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Practice and Analysis of Dynamic Mechanical Experiments of Low-Temperature Rocks in Blasting Engineering Educations

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Abstract: Aiming at the issues of low restoration accuracy in dynamic mechanical experiments on low-temperature rocks and insufficient theoretical understanding of impact dynamics in traditional Blasting Engineering courses, this study innovatively developed a comprehensive experimental curriculum by integrating a low-temperature environmental chamber, split Hopkinson pressure bar (SHPB), and high-speed digital image correlation (DIC) technology. The curriculum encompasses the entire workflow, including frozen rock sample preparation, impact loading, and theoretical analysis of strength and failure characteristics. Adopting a progressive "theoretical cognition-dynamic observation-mechanism exploration" teaching model, it guides students to understand impact loading experimental principles, analyze temperature/strain rate effects on strength and energy dissipation, and achieve visual observation of transient rock failure processes. Teaching practice demonstrates that this approach effectively integrates abstract impact dynamics theories with quantifiable experimental data, enabling students to clearly comprehend temperature/strain rate influences on rock strength and failure characteristics. It significantly enhances theoretical understanding depth and scientific research innovation capabilities, laying a solid foundation for advanced studies in blasting engineering theories.

Keywords: experimental teaching; blasting engineering; frozen rock; dynamic characteristics; high-speed DIC

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1. Introduction

As a core construction technology in engineering fields such as mining and cold-region tunnel excavation, the drilling and blasting method relies heavily on a profound understanding of the dynamic mechanical characteristics of rocks to ensure scientific rigor and operational safety [1]. With the advancement of resource development in China's cold regions and high-altitude tunnel construction, the dynamic response mechanisms of geotechnical materials under low-temperature conditions have become critical factors influencing blasting efficacy. Blasting Engineering, as a core course in civil engineering, mining engineering, and related disciplines, urgently requires experimental teaching to enhance students' comprehension of rock dynamic behaviors in complex environments [2]. However, traditional pedagogy faces dual challenges: Firstly, the transient nature of blasting loads and the strain rate effects of rocks result in dynamic mechanical properties that differ significantly from static characteristics. Conventional laboratory experiments, constrained by limitations in low-temperature environmental simulation technologies, struggle to authentically replicate the impact-induced failure processes of frozen rocks [3]. Secondly, most undergraduate students possess only foundational knowledge of classical mechanics and lack an intuitive grasp of theories such as wave dynamics and the low-temperature-induced brittle enhancement effect in rocks. This gap leads to an insufficient understanding of core concepts like stress wave propagation and frost-heave damage evolution.

To address this teaching bottleneck, an improved SHPB system integrating cryogenic and impact loading was introduced. By combining a low-temperature environmental chamber with high-strain-rate loading technology, this system can accurately simulate the mechanical failure behavior of frozen rocks under impact loads, enabling students to gain an in-depth understanding of how low temperatures affect rock strength, fragmentation patterns, and energy dissipation mechanisms. In recent years, we have conducted extensive research on the dynamic mechanical properties of frozen and freeze-thaw cycled rocks using the improved SHPB system, accumulating substantial scientific achievements. The low-temperature SHPB experimental course has been incorporated into the practical component of "Blasting Engineering". By designing a comprehensive experimental process encompassing frozen rock sample preparation, dynamic loading, and theoretical analysis, students are guided to quantitatively analyze the effects of strain rate and temperature on the dynamic mechanical response characteristics of rocks. This practice not only addresses the shortcomings of traditional dynamics experiments but also deepens students' theoretical understanding of impact dynamics through the visualization of stress wave propagation and specimen failure processes. It provides effective support for cultivating competencies in blasting design and disaster prevention and control under complex environmental conditions.

Through the low-temperature SHPB experimental course, students are able not only to observe the failure processes of frozen rock under impact loading but also to quantitatively analyze the effects of strain rate and temperature on rock mechanical properties. This hands-on approach strengthens the integration of theory and experiment, providing students with an intuitive understanding of impact dynamics, stress wave propagation, and rock failure mechanisms. Meanwhile, it enhances their competencies in blasting design and disaster prevention under complex environmental conditions. By following a systematic experimental procedure, students' practical skills, analytical abilities, and engineering judgment are effectively developed, laying a solid foundation for operations in cold-region and high-strain-rate engineering contexts.

2. Improved SHPB Experimental System

2.1. SHPB System Composition

The modified SHPB system used in this experiment primarily consists of a loading drive system, velocity measurement system, pressure bar system, cryogenic freezing system, and data acquisition system. The loading drive system includes a high-pressure nitrogen gas cylinder, pressure control valve, high-pressure chamber, and launch chamber. The velocity measurement system comprises a speed measurement circuit, a parallel light source, and a timer. The pressure bar system consists of a punch, incident bar, transmission bar, and energy absorption device. The cryogenic freezing system is composed of a refrigeration unit and a freezing chamber. The data acquisition system includes strain gauges, a bridge box, an SDY2107A ultra-dynamic strain gauge, and a Yokogawa-DL850E oscilloscope recorder, see Figure 1. The punch features a spindle-shaped design, with pressure bars of 50 mm diameter. Both the pressure bars and punch are made of alloy steel, with a density of 7.8×103 kg/m3, elastic modulus of 210 GPa, and longitudinal wave velocity of 5190 m/s.

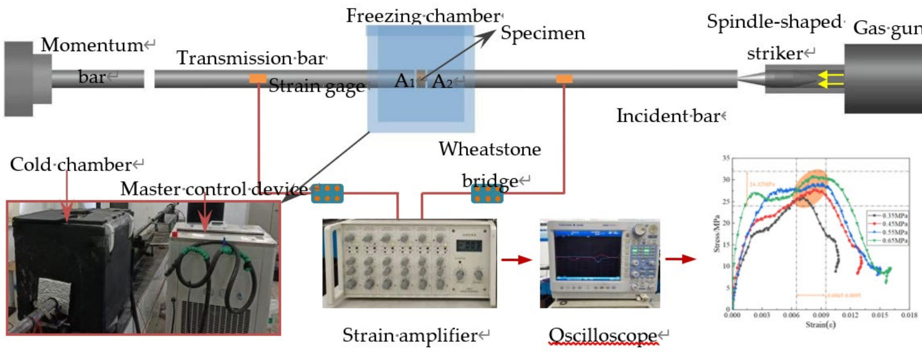

Figure 1. Low-temperature impact loading coupled SHPB system diagram.

During the experiment, the striker driven by high-pressure nitrogen gas impacts the incident bar at a specific velocity, generating a stress pulse within the elastic bar. The waveform of this stress pulse correlates with the striker's geometry and is recorded by the data acquisition system. Due to the differing wave impedances between the rock specimen and the elastic bars, the stress pulse undergoes multiple transmissions and reflections at interfaces A1 and A2. This process continues until the stresses at both ends of the rock specimen essentially equilibrate.

2.2. Principle of SHPB Testing

To obtain the stress-strain characteristics of rock materials, the method is based on two fundamental assumptions: the one-dimensional stress wave assumption and the stress uniformity assumption. The former assumes that during the propagation of stress waves in the incident and transmitted bars, any cross-section of the elastic bars remains planar, and the waveform remains consistent across different positions within the same bar. The latter assumes that the stress and strain fields along the specimen's length direction are uniform, which can be satisfied when the specimen is sufficiently short. Based on these assumptions, the stress data at both ends of the specimen, as well as the strain rate and strain data, can be derived from the strain measurements in the incident and transmitted bars. The commonly used three-wave method equations are [4]:

$$\sigma(t) = \frac{A_b E_b}{2A_s}[\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)] \quad (1)$$

$$\varepsilon(t) = \frac{C_b}{L_s}\int_0^t [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]\, dt \quad (2)$$

$$\dot{\varepsilon}(t) = \frac{C_b}{L_s}[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]dt \quad (3)$$

In the equations, $\sigma(t)$, $\varepsilon(t)$, and $\dot{\varepsilon}(t)$ represent the axial stress, strain, and strain rate of the specimen, respectively; A_b, E_b, and C_b denote the cross-sectional area, elastic modulus, and longitudinal wave velocity of the elastic bars; A_s and L_s are the cross-sectional area and length of the specimen; while $\varepsilon_I(t)$, $\varepsilon_R(t)$, and $\varepsilon_T(t)$ correspond to the incident strain, reflected strain, and transmitted strain, respectively.

2.3. Energy Calculation in SHPB Tests

As can be seen from the composition of the SHPB test loading system and the types of stress waves during the impact process, the main forms of energy during the test include the kinetic energy of the impact head W_B, the energy densities carried by the incident stress wave W_I, reflected stress wave W_R, and transmitted stress wave W_T, as well as the absorbed energy density of the specimen W_A. The specific calculation formulas are given in Equations (4)-(7) [5]:

$$W_I = \frac{c_B A_B}{E_B}\int \sigma_I{}^2(t)dt \quad (4)$$

$$W_R = \frac{c_B A_B}{E_B}\int \sigma_R{}^2(t)dt \quad (5)$$

$$W_T = \frac{c_B A_B}{E_B} \int \sigma_T{}^2(t)dt \quad (6)$$

$$W_A = W_I - W_R - W_T \quad (7)$$

Where $\sigma_I(t)$, $\sigma_R(t)$, and $\sigma_T(t)$ are the incident stress, reflected stress wave, and transmitted stress wave at time t, respectively.

3. Experimental Course Design

3.1. Pre-Experiment Preparation

Prior to the experiment, instructors should polish the specimens in advance to ensure intact and homogeneous surfaces of the rock samples. This test uses relatively homogeneous sandstone with a density of 2350 kg·m^{-3} and a static Poisson's ratio of 0.22. The cylindrical specimens for impact testing have dimensions of Φ50 mm × 50 mm, with end face flatness controlled within 0.02 mm. The observation surface is coated with matte white paint as a base, air-dried, and then dotted with black speckles using a marker pen. The size and density of the speckles should be optimized for DIC software processing, as shown in Figure 2. Specimens must undergo water saturation before testing. Freezing temperatures are set at -10℃, -20℃, and -30℃ for over 48 hours, with room-temperature 20℃ specimens as controls. Four impact air pressure levels are applied: 0.35 MPa, 0.45 MPa, 0.55 MPa, and 0.65 MPa. Considering the SHPB experimental setup and teaching requirements, instructors should divide students into groups of no more than 15 per group and provide DIC-related theoretical materials for advanced review. Detailed explanations will be given during the experimental session.

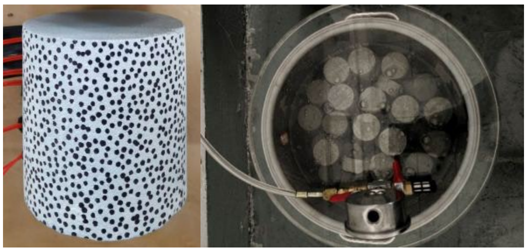

Figure 2. Specimen Speckle Preparation and Water Saturation Treatment.

3.2. Experimental Teaching Content

3.2.1. On-Site Introduction and Demonstration of the Experimental System

(1) Low-temperature SHPB Testing Principles. Introduce the components of the SHPB system using the physical setup. Use display boards to detail the stress wave propagation process during impact and the principles of stress-strain measurement. Explain the high-speed DIC technique for measuring surface deformation of specimens. Guide students in understanding the stress-strain curve calculation process and energy analysis methods for impact-induced fracture. Highlight that the mechanical failure characteristics of water-saturated frozen rocks differ from those at room temperature. Pose the question: "How do the dynamic properties of rocks change after freezing?" to engage students in hypothesis-driven experimentation.

(2) Impact test demonstration. Apply an appropriate amount of Vaseline to both ends of the specimen. Secure the specimen between the impact bar and the incident bar, ensuring alignment at the interfaces between the specimen and the elastic bars. Position the incident bar consistently for each test and set the temperature in the freezing chamber. Move the bullet to a predetermined marked position using a soft plastic rod. Adjust the nitrogen gas pressure to control the bullet's impact velocity. After impact, as illustrated in Figure 3(b), the waveform recorded by the oscillograph demonstrates the data processing procedure using Xviewer software. Emphasize that stress equilibrium validation is a critical criterion for ensuring the reliability of experimental data [6], as shown in Figure 3(b).

Strictly follow safety protocols: students must maintain a safe distance from the pressure bars during testing.

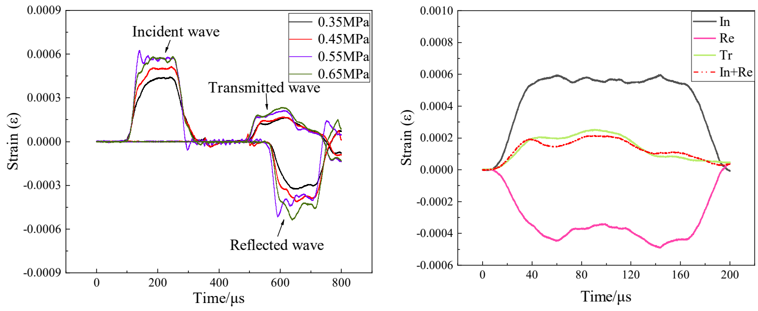

Figure 3. Impact waveform and effectiveness verification. (a) Waveform curves under different impact pressures. (b) Stress equilibrium verification.

(1) Stress-strain characteristics. Figure 4(a) shows the typical shape of a stress-strain curve, which can be broadly divided into three stages: ①Linear elastic stage: The stress varies linearly with strain, exhibiting distinct elastic deformation characteristics of the rock. ②Plastic development stage: The stress growth rate gradually slows with increasing strain, accompanied by strain softening phenomena. ③Post-failure stage: The stress-strain curve begins to decline with further strain, indicating rapid failure of the rock due to loss of bearing capacity. The stress-strain relationships under different impact pressures all demonstrate significant strain rate effects. The peak stress, peak strain, and dynamic elastic modulus generally increase with rising impact pressure, following an approximately linear growth trend.

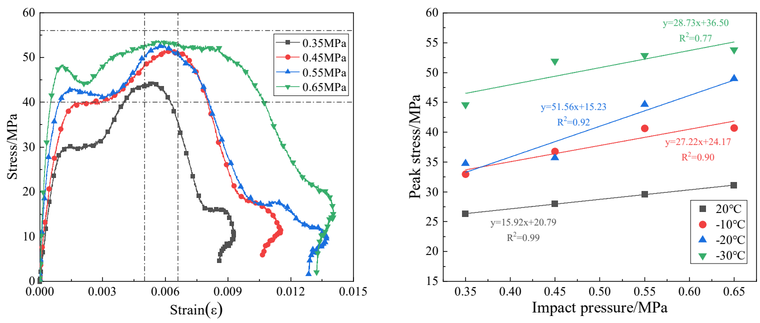

Figure 4. Stress-strain curves and strength variation characteristics of specimens. (a) Stress-strain curves. (b) Peak stress variation.

(2) Energy dissipation characteristics. Table 1 presents the energy density values at 20℃ and -30℃. Statistical analysis reveals that reflected energy accounts for the largest proportion of incident energy, followed by dissipated energy, with transmitted energy being the smallest. The proportion of reflected energy shows a gradually decreasing trend as air pressure increases, particularly under low-temperature conditions where this reduction becomes more pronounced, indicating greater energy absorption by the specimen. Both transmitted and dissipated energy proportions exhibit increasing trends with decreasing temperature, suggesting altered rock wave impedance in cold environments that enhances stress wave transmission capacity. This allows the specimen to absorb more energy for internal damage, especially under higher impact air pressures, where this phenomenon becomes more evident.

Table 1. Calculation results of rock energy density.

Temperature/℃	Impact air pressure/MPa	W_I /J	W_R /J	W_T /J	W_A /J
20	0.35	55.36	33.30	3.40	18.65
	0.45	79.31	51.40	4.45	23.46
	0.55	91.74	63.48	4.19	24.07
	0.65	104.43	73.93	4.81	25.70
-30	0.35	54.27	26.46	7.97	19.84
	0.45	80.59	40.88	11.26	28.45
	0.55	99.95	58.13	10.51	31.31
	0.65	124.35	59.81	16.02	48.51

(3) Surface Deformation and Failure Characteristics. Figure 5 displays the strain contour map characteristics in the y-direction (parallel to the specimen cross-section). During impact loading, the rock initially exhibited significant localized deformation in the upper-central region of the specimen. As the impact load propagated internally, fine localized cracks began to develop on the specimen surface. These cracks progressively widened over time and eventually interconnected, forming several distinct macroscopic fractures. The strain contour map visually demonstrates the evolution of y-directional strain, with the numerical scale range expanding from an initial value of 0.002 to over 0.1. This indicates the formation of pronounced axial cracks and demonstrates typical splitting failure characteristics in the specimen.

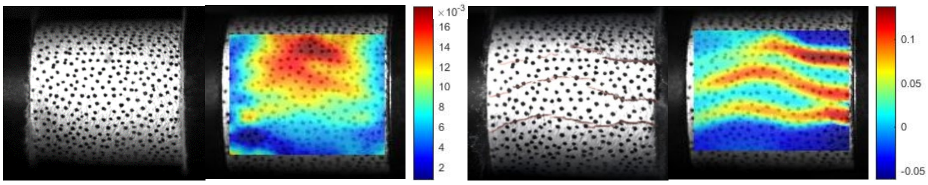

Figure 5. Surface deformation characteristics of the specimen during failure. (a) 20μs. (b) 200μs.

3.2.2. Teaching Methods

This experiment adopts a combined approach of demonstration and analysis, emphasizing the bidirectional integration of theoretical cognition and laboratory testing. First, the instructor visually demonstrates the stress wave propagation process using the physical low-temperature SHPB system. During the impact loading phase, after demonstrating procedures such as specimen installation, air pressure adjustment, and data acquisition, students are arranged in groups to complete bullet resetting, air pressure control, and impact waveform collection to reinforce their grasp of key rock dynamic testing techniques. The data processing phase is primarily instructor-guided, directing students to interpret waveform curves and derive stress-strain curves. By comparing energy dissipation data and brittle failure characteristics of frozen rocks at different temperatures, along with contrasting failure patterns between room-temperature and low-temperature control specimens, students are guided to explore temperature effects on rock wave impedance and energy distribution mechanisms. High-speed photographic images and DIC strain contour maps are introduced to clearly observe transient rock failure processes.

3.2.3. Experimental Discussion and Evaluation

To deepen students' understanding of low-temperature rock dynamic mechanical responses and energy dissipation mechanisms, dedicated discussion and evaluation sessions are implemented. The instructor first guides students to compare stress-strain curves and energy density data between 20℃ and -30℃ specimens, facilitating group discussions on temperature effects on dynamic strength and energy distribution mechanisms. For the observed increase in transmitted energy in low-temperature groups, students are prompted to derive wave velocity variations in frozen rocks using wave impedance formulas. Advanced evaluation questions include: how stress wave propagation paths would change in specimens with pre-existing cracks; quantitative effects of moisture content on dynamic strength degradation; and theoretical explanations of low-temperature brittle failure patterns using dynamic strength enhancement effects. Students are required to utilize academic platforms, e.g., CNKI, Springer, and integrate fracture mechanics with wave dynamics theories for comprehensive analysis. To assess students' mastery, experimental reports must be submitted within one week, focusing on strain rate-temperature coupling effects on rock strength and energy distribution patterns.

3.2.4. Teaching Effectiveness Analysis

In the experimental teaching of low-temperature rock dynamics characteristics, the progressive teaching model of "theoretical cognition-dynamic observation-mechanism exploration" effectively achieved the visualization of complex mechanical concepts. By limiting group sizes, 90% of participants mastered safety protocols and technical essentials of dynamic testing. The integrated application of low-temperature SHPB systems and high-speed DIC technology enabled students to directly observe transient failure processes in frozen rocks, significantly enhancing their understanding of abstract theories such as stress wave propagation and strain rate effects. Experimental reports indicated that 85% of students could accurately summarize the dynamic strength enhancement effect of frozen rocks, while 88% could independently derive the three-wave method energy calculation formula. Recent course assessments revealed a 30% improvement in students' comprehension of blast stress wave propagation and rock frost damage mechanisms. This integrated approach, combining low-temperature rock impact experiments with theoretical courses, has effectively alleviated students' perception of theoretical learning as tedious, substantially enhanced hands-on experimental design capabilities, and strengthened engineering thinking and research literacy.

4. Conclusions

To address the insufficient understanding of dynamic mechanical properties of frozen rocks in traditional "Blasting Engineering" education, this study introduced a low-temperature-loading coupled SHPB experimental system combined with high-speed DIC technology, establishing a practical teaching framework covering frozen sample preparation, dynamic loading, data processing, and mechanism analysis. This well-designed method effectively revealed brittle enhancement effects and energy distribution patterns under temperature-strain rate coupling. Through visual observation of failure processes and quantitative experimental data analysis, it overcame the limitations of traditional teaching in reproducing transient mechanical failure behaviors. Teaching evaluations in recent years demonstrate heightened student engagement, successful achievement of course objectives, and inspired deeper exploration in rock dynamics. This approach provides a replicable paradigm for cultivating professionals in cold region engineering, blasting design, and disaster prevention and control.

Additionally, integrating high-speed DIC technology with the low-temperature SHPB system allows students to observe strain distribution and crack development in real time. This enhances understanding of stress wave propagation and failure mechanisms, strengthens experimental skills, and helps students better connect theory with practical challenges in cold-region blasting projects.

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References

1. P. Kumar, H. Mohammadi, R. Chopra, S. K. Tyagi, and S. K. Pandey, "A newly developed blasting cut in tunnels; application of "combined method" in small to medium-sized tunnels," *Tunnelling and Underground Space Technology*, vol. 142, p. 105426, 2023, doi: 10.1016/j.tust.2023.105426.
2. S. F. LIANG, "Teaching experiment and simulation practice of dynamic mechanical properties of materials in blasting engineering course," Blasting, vol. 40, no. 2, pp. 223-229, 2023.
3. M. N. Luc Leroy, F. W. Marius, and N. François, "Experimental and theoretical investigations of hard rocks at high temperature: applications in civil engineering," *Advances in Civil Engineering*, vol. 2021, no. 1, p. 8893944, 2021, doi: 10.1155/2021/8893944.
4. C. Li, Y. Xu, P. Chen, H. Li, and P. Lou, "Dynamic mechanical properties and fragment fractal characteristics of fractured coal-rock-like combined bodies in split Hopkinson pressure bar tests," *Natural Resources Research*, vol. 29, no. 5, pp. 3179-3195, 2020, doi: 10.1007/s11053-020-09656-w.
5. X. U. Ying, "Dynamic Mechanics Experiment Practice and Analysis Methods of Rock Materials in Blasting Engineering Teaching," BLASTING, vol. 41, no. 3, pp. 248-260, 2024.
6. Y. A. N. G. Rongzhou, and X. U. Ying, "Study on the application of SHPB cyclic impact experimental technology in the teaching of rock impact dynamics," Experimental Technology and Management, vol. 41, no. 5, pp. 195-202, 2024.