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Effect of Operating Parameters on Rock-Breaking and Hole-Forming Characteristics of High-Pressure Abrasive Water Jet

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Abstract

High-pressure abrasive water jet (AWJ) technology offers a promising alternative to traditional mechanical drilling in coal and geotechnical engineering. This study investigates the rock-breaking and hole-forming characteristics of AWJs on typical sandstone (70 MPa) using a custom-built experimental system. Single-factor experiments were conducted to evaluate the effects of abrasive particle size, jet pressure, and standoff distance. Results indicate that hole depth and diameter peak at an optimal abrasive size of 60 mesh. Increasing jet pressure (20–50 MPa) significantly enhances both penetration depth and hole diameter. Conversely, increasing the standoff distance (30–60 mm) enlarges the hole diameter but reduces the penetration depth. These findings provide a reliable basis for optimizing AWJ drilling parameters in engineering applications.

Keywords

High-pressure abrasive water jet; Rock breaking and hole forming; Abrasive particle size; Jet pressure; Standoff distance

1. Introduction

High-pressure abrasive water jet (AWJ) technology has emerged as a highly promising alternative to traditional mechanical drilling in coal and geotechnical engineering. However, its rock-breaking efficiency is heavily influenced by complex variables such as jet parameters and abrasive characteristics. Currently, there is a lack of systematic experimental data to support the optimal matching of operating parameters for different rock strengths[1-4]. Therefore, this study utilizes a custom-built AWJ experimental system to investigate the hole-forming characteristics of typical sandstone. By analyzing the effects of single variables on hole depth and diameter, this research aims to provide a reliable experimental basis for optimizing AWJ drilling parameters and engineering practices in underground coal mines[5-7].

2. Experimental System and Materials

To ensure high pressure, precision, and repeatability for the rock-breaking experiments, a proprietary integrated high-pressure abrasive water jet (AWJ) generation and control platform was developed. The system comprises three core modules:

High-Pressure Power Module: Utilizes a high-pressure water pump as the core power unit to continuously deliver a stable water flow at a maximum pressure of 70 MPa.

Solid-Liquid Mixing Module: Employs a QSM-4.8-ZL water cutting machine (up to 70 MPa). Abrasive concentration is controlled by adjusting a precision bolt, allowing abrasives from a sealed tank to fully mix with high-pressure water in a dynamic chamber, forming a homogeneous slurry.

Motion and Execution Terminal: Features a highly durable tungsten steel nozzle mounted on a servo-driven 3D motion platform. This enables precise spatial positioning and standoff distance control, complemented by a rigid sample fixture to ensure experimental accuracy and safety.

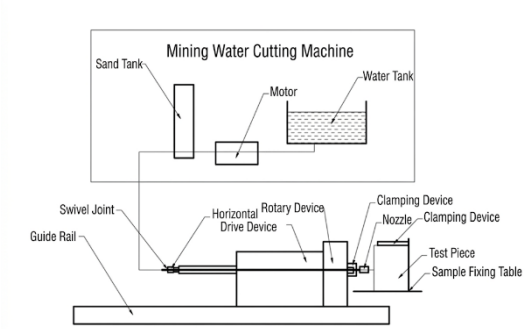


Figure 1. Schematic diagram of the high-pressure abrasive jet generation and control platform

3. Study on the Law of Rock Breaking by Fixed Single Jet

3.1. Abrasive Particle Size Experiment

Abrasive water jet (AWJ) technology improves upon traditional water jets by adding hard abrasive particles, which significantly enhances the machining mechanism and performance.

To ensure reliability, experiments were conducted on sandstone with a compressive strength of 70 MPa. Unless otherwise specified, the standard "fixed-jet" operating conditions are defined as follows:Jet pressure: 30 MPa ;Standoff distance: 30 mm ;Impact time: 5 s ;Nozzle setup: Fixed (no rotation) with a 1.2 mm orifice.



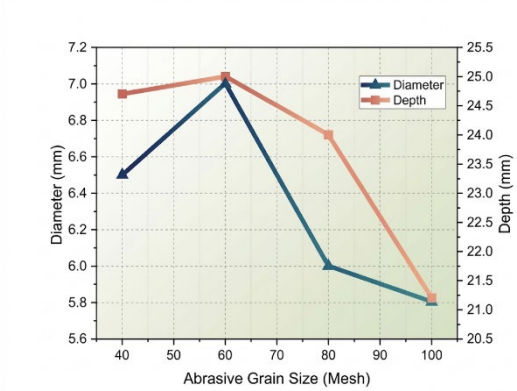


Figure 2. Single-factor experiment on jet abrasive particle size

Under these standard conditions, single-factor experiments were conducted to evaluate the effect of various abrasive particle sizes (Figure 2 Single-factor experiment on jet abrasive particle size).

Results and Analysis: The data reveals a non-monotonic relationship between abrasive size and rock-breaking performance. As the particle size decreases from 40 mesh to 100 mesh, both hole depth and diameter initially increase and then decrease, peaking at 60 mesh.

40 mesh (Coarser): Particles possess high individual momentum for deep penetration, but their lower quantity in the jet limits uniform cutting and hole expansion efficiency.

60 mesh (Optimal): Achieves the best dynamic balance. The particles retain sufficient impact kinetic energy while their increased quantity per unit volume maximizes the synergy between impact fragmentation and continuous micro-cutting, resulting in the maximum hole depth and diameter.

3.2. Jet Pressure Parameter Experiment

The core of the jet system relies on converting pressure energy into kinetic energy. Assuming the fluid is incompressible and ignoring potential energy and pipeline losses, this energy conversion from the high-pressure state to the nozzle exit can be described by the simplified Bernoulli equation:

$$P = \frac{1}{2}\rho v^2$$

where P is the pressure (Pa), ρ is the density of water (approximately 1000 kg/m^3), and v is the exit velocity (m/s). This fundamental law indicates that the jet velocity is entirely determined by the system's working pressure, which dictates the theoretical upper limit of the jet's impact capability. Single-factor experiments were conducted under previously stated conditions to evaluate this (Figure 3 Single-factor experiment on jet pressure).

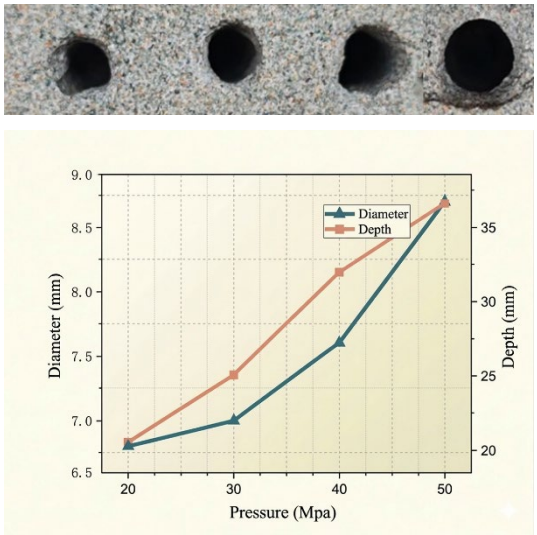


Figure 3. Single-factor experiment on jet pressure

Results and Analysis:The experimental data clearly reveals the decisive impact of jet pressure on rock-breaking performance.

Overall Enhancement: As the pressure escalates from 20 MPa to 50 MPa, the penetration depth significantly increases from 20.5 mm to 36.5 mm (a 78% increase), while the hole diameter expands from 5.9 mm to 7.6 mm. Pressure acts as the core dynamic parameter driving both longitudinal and lateral penetration.

Low-Pressure Phase (20–30 MPa): The growth in depth is relatively gradual (from 20.5 mm to 24.5 mm). During this stage, energy is primarily expended on overcoming the rock's surface strength and initiating initial cracks.High-Yield Phase (30–40 MPa and above): The slope of depth growth steepens noticeably. The jet possesses ample kinetic energy to not only stably propagate cracks but also effectively flush out rock cuttings, entering a highly efficient "high-yield" rock-breaking zone.

3.3. Jet Standoff Distance Experiment

Standoff distance (the distance from the nozzle exit to the rock surface) is a core spatial parameter that regulates the kinetic energy density and impact area of the jet. To investigate its effect, single-factor experiments were conducted under the standard conditions outlined previously (Figure 4 Single-factor experiment on jet standoff distance).



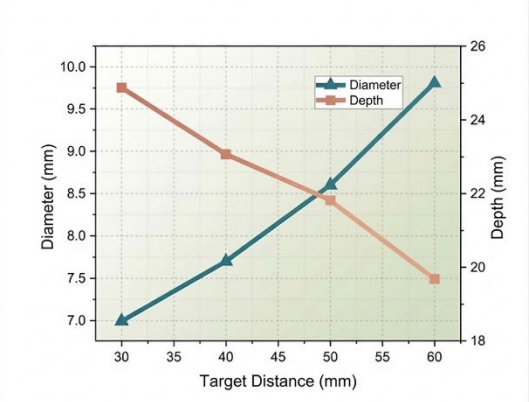


Figure 4. Single-factor experiment on jet standoff distance

Results and Analysis:Trade-off Relationship: The experimental data reveals a clear trade-off between hole diameter and depth as the standoff distance changes.

Diameter Expansion vs. Depth Reduction: Increasing the standoff distance from 30 mm to 60 mm significantly enlarges the hole diameter from 7.0 mm to 9.8 mm (an increase of over 40%). Simultaneously, the penetration depth systematically decreases from 7.9 mm to 5.6 mm.

Energy Distribution: This "diameter increase, depth decrease" trend demonstrates how standoff distance fundamentally controls the jet's energy distribution state.

Operational Conclusion: Standoff distance is not a fixed equipment parameter; rather, it is a key operational variable that should be actively adjusted according to real-time working conditions and process requirements.

4. Conclusion

Based on single-factor experiments of AWJ rock breaking on sandstone, the main conclusions are:

Optimal Abrasive Size: Rock-breaking performance does not scale linearly with particle size. Both hole depth and diameter peak at 60 mesh, achieving an optimal balance between particle kinetic energy and cutting quantity.

Pressure as the Decisive Factor: Jet pressure dictates the breaking capacity. Elevating the pressure from 20 MPa to 50 MPa increases hole depth by 78% and significantly enlarges the diameter, with a highly efficient rock-breaking zone emerging above 30–40 MPa.

Standoff Distance Trade-off: Increasing the standoff distance from 30 mm to 60 mm expands the hole diameter by over 40% but systematically decreases the penetration depth. Thus, standoff distance should be treated as an actively adjustable variable based on specific process requirements.

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