Brazilian splitting were mainly distributed in the 40–50 dB interval with an average of 70.66%, followed by those distributed in the 50–60 dB interval with an average of 22.72% and those distributed in the 60–70 dB interval with an average of 5.78%, as shown in Figure 6a. When the specimens were heated at 250 °C, 350 °C, and 450 °C, the distribution of the amplitude values of the specimens significantly changed compared with room temperature after different times of hot and cold cycles, the percentage of the 40–50 dB range significantly decreased, the percentage of the 50–60 dB range increased relatively, and the percentage of the 60–70 dB range slightly changed, as shown in Figure 6b–d.

When the temperature reached 550 °C and 650 °C, the specimen amplitudes are mainly distributed in the two intervals of 40–50 dB and 50–60 dB, and the amplitudes in the intervals of 60–70 dB and 70–80 dB disappear. This is mainly due to two reasons, one which is due to the more significant damage to the internal structure of the specimen due to the hot and cold shock at this temperature; the second is due to the quartz in the granite specimen near 573 °C, which undergoes phase change, thus leading to more serious damage to the granite specimen during the high temperature–water cooling treatment. Therefore, more microcracks were generated inside the specimen, and the expansion and penetration of the cracks will lead to the generation of small-scale cracks. Due to the aggravation of the damage, the number of acoustic emission amplitude values of the specimens significantly decreased, especially when the temperature reached 650 °C; when the number of hot and cold cycles N ≥ 10 times, the brittle characteristics of the specimens almost all disappeared, and only two acoustic emission count values were collected by the AE monitoring equipment during its stretching process, as shown in Figure 6e,f.

3.3. Acoustic Emission Energy Characteristics

The results of related studies suggest that the acoustic emission energy can be evaluated as a quantity of material damage [35–37], and larger energy values correspond to the massive damage or fracture of the rock. During the loading process, the maximum energy usually occurs at the peak stress point. After the high temperature–water cooling treatment, the granite disc specimens all experienced different degrees of hot and cold impact damage. The maximum energy was selected to analyze the fracture degree near the peak stress with temperature and the number of hot and cold cycles (as shown in Figure 7). The maximum energy of the granite disc specimen showed the typical effect of the high temperature–water cooling cycle treatment: when the treatment temperature is low, the number of hot and cold cycles is small and the maximum energy value of the peak stress point is larger. As the treatment temperature increases and the number of cycles increases, the maximum energy value gradually decreases, indicating that smaller-scale cracks occur when the peak stress is reached. This is mainly because the internal structure of the granite specimen will be damaged by hot and cold shock after the high temperature–water cooling cycle treatment. As the treatment temperature increases and the number of hot and cold cycles increases, the degree of damage is further deepened. Therefore, as the treatment temperature increases and the number of hot and cold cycles increases, the cracks at the stress peak shift from large-scale cracks to small-scale cracks and large-scale crack closure occurs.
In order to study the relationship between tensile mechanical parameters and the acoustic emission parameters of granite specimens after the action of high temperature–water cooling cycle treatment, as shown in Figure 7b–e.

As the treatment temperature increases and the number of hot and cold cycles increases, the degree of damage is further deepened. Therefore, as the treatment temperature increases and the number of hot and cold cycles increases, the maximum energy value gradually decreases, indicating that small-scale cracks occur when the peak stress point is larger. As the treatment temperature increases and the number of hot and cold cycles increases, the number of hot and cold cycles increases, the degree of damage is further deepened.

Figure 7. Variation of maximum energy after the action of hot and cold cycles at different temperatures.
When the heating temperature is 250 °C, the value of the maximum energy after experiencing five hot and cold cycles decreases less than that after experiencing the first water cooling, and the maximum energy decreases from $1.29 \times 10^2 \text{mv} \cdot \mu\text{s}$ to $1.02 \times 10^2 \text{mv} \cdot \mu\text{s}$, with a decreasing amplitude of 20.93%. When experiencing 10 hot and cold cycles, the maximum energy of the acoustic emission drops significantly to $0.56 \times 10^2 \text{mv} \cdot \mu\text{s}$, with a decrease of 45.10% compared with experiencing 5 hot and cold effects, and after experiencing 15 and 20 hot and cold cycles, the maximum energy is almost in a stable state, as shown in Figure 7a. When the heating temperature reached 350 °C, 450 °C, 550 °C, and 650 °C, the values of the maximum energy all showed a significant decrease after 5 cold and hot cycles, and the maximum energy tended towards a stable state after 10 cold and hot cycles of treatment, as shown in Figure 7b–e.

In order to study the relationship between tensile mechanical parameters and the acoustic emission parameters of granite specimens after the action of high temperature–cold water cycles, the relationship between the maximum energy of acoustic emission and the corresponding mechanical parameters (peak load, average stiffness, peak displacement) of the specimens was analyzed, as shown in Figure 8. It can be clearly seen that the peak load and the average stiffness change in a nearly consistent trend, and the overall increase with the increase in the maximum energy of acoustic emission of the specimen, while the peak displacement change has no obvious regularity. When the temperature is 250 °C, the peak load and average stiffness of the specimen with the maximum energy of acoustic emission showed a rapid increase and then a slowly increasing trend, whilst the peak displacement with the maximum energy first appeared to decrease, increase, and then follow a decreasing trend, as shown in Figure 8a. When the temperature is 350 °C, the peak load and average stiffness of the specimen rapidly increase with the maximum energy of acoustic emission and then slowly increase and then rapidly increase, and the peak displacement increases with the maximum energy, decreases, and then increases, as shown in Figure 8b. When the temperature is 450 °C, 550 °C, and 650 °C, the peak load and average stiffness of the specimen show a continuous increasing trend with the maximum energy of acoustic emission, however, the peak displacement appears to fluctuate significantly, as shown in Figure 8c–e. Therefore, the maximum energy value can be used as a valid acoustic emission parameter to predict the change in mechanical parameters in the tensile mechanical tests of the granite disc specimens after experiencing the effect of high temperature–cold water cycles.
Figure 8. Relationship between maximum energy and mechanical parameters after the action of hot and cold cycles at different temperatures.

### 4. Discussion

Acoustic emission is mainly generated by the release of energy caused by the contact and friction of the fracture surfaces during the fracture closure within the material [38–40]. In the study of the acoustic emission characteristics of granite during the tensile process after the action of the high temperature-water cooling cycle, it was found that the following pattern of acoustic emission exists in the initial tensile stage of the specimen: with the increase in the number of hot and cold cycles, the percentage of acoustic emission counts (α value) in the initial tensile stage of the specimen showed a gradually increasing trend, so the damage degree of the specimen at different temperatures of hot and cold impacts can be evaluated based on the acoustic emission characteristics in the initial tensile stage.

In order to reveal this law, some representative specimens were selected for electron microscope scanning tests in this paper to explain the effect of high temperature–cold water cycling action on the change pattern of acoustic emission during granite splitting from microstructural changes. The electron microscope scans of the granite surface magnified by 2000 times are given in Figure 9 after 1, 5, 10, and 15 cycles of hot and cold action at 250 °C, 350 °C, 450 °C, 550 °C, and 650 °C with a 20 °C specimen, respectively. The surface of the granite specimen particles at 20 °C is only sporadically distributed with a small number of micro-pores, and the internal structure is more complete, as shown in Figure 9a, which means that the granite specimen is almost intact in the initial state, so the α value of the specimen in the initial tensile stage is small. When the temperature and the number of hot and cold cycles increases, the surface damage of the specimen is mainly in the form...
of: microporosity → microfracture sprouting → fracture expansion → fracture penetration → lamellar cracking → fracture width increase transformation process, so the specimen gradually develops a loose microstructure due to the increase in fracture and openness, the deepening of the fracture, and the initial tensile stage $\alpha$ value gradually increased. Taking 350 °C as an example, when experiencing one and five hot and cold shock effects (Figure 9i,g), the mineral particles expand thermally, some of the primary pores appear to be closed, and only some fish scale cracking ($N = 1$) and flake cracking ($N = 5$) occur, whilst the number and area of the microscopic defects are reduced to some extent, so both $\alpha$ values are smaller. After 10 and 15 hot and cold cycles, cracks appeared on the specimen surface and the crack width increased from 1 $\mu$m ($N = 10$, Figure 9h) to 3 $\mu$m ($N = 15$, Figure 9i), so that the crack closure or friction during the initial stretching phase leads to an increase in acoustic emission counts, which is more consistent with the results of the previous test analysis.

![Microstructural evolution of granite specimens after high temperature–water cooling cycles.](image)

Figure 9. Microstructural evolution of granite specimens after high temperature–water cooling cycles.
5. Conclusions

In this study, the effects of temperature \(T\) and the number of hot and cold cycles \(N\) on the variation pattern of acoustic emission parameters during the tensile process of granite were evaluated, and then the damage processes of the specimens during hot and cold impacts were analyzed and discussed, and the following conclusions were drawn:

(1) At a temperature of 350 °C, the peak loads of the specimens were reduced by 35.13%, 47.25%, 47.36%, 44.47%, and 55.63% when the number of cycles was 1, 5, 10, 15, and 20, respectively, compared with the peak loads of the specimens at 20 °C. When the number of hot and cold cycles is in the range of 5–15, the number of hot and cold shocks has little effect on the change in the internal damage of the specimen. The acoustic emission counts, cumulative acoustic emission counts, and amplitudes of the specimens at the initial stretching stage tend to decrease \((N \leq 5\) cycles\), then increase \((10 < N \leq 15\) cycles\) and decrease \((15 < N = 20\) cycles\) with the number of cycles \(N\).

(2) When \(T = 250, 350,\) and \(450 \degree C\), the amplitude values of the specimens decreased significantly in the 40–50 dB range, increased relatively in the 50–60 dB range, and did not change much in the 60–70 dB range after different times of hot and cold cycle treatment. When \(T = 550 \degree C\) and \(650 \degree C\), the specimen amplitudes are mainly distributed in the two intervals of 40–50 and 50–60, and the amplitudes in the intervals of 60–70 dB and 70–80 dB disappear.

(3) When \(T = 250 \degree C\) and \(N = 5\) times, the value of the maximum energy decreases less whilst experiencing the first water cooling, and the maximum energy decreases from \(1.29 \times 10^2\) mv·s to \(1.02 \times 10^2\) mv·s, with a reduction of 20.93%; when \(N = 10\) cycles, the maximum energy of the acoustic emission decreases significantly to \(0.56 \times 10^2\) mv·s, with a reduction of 45.10%; when \(10 < N \leq 20\) cycles, the maximum energy then did not change significantly. When \(T = 350, 450, 550,\) and \(650 \degree C\) and when \(T = 5\) cycles, the maximum energy showed a significant decline, whilst when \(N \geq 10\) cycles, the maximum energy tended towards a stable state.

This paper only focused on the acoustic emission characteristics of granite in the tensile process after high temperature–water cooling cycles. Subsequent research will be conducted on the mechanical characteristics of granite under real-time high temperature–water cooling cycles, such as uniaxial compression, shear strength, tensile strength tests, and creep tests under real-time high temperature–water cooling cycles, so that the laboratory research is closer to the actual working conditions in enhanced geothermal mining (EGS).

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