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Research Article

Investigation of Fracture Evolution and Failure Characteristics of Rocks under High-Temperature Liquid Nitrogen Interaction

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The utilization of liquid nitrogen as a sustainable and water-free fracturing medium exhibits immense promise in engineering applications. In this investigation, Brazilian split tests and acoustic emission tests were conducted to explore the impact of liquid nitrogen cooling on the internal structure and mechanical properties of rock specimens. To examine the influence of liquid nitrogen cooling on the tensile strength of rocks, displacement-load curves were obtained from samples subjected to varying cycles of high-temperature liquid nitrogen cooling using Brazilian split tests. Acoustic emission experiments were conducted to investigate the characteristics of granite samples exposed to various cycles of high-temperature liquid nitrogen cooling. Based on these findings, the impact of liquid nitrogen cooling on the internal structure of rock masses was analyzed. The findings of this study demonstrate that high-temperature liquid nitrogen thermal treatment significantly modifies the microscopic structure and mechanical properties of rocks, with potential implications for overall stability and reliability. Notably, an observable decline in tensile strength was observed as the number of cycles of high-temperature liquid nitrogen treatment increased. These findings underscore the substantial impact of liquid nitrogen cooling on the behavior of rocks. High-temperature liquid nitrogen treatment effectively promotes the generation of microcracks within rocks, thereby increasing their permeability. During the experiment, granite specimens primarily exhibited shear-type fractures when subjected to high-temperature freeze-thaw cycles induced by liquid nitrogen.

1. Introduction

As a country undergoes scientific and technological advancements and accelerates its modernization process, the demand for oil and gas resources becomes paramount. This holds true for China, where the need for these resources has considerably surged. Unfortunately, domestic production falls short of meeting the developmental demands, leading to the substantial annual importation of oil and gas resources from foreign countries. In order to get rid of China's dependence on oil and gas resources and to achieve the strategic goal of sustainable development, the search for sustainable energy resources has become a top priority [1–3].

Geothermal energy, as a renewable source, offers stability, reliability, and sustainability in meeting energy demands. By reducing reliance on fossil fuels, it presents a viable alternative that addresses environmental concerns associated with conventional energy sources. Abundant geothermal resources exist within the Earth's interior. However, the development of geothermal energy faces significant challenges due to limitations in current fracking capabilities [4, 5]. Hydraulic fracturing is widely employed in geothermal extraction and is a well-established technique in underground rock fracturing. Nevertheless, it poses substantial challenges in terms of water usage and environmental protection [6]. The attention has shifted towards nonaqueous fracking technology, and ongoing research is exploring the potential application of liquid nitrogen (LN_2) as a complementary or alternative method to conventional hydraulic fracturing techniques [7–10]. The liquid nitrogen fracturing technique involves pumping liquid nitrogen into the well at typical flow rates and pressures, resulting in the formation of artificial fractures [11]. Underground rocks typically have high temperatures, and the extremely low temperature (-195.8°C) of liquid nitrogen can rapidly decrease the temperature in the vicinity of the reservoir. The pronounced shift in external rock temperature, accompanied by a substantial temperature gradient, induces notable thermal shock loads that lead to rock damage, manifesting as the propagation of existing natural fractures or the generation of novel fractures [12]. Additionally, underground rock formations are not comprised of a single material but consist of multiple materials. Treatment with liquid nitrogen leads to substantial temperature stress and damage within the rock layers due to their different coefficients of expansion. Furthermore, when encountering high temperatures, liquid nitrogen rapidly expands into gas, promoting the expansion of rock fractures. Moreover, nitrogen gas serves as a stable and environmentally friendly medium, mitigating environmental pollution and reducing unnecessary operational accidents when used as a fracking medium. By conducting comprehensive investigations into the underlying principles and effects of high-temperature liquid nitrogen fracturing, novel methods and technologies can be developed to enhance the extraction of geothermal energy. These advancements are aimed at improving permeability in rock formations, leading to increased efficiency and economic viability in geothermal energy development. Through such research, the potential for harnessing geothermal energy can be optimized, contributing to sustainable energy solutions. Compared to traditional hydraulic fracturing, liquid nitrogen fracturing technology has significant advantages in terms of economic feasibility and practicality. Liquid nitrogen is easy to obtain locally and does not pollute the environment after evaporation, making it an ideal fracturing fluid.

In recent years, a substantial body of research, conducted by scholars from both domestic and international institutions, has been dedicated to investigating the utilization of liquid nitrogen as a fracturing medium for enhancing permeability in rocks. Upon contact with liquid nitrogen, McDaniel et al. observed the detachment of cubic fragments from rock samples, accompanied by cracking sounds during both immersion in and removal from the liquid nitrogen [13]. Kocabas employed a planar strain model to examine the stress distribution surrounding wellbores during the injection of cold water into reservoirs, suggesting that thermal stresses could play a role in the initiation and propagation of fractures [14]. Tran et al. emphasized the paramount significance of thermal stresses originating from temperature differentials between the heated rock and the cold fluid injection in the formation of secondary fractures [15]. Their study sheds light on the crucial role these thermal stresses play in fracture development processes. Enayatpour et al. showcased that hydraulic fracturing operations can induce thermal shocks, resulting in the formation of small fractures and a consequential notable enhancement in productivity [16]. Cai et al. utilized nuclear magnetic resonance, acoustic emission (AE), and uniaxial compression tests to investigate the impact of nitrogen cooling. Their research findings shed light on multiple aspects, revealing that nitrogen cooling not only promotes the expansion of micropores and enhances coal pore connectivity but also leads to increased permeability. However, it is worth noting that this cooling method can also result in a reduction in strength. Furthermore, the study demonstrated that nitrogen cooling exhibits potential as a viable approach for optimizing coal reservoirs. The expansion of micropores and the improved connectivity among coal pores contribute to enhanced fluid flow capabilities, thus increasing the overall permeability [17].

Zhang and Tingyun observed shrinkage deformation of rock matrix due to nitrogen cooling, resulting in the expansion of microcracks and increased permeability [18]. Li et al. examined the impact of freeze-thaw cycles using liquid nitrogen on microcracks in coal and revealed a correlation between crack width and temperature difference, as well as water saturation levels [19]. Zhai et al. investigated the dynamic transformations of the pore structure in coal induced by cyclic nitrogen cooling [20]. Halbert [21] proposed the injection of liquid nitrogen into fractured production wells to freeze the target reservoir at subzero temperatures, followed by injection of high-temperature steam to dissolve the frozen reservoir, and obtained significant production enhancement through this freeze-thaw method. Sun et al. undertook an extensive investigation to examine the impact of temperature variations on the thermal damage in granite. The study focused on the degradation characteristics of high-temperature granite when subjected to cyclic nitrogen cooling at different scales, including macro-, micro-, and mesolevels. To achieve comprehensive insights, a combination of theoretical analysis, physical experiments, and numerical simulations was employed [22]. The findings of this research shed light on the behavior of granite under varying temperature conditions. The analysis revealed distinct patterns of degradation at different scales. At the macroscale, significant changes were observed in terms of structural stability and mechanical properties. Microscopically, the investigation unveiled intricate crack formations, fissures, and alterations in the mineral composition. Furthermore, at the mesoscale, the research identified the redistribution of stress and strain within the granite matrix [23, 24].

Shao et al. examined the impact of nitrogen cooling on the acoustic propagation characteristics of coal. The study revealed a substantial reduction in both velocity and amplitude, indicating notable alterations in the internal structure and mechanical strength of coal rock induced by nitrogen cooling [25]. Li et al. and other researchers explored the influence of cyclic nitrogen freeze-thaw processes on the expansion of preexisting fractures and compressive strength in coal rock. Their investigations revealed that such cycles fostered the development of fractures, thus promoting fracture propagation [26, 27]. The expansion of original fractures during the cyclic nitrogen freeze-thaw processes was attributed to the thermal stress induced by the alternating freeze and thaw cycles. This thermal stress resulted in the widening and lengthening of existing fractures, ultimately leading to enhanced fracture development. Moreover, the compressive strength of coal rock experienced a noticeable decrease after undergoing these freeze-thaw cycles, underscoring the significant impact of cyclic nitrogen cooling on the mechanical properties of coal rock.

In the study of rock mechanics and fracture evolution, Kaiser [28] initially proposed that metal specimens subjected to reloading after unloading would hardly produce acoustic emission until the stress reached the previously applied load. Only when the stress on the specimen reached its maximum preexisting stress would significant acoustic emission occur. Subsequently, Schofield started studying acoustic emission techniques to verify Kaiser's findings and measure the acoustic emission sources in rocks. In 1963, Goodman conducted experiments to validate the presence of the Kaiser effect in rocks and demonstrated its utility in determining the historical triaxial stress distribution within rocks [29]. However, subsequent findings revealed limitations in Goodman's simplified experimental approach, resulting in inaccuracies in the obtained results. Over time, through meticulous experimentation, significant advancements have been made in the technology of observing the generation and evolution of internal cracks in rocks using acoustic emission techniques, leading to more refined analyses [30, 31]. The initial shortcomings of Goodman's experimental method prompted researchers to delve deeper into the complexities of rock fracture processes and seek more precise methodologies for studying internal crack formation. By employing advanced acoustic emission techniques and conducting extensive investigations, researchers have made substantial progress in enhancing our understanding of the dynamics of internal crack generation and propagation within rocks. These refined methodologies have paved the way for more accurate and comprehensive analyses of rock fracture behaviors, contributing to improved interpretations of geological phenomena and enhancing the reliability of related studies. Simultaneously, laboratory research on rock acoustic emission has attracted widespread attention, especially in the study of the process and mechanism of rock brittle failure, with numerous scholars making important contributions [32–36]. In summary, the current research on rock fracturing induced by liquid nitrogen cooling is still incomplete.

In order to explore the specific damage and degradation effects of liquid nitrogen on granite, this article studied the effect of nitrogen cooling on the internal structure and mechanical properties of rocks through Brazilian splitting experiments and acoustic emission tests and explored the potential application of liquid nitrogen in geothermal development. The findings of this study provide valuable insights into the effects of liquid nitrogen cooling on rocks, specifically focusing on changes in their internal structure and mechanical behavior. By employing Brazilian splitting experiments, which involve subjecting rock samples to controlled compressive forces, and acoustic emission tests, which monitor the release of stress-induced microcracks, researchers were able to comprehensively analyze the response of rocks to nitrogen cooling under laboratory conditions.

2. Experimental Materials and Procedures

2.1. Brazilian Splitting Principle. The Brazilian splitting test has emerged as a widely employed experimental approach for assessing the tensile strength and fracture characteristics of rocks. This method has gained popularity due to its effectiveness in offering valuable insights into the mechanical properties and behavior of rock specimens subjected to tensile loading conditions. In this test, a disc-shaped rock sample is placed on a loading machine, and two parallel plates apply vertical forces. These forces applied to the rock sample act perpendicular to its axial direction, generating tensile stress. The application of external forces to the rock sample induces tensions along a plane perpendicular to its axial direction, giving rise to a state of tensile stress. This phenomenon is crucial for understanding the mechanical behavior and failure mechanisms of rocks subjected to different loading conditions.

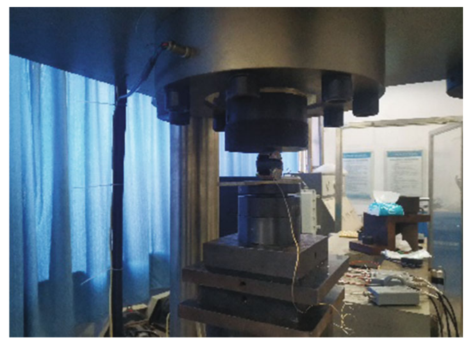
Tensile stress arises when external forces are exerted on a rock sample in a direction perpendicular to its axial alignment. Under such circumstances, the intermolecular bonds within the rock material experience stretching, potentially leading to crack initiation and propagation. During the Brazilian splitting test, the rock sample experiences fracture when the tensile stress surpasses its respective tensile strength. This fracture precisely occurs along a plane that is perpendicular to both the loading axis and the diameter direction of the rock sample. As a result, the distinct fracture pattern known as Brazilian splitting becomes apparent. To measure the tensile strength in the Brazilian splitting test, strain gauges are typically installed at both ends of the rock sample to measure strain. The stress-strain curve of the rock sample can be obtained by applying various loads and measuring the corresponding strain and stress. Characterizing the mechanical behavior of the rock sample involves subjecting it to different magnitudes of load while meticulously monitoring the resulting strain and stress. By systematically varying the applied loads and measuring the corresponding responses, we can construct a comprehensive load-displacement curve that provides valuable insights into the material's deformation characteristics and mechanical properties. The Brazilian splitting test yields crucial data concerning the strength properties of the rock material, encompassing key parameters such as its tensile strength, elastic modulus, and fracture toughness. This experimental technique involves subjecting a cylindrical rock specimen to diametrical compressive forces, enabling the determination of its mechanical response and failure behavior under tension. These parameters are crucial for applications in rock engineering and geological exploration, as they offer insights into the mechanical performance and reliability of rocks. In this study, the Brazilian splitting test was employed to investigate a series of rock properties, including the stress-strain curve, under high-temperature liquid nitrogen treatment. The experimental setup and detection equipment are illustrated in Figure 1.

2.2. Principle of Acoustic Emission. Rock acoustic emission testing is an experimental method used to investigate the formation and propagation of microcracks within rocks. Based on the principle that small fracturing events generated by stress in rocks produce elastic wave signals, valuable information regarding the fracture behavior of rocks can

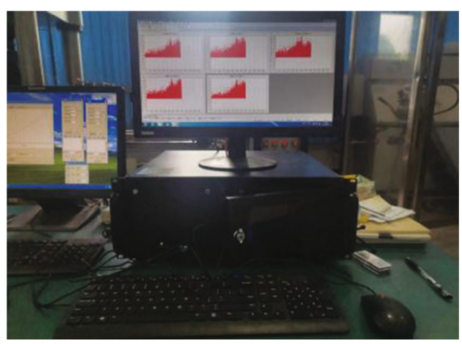
(a) Heating box

(b) Liquid nitrogen tanks

(c) Electronic scales



(d) Brazilian splitting apparatus



(e) Acoustic emission apparatus

Figure 1: Experimental equipment diagram.

be obtained by detecting and recording these acoustic emission signals. In the rock acoustic emission test, rock samples are typically placed in the testing apparatus and subjected to loading or stress loads. As stress is applied to the rock, small internal cracks begin to form and propagate. The energy released during this process generates elastic wave signals known as acoustic emission events. Sensors such as pressure sensors and acoustic emission sensors are used in the experiment to detect and record these signals. The sensors capture the elastic wave signals caused by microfracturing events within the rock, and characteristics such as amplitude, duration, and frequency of these signals can be recorded. Through the analysis and processing of acoustic emission signals, a variety of parameters and charts can be derived, encompassing factors such as the frequency of acoustic emission events, energy distribution, and amplitude characteristics. These parameters and charts provide quantitative information about rock fracture, such as the location, quantity, size, and activity intensity of crack formation and propagation. The principles of rock acoustic emission testing contribute to researchers' understanding of rock fracture behavior and failure mechanisms, enabling them to assess rock stability and strength characteristics. Moreover, rock acoustic emission testing plays a vital role in areas such as rock mass monitoring and geological hazard warning, providing reliable experimental data and analytical tools for rock engineering and geological research. In this study, the rock samples of granite treated under high-temperature liquid nitrogen are processed using acoustic emission testing, producing density maps of acoustic emission points, which are then analyzed. The experimental setup and detection equipment are illustrated in Figure 1.

2.3. Experimental Scheme and Equipment. In this study, multiple granite samples were carefully selected and organized into 7 groups. One group was designated as the control group without any treatment. The remaining 6 groups underwent different numbers of high-temperature liquid nitrogen cycles: 3, 5, 7, 9, 15, and 20 cycles, respectively. In addition, the granite sample used in this study is from Xuzhou City, Jiangsu Province, China. The granite belongs to coarse-grained granite with white appearance, which is a typical dense hard granite.

Due to the available dry hot rock temperature range between 180°C and 600°C, in order to simulate the state of high-temperature dry hot rock, the rock undergoes high-temperature heating before liquid nitrogen freezing. Many previous studies have set the rock temperature to 300°C to investigate the damage and cracking effect of liquid nitrogen on high-temperature granite [37]. Therefore, we have also set the heating temperature at 300°C, which can simulate the high-temperature state of rocks and compare it with other research results. The instruments used for the high-temperature liquid nitrogen treatment are shown in Figure 1. Following the thermal treatment of the rock samples, laboratory-based Brazilian tensile strength tests and acoustic emission tests were performed. The Brazilian splitting test was conducted on the TAWD-2000 testing machine using displacement control with a loading rate of 0.1 mm/min. At the same time, the acoustic emission probe is fixed on the surface of granite to record the acoustic emission signal of rock fracture in real time. These meticulous examinations yielded crucial insights into the acoustic emission characteristics and stress-strain behavior of the rocks. Thorough analysis of these data is paramount in comprehending the performance of rocks when subjected to high-temperature liquid nitrogen treatment, thereby contributing to the advancement of geothermal energy extraction techniques.

3. Results and Analysis of Experiments

3.1. Analysis of Mechanical Behavior. The experiment reveals the fracture behavior of rocks, reflecting the complete process from initial loading to ultimate failure in granite samples. The mechanical effects and variations induced by liquid nitrogen cyclic freezing-thawing under Brazilian tensile conditions on granite samples were obtained by plotting load-displacement curves. As depicted in Figure 2, typically, the load-displacement curve of granite undergoes four distinct stages.

(1) The initial stage of crack formation in granite, known as the nonlinear stage, is characterized by a gradual stress increment and the absence of microcrack propagation

(2) The second stage is the elastic deformation stage. At this stage, the load-displacement curve exhibits linear growth, indicating no internal damage or microcrack propagation in the granite. Analysis indicates that subsequent to the treatment with liquid nitrogen, a discernible reduction is observed in the load-displacement curve when compared to the untreated counterpart. This outcome suggests the occurrence of specific damages brought about by the liquid nitrogen treatment on the granite material

(3) The third stage involves the propagation of cracks. Nonelastic deformation occurs in the granite, with microcracks initiating and continuously propagating. As the load continuously reaches its peak, macroscopic cracks start forming from the microcracks, eventually leading to rock failure

(4) The fourth stage of the testing process signifies the onset of rock failure, characterized by fracture and subsequent damage to the granite specimen following the attainment of peak load. This critical stage highlights the structural integrity limitations of the rock material under investigation. The applied stress begins to rapidly attenuate, resulting in a noticeable downward trend in the load-displacement curve

Figure 2 presents the displacement-load curve of the granite samples, while Figure 3 illustrates the load comparison at peak values. In both figures, it can be observed that the peak load of the samples subjected to three cycles of high-temperature liquid nitrogen treatment is significantly lower compared to the untreated samples. In addition, an ongoing reduction in the peak load is observed as the number of high-temperature liquid nitrogen cycles escalates. This observation indicates that the application of high-temperature liquid nitrogen treatment induces substantial damage to the interior of the rock. Moreover, as the number of cycles increases, the internal damage intensifies, signifying a progressive decline in the rock's structural integrity.

During the liquid nitrogen cooling treatment of high-temperature rocks, a substantial temperature gradient is formed due to the rapid decrease in external temperature while the internal temperature changes more slowly. This results in the generation of thermal shock loads, inflicting considerable damage on the rock. In addition, rocks consist of diverse and disparate materials that exhibit differential coefficients of thermal expansion and contraction. Consequently, the application of high-temperature liquid nitrogen treatment induces substantial thermal stresses within the rock, exacerbating its internal degradation. This phenomenon underscores the intricate interplay between material heterogeneity and thermal effects, which significantly influence the overall behavior and integrity of the rock specimen.

The calculation of the samples' tensile strength in this study utilized the widely adopted Brazilian splitting model. The model construction is as follows:

$$\sigma_x = \frac{2P}{\pi L}\left(\frac{\sin^2\theta_1 \cos\theta_1}{r_1} + \frac{\sin^2\theta_2 \cos\theta_2}{r_2}\right) - \frac{2P}{\pi DL}, \quad (1)$$

$$\sigma_y = \frac{2P}{\pi L}\left(\frac{\cos^3\theta_1}{r_1} + \frac{\cos^3\theta_2}{r_2}\right) - \frac{2P}{\pi DL}. \quad (2)$$

In the equation provided above, we define several key parameters. The variable D signifies the diameter of the disk, measured in meters (m). Similarly, L represents the thickness of the disk, also measured in meters (m). Lastly, P

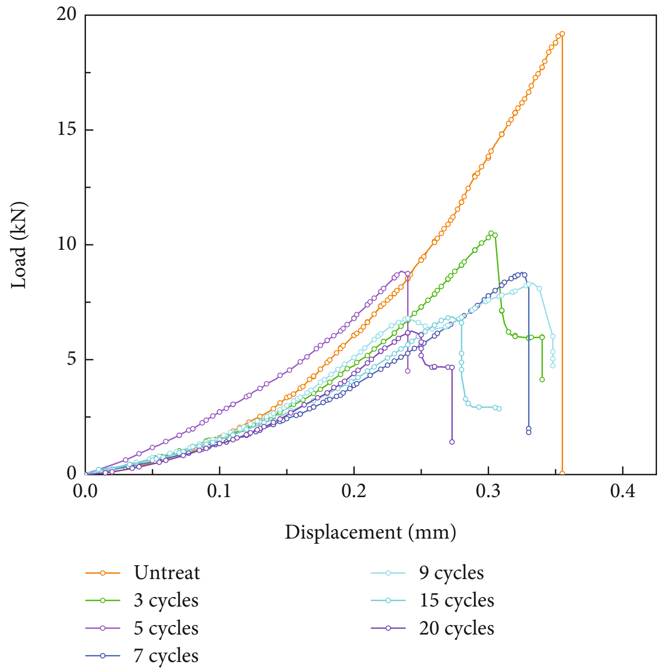


Figure 2: Load-displacement curve.

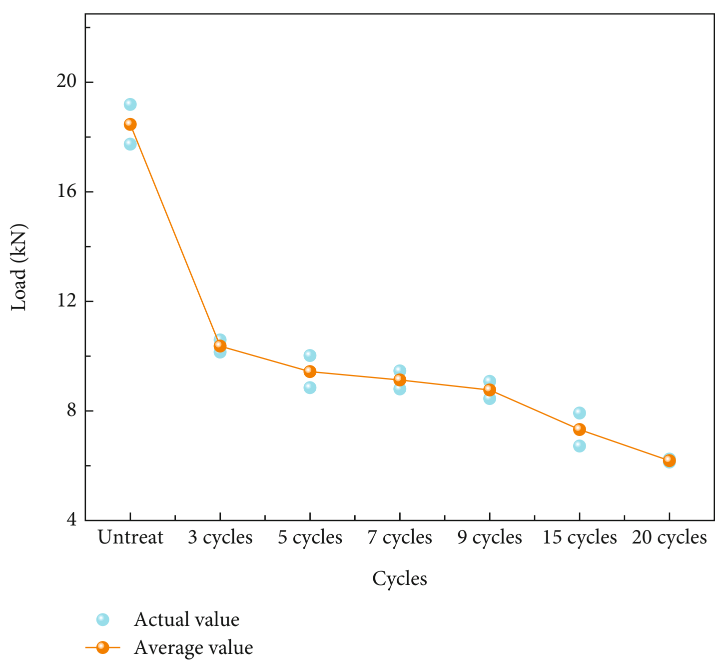


Figure 3: Load comparison at peak values.

denotes the peak load exerted on the disk, measured in newtons (N).

Table 1 presents the tensile strength values of granite in the Brazilian splitting test. Figure 4 shows the variation in tensile strength. The diameter and thickness of the discs used in this study were fixed at 0.05 m and 0.025 m, respectively. The table presented above clearly demonstrates a notable decrease in the tensile strength of the granite samples following three cycles of high-temperature liquid nitrogen treatment, as compared to the untreated control group. Furthermore, as the number of high-temperature liquid nitrogen cycles increased, the overall trend of decreasing tensile strength became more pronounced. Granite, being a heterogeneous material, possesses numerous microcracks within its structure. During high-temperature liquid nitrogen treatment, these internal microcracks propagate and gradually coalesce, resulting in the formation of larger fractures, ultimately compromising the structural integrity of

Table 1: Tensile strength analysis of Brazilian split sample.

Cycles	P_{max} (N)	D (m)	B (m)	σt (Pa)
Untreated	19190	0.05	0.025	9778343.949
3	10590	0.05	0.025	5396178.344
5	8850	0.05	0.025	4509554.14
7	8800	0.05	0.025	4484076.433
9	8450	0.05	0.025	4305732.484
15	6720	0.05	0.025	3424203.822
20	6240	0.05	0.025	3179617.834

the rock and leading to a gradual reduction in tensile strength. In essence, these findings emphasize the notable implications of subjecting rocks to high-temperature liquid nitrogen cyclic treatment, particularly in terms of their tensile strength. The present study contributes valuable insights into comprehending the repercussions of high-temperature liquid nitrogen freeze-thaw cycles on rock properties, thereby serving as a valuable reference for engineering applications in related disciplines.

3.2. AE Characteristic Analysis of Granite. This study conducts a quantitative analysis and evaluation of acoustic emission (AE) activities by analyzing parameters such as cumulative AE counts, cumulative AE energy, AF value, and RA value. In this context, AE counts refer to the number of oscillations that exceed a threshold signal, serving as an indicator of AE activity. Cumulative AE counts and cumulative AE energy represent the sum of all AE counts and energy prior to a specific moment, respectively. Any signal that surpasses the threshold is considered an impact, reflecting the overall quantity and frequency of AE activities. The AF value, measured in kHz, denotes the mean frequency of AE impacts surpassing a specific threshold. Its calculation involves dividing the total number of AE counts by the duration of the corresponding AE impacts. In contrast, the calculation of the RA value entails dividing the interval from the initial threshold crossing of the AE signal to its maximum amplitude by the magnitude of the AE signal itself. This value is typically expressed in units of milliseconds per volt (ms/V). These parameters assist in assessing the structural health condition and predicting potential failures.

The load-time relationship, AE ringing count-cumulative ringing count, and energy-cumulative energy were plotted based on the acoustic emission (AE) results, as depicted in Figure 5.

According to Figure 5, the acoustic emission (AE) activity can be broadly classified into four distinct stages. In the first phase, which represents the early development of cracks, the level of acoustic emission (AE) activity remains minimal. In the subsequent phase, the granite undergoes elastic deformation, which yields a small number of AE signals characterized by longer durations and relatively lower energy levels. The third stage is characterized by the occurrence of nonelastic deformation in the granite. Within this stage, a significant number of AE signals are produced, showcasing a heightened intensity and a gradual augmentation in energy magnitude. Upon reaching the maximum load, the energy of the AE signals likewise attains its pinnacle. Subsequently, the fourth stage delineates the postpeak destructive phase following the culmination of stress accumulation. Throughout this stage, AE activity persists, albeit with a diminishing energy profile.

Figure 5 clearly demonstrates that with an increase in the number of high-temperature liquid nitrogen cyclic freeze-thaw cycles, there is a notable increase observed in both the ringing count and energy count. During periods of relatively low load, the augmentation in both the ringing count and energy count is characterized by a comparatively gradual progression. However, upon reaching the peak load, both the ringing count and energy count generally attain their maximum values. With an increasing number of high-temperature liquid nitrogen cyclic freeze-thaw cycles, the damage inflicted on the granite becomes more extensive, resulting in more acoustic emission signals being generated, along with an increase in energy.

Upon careful analysis of the ringing count graph, a clear correlation emerges whereby the number of liquid nitrogen freeze-thaw cycles exhibits a direct impact on the ringing count of the granite, leading to a substantial increase. An incremental escalation in the intensity of acoustic emission activity can be discerned across the stages of fracture, plasticity, compaction, and elasticity as the number of liquid nitrogen freeze-thaw cycles rises. By analyzing the AE signals emitted during the fracture process of granite, it becomes apparent that they serve as a reliable measure of the activity present within the granite. As the number of cycles increases, certain regions are susceptible to encountering extensive areas of damage. Upon the application of load, an abrupt surge in the acoustic emission (AE) ringing count is observed, leading to a pronounced elevation in the cumulative ringing count curve. In essence, the utilization of liquid nitrogen freeze-thaw treatment effectively harnesses the fracturing capability of liquid nitrogen, thereby activating the inherent damage potential within the granite and influencing the distribution of damages, consequently altering the characteristics of the granite.

By analyzing the acoustic emission (AE) ringing count and energy, a clear distinction arises between the granite treated with liquid nitrogen and the untreated samples during the compaction stage. Specifically, the former showcases noticeably higher values for both ringing count and energy. This observation highlights the substantial impact of freeze-thaw treatment on the acoustic properties of the granite. However, the probability of such occurrences gradually decreases. Acoustic emission events transpire at the interface between the granite and the loading plate during the compaction stage. Subsequently, internal cracks in the granite close under the applied load, resulting in acoustic emission activity. During the elasticity stage, the acoustic emission energy experiences marginal changes, displaying a relatively stable pattern. Nevertheless, in the fracture stage, as the applied pressure steadily increases, the acoustic emission activity becomes more prominent and dynamic, culminating in the ultimate failure of the granite. As the pressure increases gradually, the granite enters the failure stage after

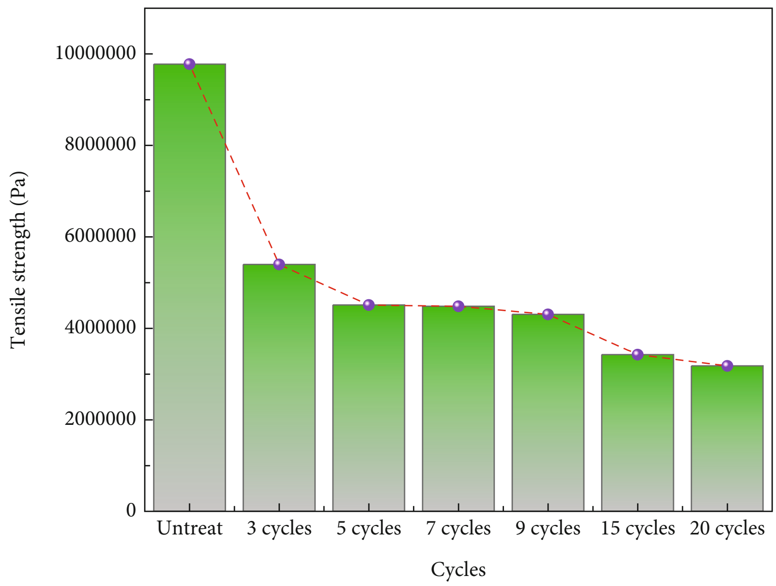


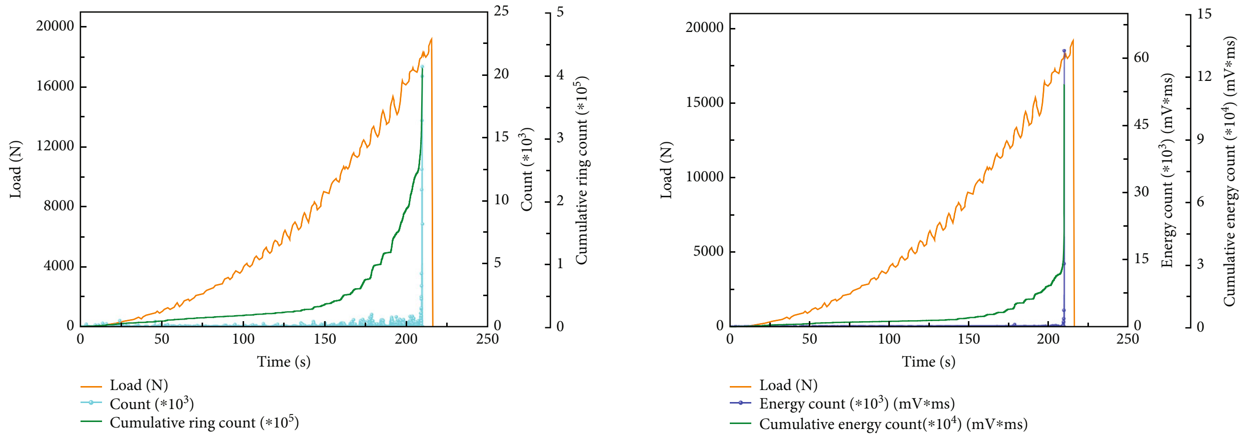
Figure 4: The variation in tensile strength.

the peak, and the load drops abruptly, leading to a decrease in acoustic emission activity. Overall, the cumulative acoustic emission energy curve exhibits parallel ascending trends with the load curve, displaying significant jumps at different stages of the peak load and postpeak load.

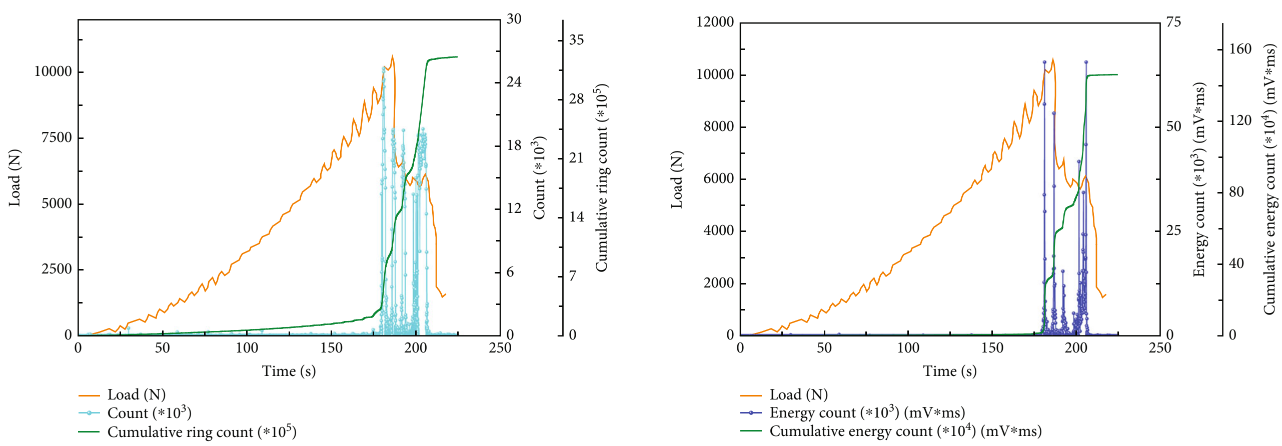
3.3. RA/AF Acoustic Emission Point Density Map Analysis. Figure 6 shows the comparison of acoustic emission characteristics under different rock failure modes. The RA/AF density plot of acoustic emission (AE) points is a commonly used analytical method for interpreting AE testing data. By plotting the relationship between the rise time-to-amplitude ratio (RA) and the average frequency (AF) of each AE event, it provides valuable information about the rupture mechanisms of AE sources. Generally, based on the numerical values of RA and AF, the rupture type of AE events can be preliminarily determined. When RA is small and AF is high, these scatter points represent tensile rupture events. Conversely, when RA is large and AF is low, it implies shear rupture events. In this way, the RA/AF density plot provides us with an intuitive visual representation that helps us understand the rupture mechanisms of AE sources. During the elastic stage of rock, AE events are mainly caused by tensile fractures. In this case, the RA/AF density plot exhibits characteristics of low RA values and high AF values. This is because during the elastic stage, the rock's fractures are relatively small, and AE events primarily reflect stress release and fracture propagation during tension. As the rock enters the plastic stage, AE events are gradually dominated by shear fractures. In this case, the RA/AF density plot shows characteristics of high RA values and low AF values. This is because during the plastic stage, the fractures in the rock become more apparent, and AE events mainly reflect the release of internal shear stress and fracture slip. When the rock approaches failure, AE events typically exhibit mixed ruptures, involving both tension and shear fractures. In this case, the RA/AF density plot displays characteristics of moderate RA values and moderate AF values. This is because near the critical point of failure, the evolution of rock fractures becomes more complex, and AE events reflect the combined effects of multiple rupture mechanisms.

The RA/AF density plot offers a comprehensive characterization of rock fracture types and magnitude, as well as the frequency characteristics of acoustic emission (AE) signals. Accordingly, leveraging the stability assessments of ring number plots and energy maps, this study will further explore the evolution of fractures in granite samples by means of the RA/AF density plot.

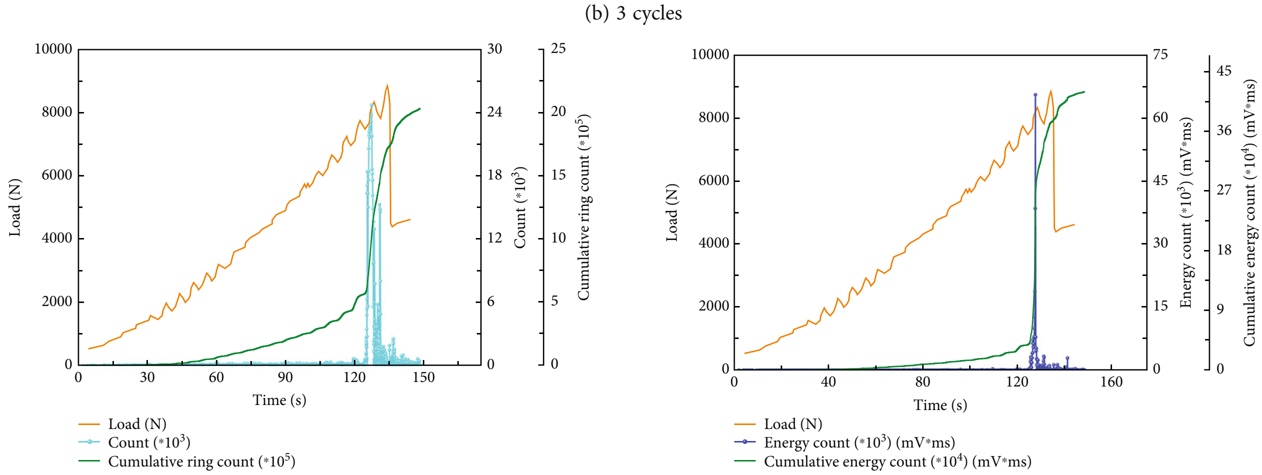
Based on the comprehensive analysis of the density plot shown in Figures 7 and 8, several conclusions can be drawn. For the investigated granite samples, the density plot primarily exhibits a distribution along the RA variation. The dominant peak frequencies are concentrated below 100 kHz, indicating the strong energy generation capability of granite. The main fracture type observed during the experiment is shear-induced, with the majority of fractures being intergranular and transgranular cracks, characterized by rapid propagation. A comparison between the samples subjected to high-temperature liquid nitrogen freeze-thaw treatment and the untreated control group reveals that the treated granite samples exhibit larger fractures, suggesting an increased susceptibility to cracking after high-temperature liquid nitrogen treatment. The obtained results provide important elucidation regarding the failure characteristics of granite samples throughout the course of the experiment, as well as the influence exerted by high-temperature liquid nitrogen treatment on the evolution of their fracture behavior. Additionally, it is noteworthy that an escalating number of freeze-thaw cycles, employing liquid nitrogen, correlates with a notable elevation in the proportion of tension-related points displayed within the distribution plot of RA-AF. This substantial increase serves as a clear indication of the progressive elevation in the shear failure ratio of the granite body as the number of freeze-thaw cycles escalates. Therefore, in order to optimize the efficacy



(a) Untreated

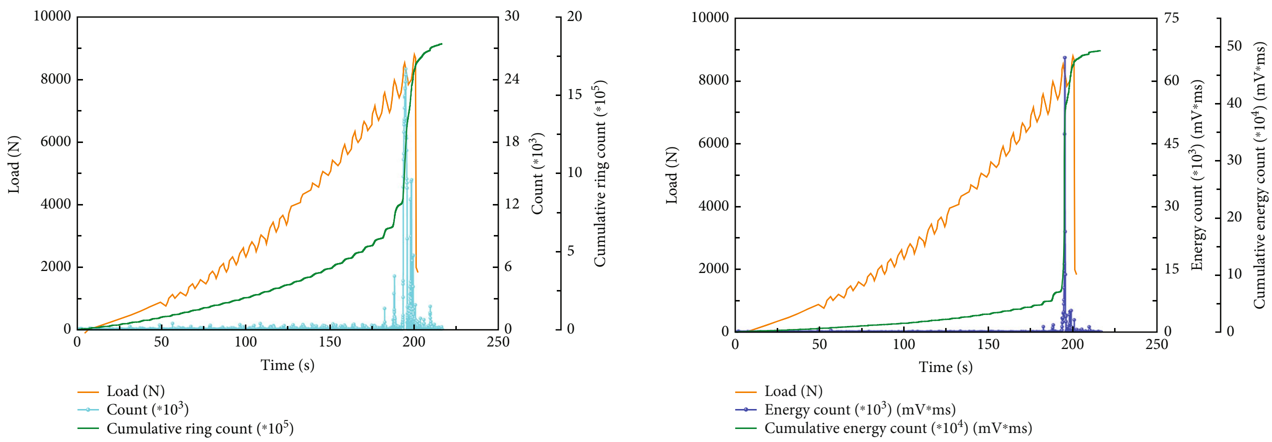


(b) 3 cycles

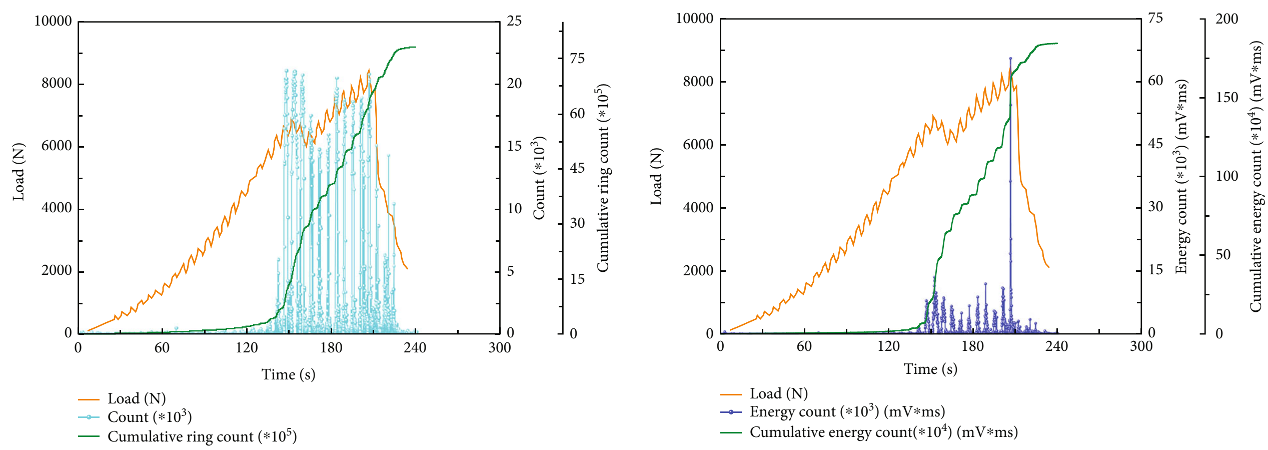


(c) 5 cycles

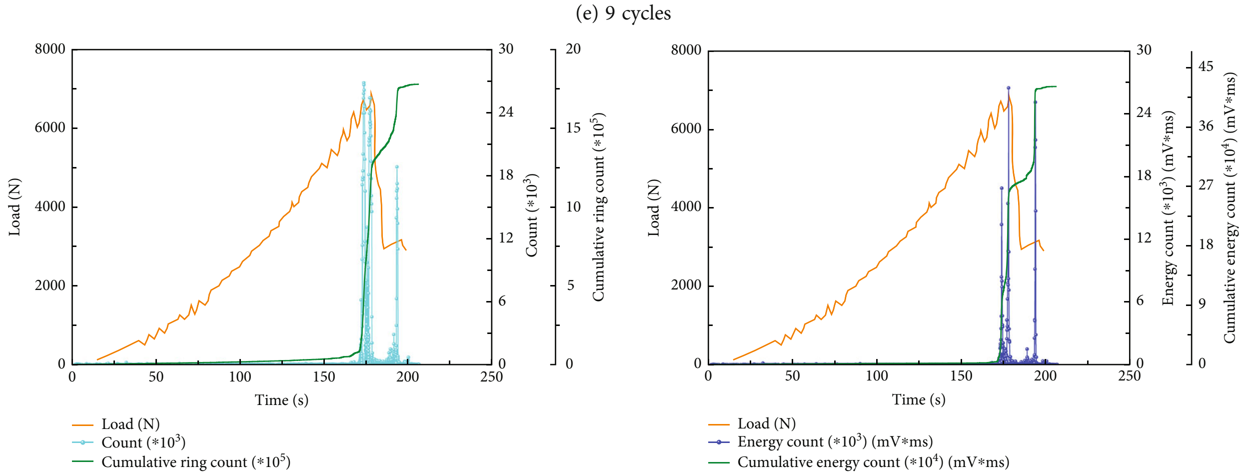
FIGURE 5: Continued.



(d) 7 cycles

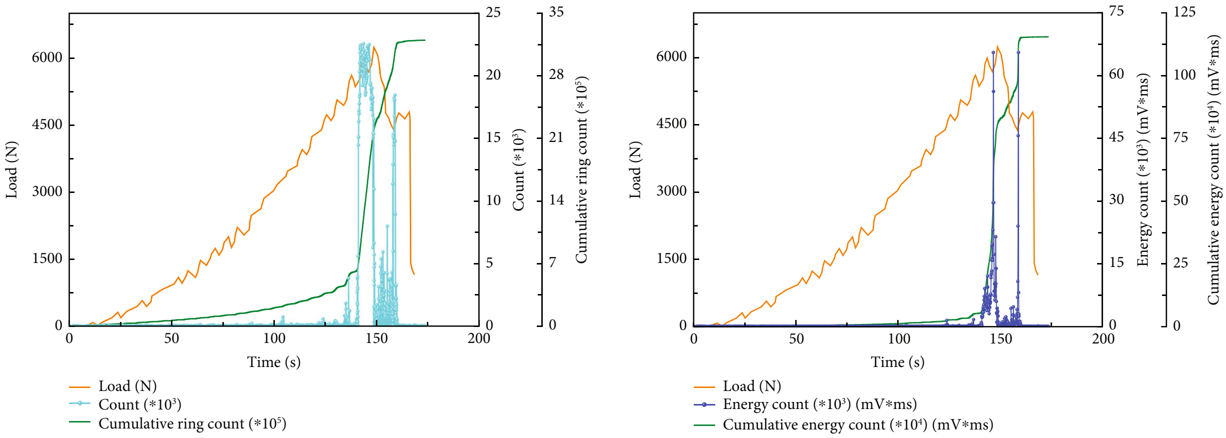


(e) 9 cycles



(f) 15 cycles

FIGURE 5: Continued.



(g) 20 cycles

FIGURE 5: Force-time and AE ringing count-cumulative ringing count and energy-cumulative energy graph with cycle number variation.

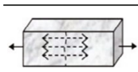
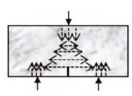
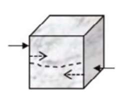
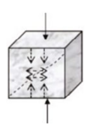
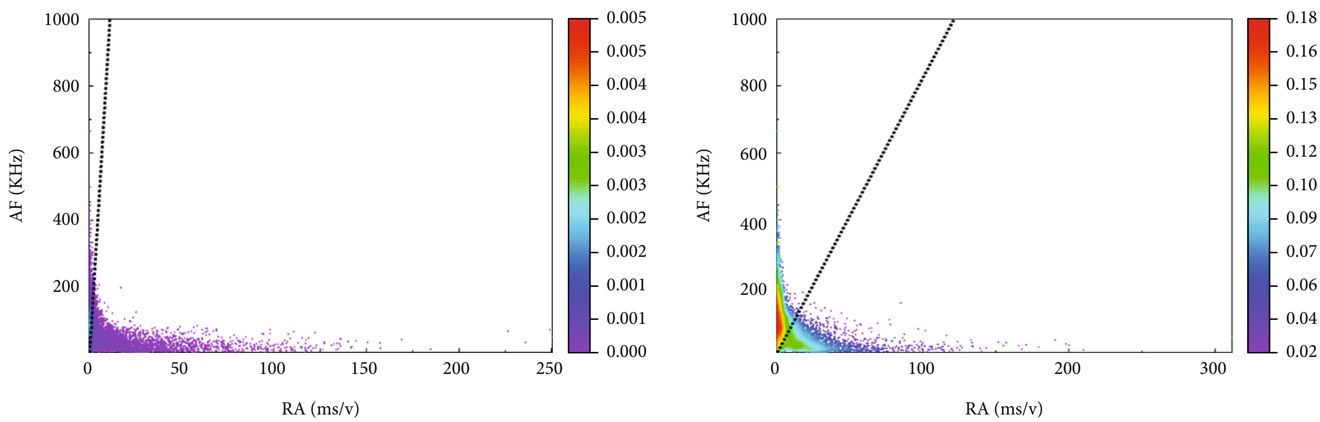
Rupture mode	AF-RA	AE peak frequency	Ability to generate AE energy
 Tensile failure	The distribution was mainly along the direction of AF change	Mainly distributed in 200–400 kHz	Very weak
 Bending failure	The distribution was mainly along the direction of AF change	Mainly distributed in 100–400 kHz	Weak
 Shear failure	The distribution was mainly along the direction of RA change	The main distribution is below 100 kHz	Strong
 Compression failure	The distribution was mainly along the direction of RA change	The main distribution is below 100 kHz	Very strong

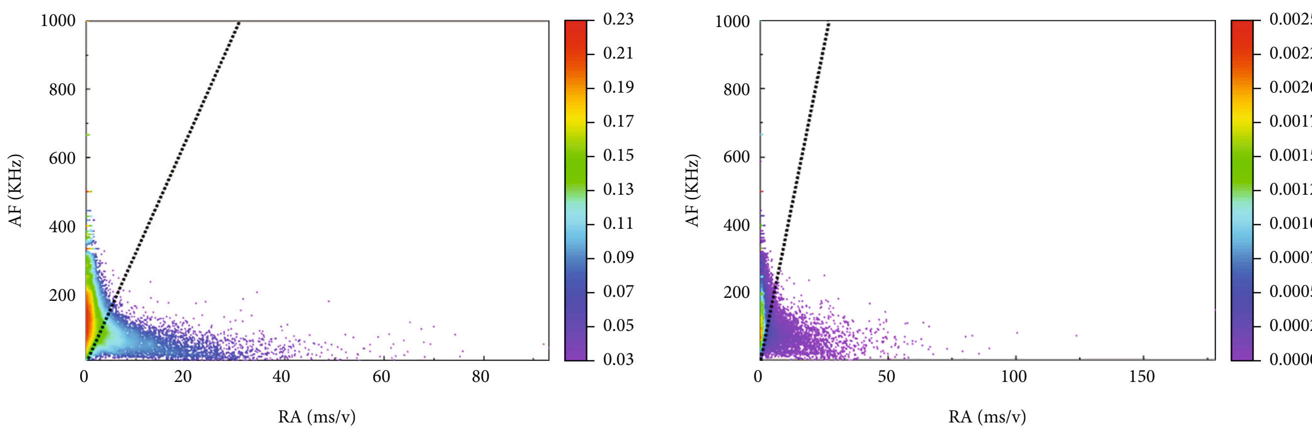
FIGURE 6: Comparison of acoustic emission characteristics under different rock failure modes [38].

of rock fracturing operations utilizing liquid nitrogen, it is advisable to maximize the number of freeze-thaw cycles. This approach ensures enhanced fracturing effectiveness while simultaneously mitigating operational risks. However, it is worth noting that an excessive number of freeze-thaw cycles does not necessarily guarantee superior fracturing outcomes. Thus, in liquid nitrogen fracturing experiments, a reasonable number of freeze-thaw cycles should be employed to avoid unnecessary resource wastage. Additionally, considering the economic benefits and work safety in practical production, it is crucial to develop rational and feasible operational strategies based on specific circumstances. This will help improve work efficiency, ensure work quality, and guarantee occupational safety. Furthermore, it is crucial to diligently address operational nuances while conducting liquid nitrogen fracturing to effectively mitigate the potential for operational errors and safeguard against safety accidents.

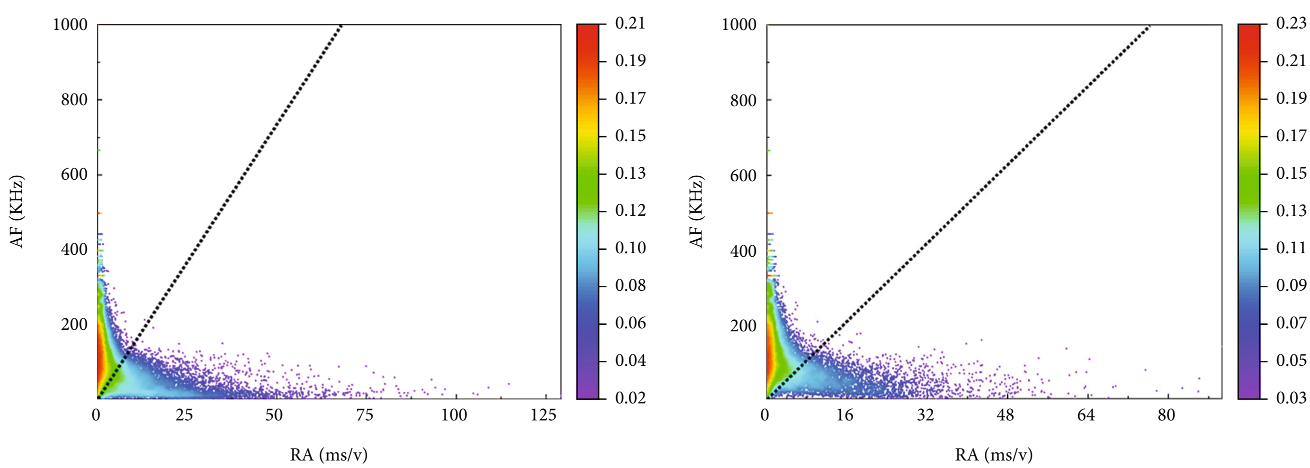
After a comprehensive analysis of the results from the Brazilian split test and acoustic emission, it can be observed that the tensile strength of granite gradually decreases with an increase in the number of cycles of high-temperature heating and liquid nitrogen cooling. The maximum decrease occurs after three cycles, and the tensile strength reaches its lowest point after 20 cycles. Analysis of the acoustic emission results indicates that as the number of cycles increases, the fracture mode of granite transitions to predominantly shear failure. This suggests that the cryogenic shock caused by liquid nitrogen weakens the mechanical properties of the rock, making it more susceptible to fracture failure. Additionally, the thermal stress induced by low-temperature liquid nitrogen causes microfractures to form within the rock, facilitating the propagation of rupture along these microfractures and resulting in shear failure [39, 40].



(a) Untreated

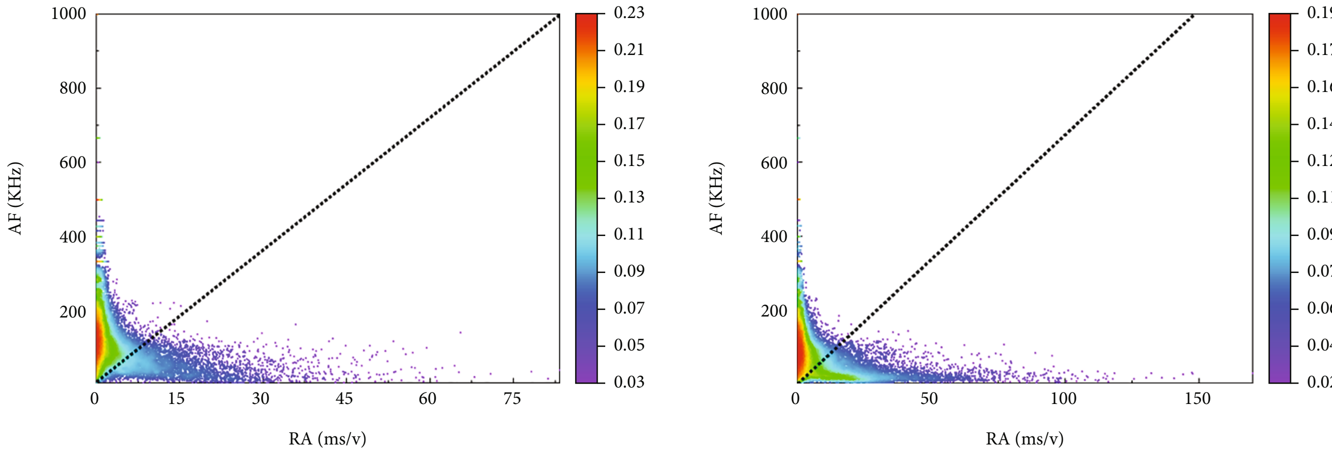


(b) 3 cycles

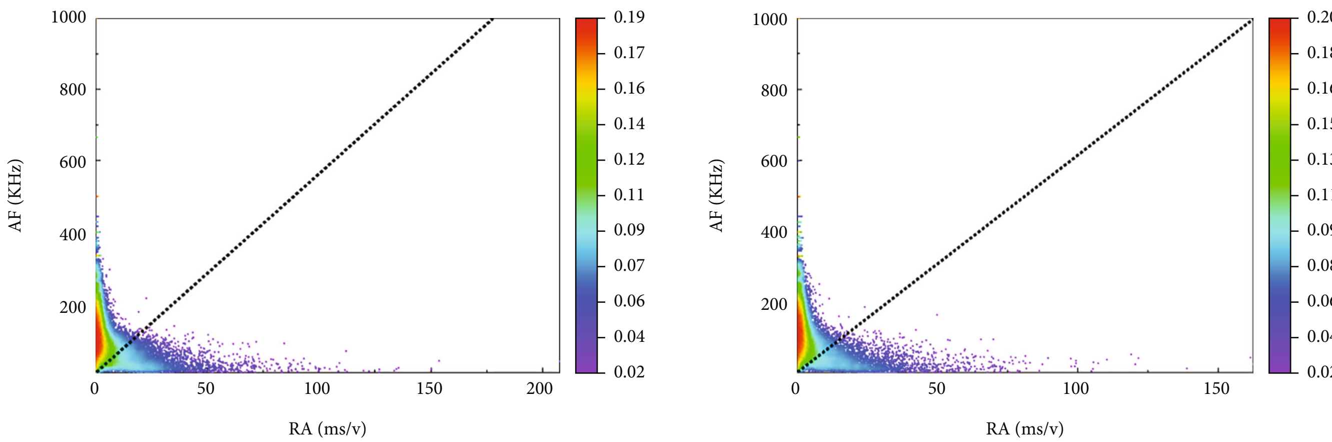


(c) 5 cycles

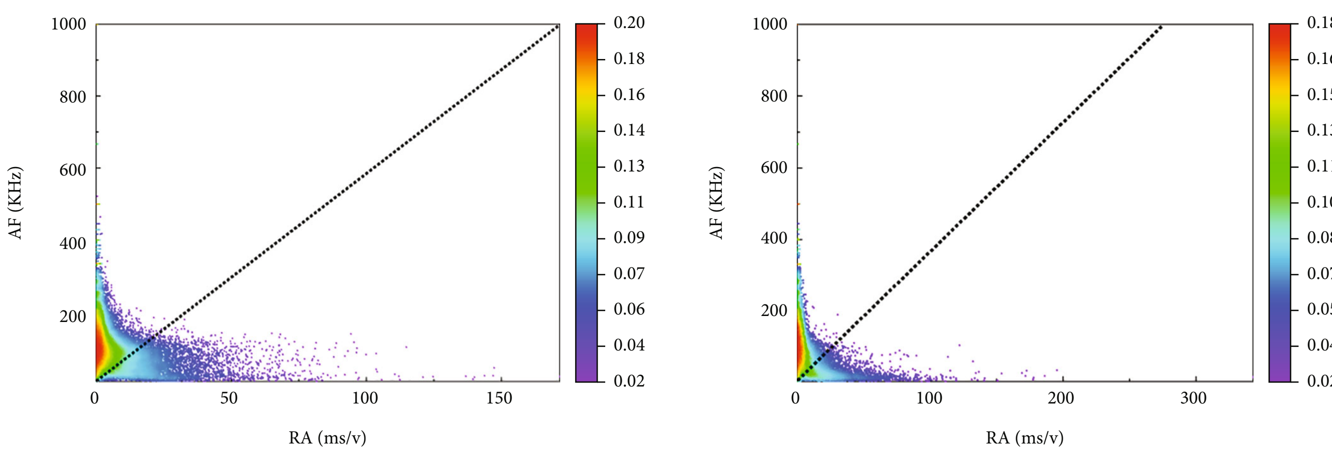
Figure 7: Continued.



(d) 7 cycles

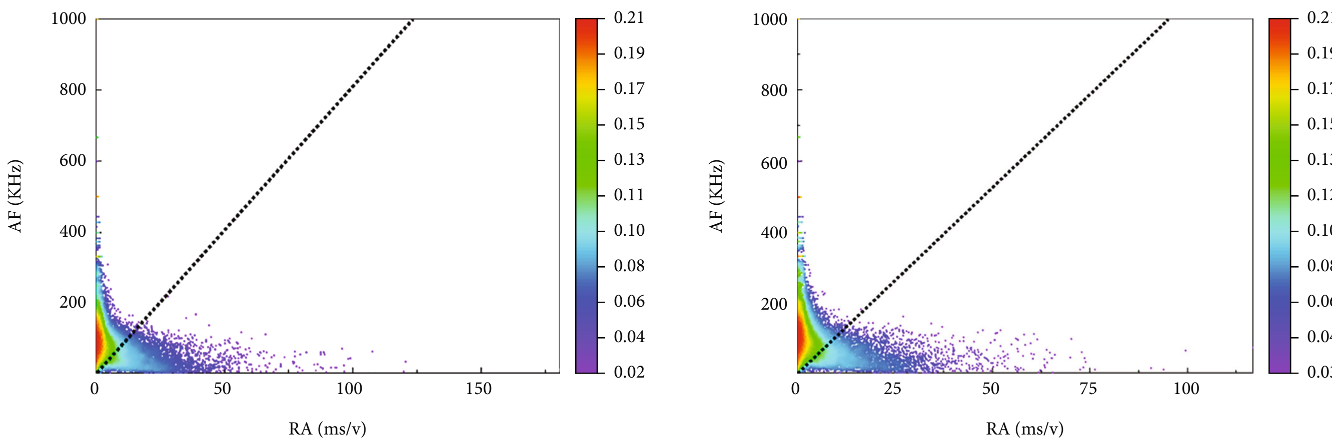


(e) 9 cycles



(f) 15 cycles

Figure 7: Continued.



(g) 20 cycles

Figure 7: Schematic diagram of RA-AF distribution under different cycles of freezing-thawing.

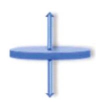
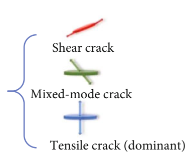
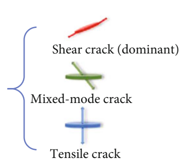
	Type of crack	AF-RA	AE peak frequency	Strength of crack propagation
 Tensile crack	Intergranular crack	The distribution was mainly along the direction of AF change	Mainly distributed in 200–400 kHz	Lower
 Shear crack	Intergranular and transgranular cracks	The distribution was mainly along the direction of RA change	The main distribution is below 100 kHz	Higher
	Intergranular and transgranular cracks	The distribution was mainly along the direction of AF change	Mainly distributed in 100–400 kHz	Medium
	Intergranular and transgranular cracks	The distribution was mainly along the direction of RA change	The main distribution is below 100 kHz	Very high

Figure 8: Comparison of acoustic emission characteristics of different microcracks [38].

4. Conclusion

Liquid nitrogen, as a novel nonaqueous fracturing medium, holds significant potential for geothermal exploitation. This study is aimed at exploring how liquid nitrogen fracturing affects the mechanical properties and internal structure of rock masses. To achieve this, Brazilian splitting tests and acoustic emission experiments were conducted on samples exposed to different numbers of high-temperature liquid nitrogen freeze-thaw cycles. A control group was also included in the study design for comparative analysis. The following conclusions were drawn:

(1) Through the analysis of displacement-load curves and tensile strength graphs, it was observed that with an increasing number of cycles, the peak load of granite consistently decreased under identical temperature conditions. Furthermore, the more freeze-thaw cycles the samples underwent, the more significant the reduction in their tensile strength. These findings suggest that the effectiveness of liquid nitrogen fracturing is markedly influenced by the number of freeze-thaw cycles involving liquid nitrogen

(2) By analyzing the ringing frequency, cumulative ringing frequency graph, energy, and cumulative energy graph, this study reveals an amplified occurrence of fractures and intensified rock damage as a result of high-temperature liquid nitrogen freeze-thaw cycles. Additionally, at specific time points, frequent acoustic

emission activities were observed in the rocks, suggesting heightened internal damage processes during those periods

(3) By closely examining the density plot of RA-AF points, it was discovered that granite samples subjected to high-temperature liquid nitrogen freeze-thaw cycles primarily exhibited shear-induced fractures during the experiment. The majority of these fractures were observed to be intergranular and transgranular cracks

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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