

Article

Effects of Static Pressure on Failure Modes and Degree of Fracturing of Sandstone Subjected to Inter-Hole Pulsed High-Voltage Discharge

Jianyu Peng, Hongpeng Xu, Fengpeng Zhang *, Haonan Wang and Jiaqiang Li

Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang 110819, China

* Correspondence: zhangfengpeng@mail.neu.edu.cn

Abstract: This research aims to explore the fracturing behaviors of sandstone subjected to pulsed high-voltage discharge (PHVD) under different static pressures. An experimental method of rock fracturing induced by inter-hole PHVD was proposed. The static pressure was applied to the specimens, then the proposed method was applied to induce electrical breakdown testing under static loading. The microscopic fracture morphology of the sandstone was observed. The influences of the direction and level of static pressure on the crack length and fractal dimension of sandstone under the effect of PHVD were discussed. The results indicated that in the absence of static pressure, there are a discharge channel and multiple radial cracks in the sandstone after electric breakdown. The microscopic analysis implies that rock failure in the zone around the discharge channel is mainly influenced by the high temperature; while radial cracks are induced by shock waves. When static pressure is vertical to the discharge channel, tensile and compressive stresses concentrate in different parts around the discharge channel, which can remarkably alter the distribution zone and propagation path of cracks. In addition, the fractal dimension and total length of cracks first decrease, then increase with increasing static pressure. When static pressure is parallel to the discharge channel, the distribution characteristics and propagation direction of cracks are unchanged; however, under this loading mode, circularly distributed hoop tensile strains are generated at the zone around the discharge channel, which enables the fractal dimension and crack length increase with increasing static pressure.

Keywords: static stress; high-voltage pulse; rock fracture; fractal dimension; crack length



Citation: Peng, J.; Xu, H.; Zhang, F.; Wang, H.; Li, J. Effects of Static Pressure on Failure Modes and Degree of Fracturing of Sandstone Subjected to Inter-Hole Pulsed High-Voltage Discharge. *Minerals* **2023**, *13*, 337. <https://doi.org/10.3390/min13030337>

Academic Editor: Gianvito Scaringi

Received: 12 January 2023

Revised: 25 February 2023

Accepted: 27 February 2023

Published: 27 February 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

To overcome the shortfalls (such as those arising from production of dust, noise, and vibration) of conventional explosive blasting and mechanical rock-breaking methods, new rock-breaking techniques including laser, liquid CO₂, microwave, and high-voltage pulse methods have been developed. Among these techniques, high-voltage pulses have aroused increasing interest due to advantages including being able to control the input of energy, selective treatment of ores, their high efficiency, and eco-friendly nature [1–6]. Rock engineering projects including mining, drilling, and tunnel construction have been advancing to greater depths [7–9]. In contrast to shallow rock engineering, high geostress is seen as a prominent feature of deep rock engineering. The high geostress plays a large role in affecting rock fracture in deep rock engineering projects, which should be considered in engineering design [10–13]. Therefore, it is necessary, and worthwhile, to study the influence of static pressure on fracturing behaviors of rock under high-voltage pulses.

Fracture of rock or rock-like materials under the effect of the pulsed high-voltage discharge (PHVD) has been the primary scholarly concern in attempts to provide a theoretical basis for recognizing rock-breaking mechanisms and the design of discharge parameters [14–19]. For example, Cho et al. [20] explored the relationships of tensile strength and

compressive strength with electric breakdown strength of rock specimens. Furthermore, they also simulated the dynamic fracturing process of rock. Kencanawati and Shigeishi [21] adopted the acoustic emission technique to conduct positioning research of microcrack developed in concrete under the effect of pulse discharge. Bao et al. [22] performed fracture testing of coal specimens under the effect of PHVD with the same water pressure, and quantitatively estimated the influence of discharge voltage on fracturing effect. Duan et al. [23] investigated the influences of the morphology of electrodes on the crack depth and volume of red sandstone by conducting high-voltage pulse drilling tests in water. It is worth noting that the aforementioned PHVD-induced rock breaking tests used water as the insulating medium.

Research related to the influence of static pressure on the PHVD-induced rock breakage has been gradually attracting more research attention; for instance, Sun et al. [24] demonstrated the changes in the crack height and morphology of red sandstone subjected to PHVD in water with varying static pressures. Li et al. [25] established a two-dimensional numerical calculation model to ascertain the fracturing status of granite under different confined pressures under the impact of high-voltage pulse. The experimental results of Ezzat et al. [26] indicated that the volume of fractured rock when drilling boreholes using high-voltage pulse reduces at first and then increases with changing pressure on the rock. Existing studies help to clarify the effect of static pressure on PHVD-induced rock breaking in liquid conditions; however, the effects of static pressure on the failure modes, complexity, and degree of fracturing of rock under the electric breakdown in air environment have rarely been studied.

In this research, an experimental method of PHVD-induced rock fracture in air environment was designed. A static load was first applied on a sandstone specimen measuring 200 mm × 200 mm × 150 mm by using a loading device. Then, based on the designed experimental method, the electric breakdown experiment on the loaded specimen was conducted with a PHVD device. The influences of static pressure on failure modes inside the sandstone were discussed. In addition, based on fractal dimension and crack length, the effects of static pressure on fracture complexity and fracture degree were studied.

2. Experimental Program

2.1. Experimental Equipment

In this study, we focus on the effect of static pressure on the fracturing behaviors of sandstone under PHVD. Therefore, a static pressure device is required to apply a static load on the specimen, and a PHVD apparatus is required to carry out electrical breakdown tests on the loaded specimens.

The experimental system consists of a static pressure device, a PHVD device and an oscillograph, as shown in Figure 1. The static pressure loading device has two modes of operation (displacement control and force control), with a maximum load of 5000 kN (Figure 1a). Herein, we adopted the displacement control mode to apply static load to the specimens. The PHVD device is mainly composed of a bipolar power supply, an energy storage module consisting of two 2-μF capacitors with rated energy storage of 7.2 kJ, and a high-voltage pulse trigger (Figure 1b). Figure 2 shows the workflow of the PHVD device. The bipolar power supply converts alternating current (220 V, 50 Hz) into direct current, while charging the energy storage module. The high-voltage pulse trigger can send pulse signals to trigger the three-electrode gas switch, releasing the energy in the energy storage module to consequently realize rock fracturing. The oscilloscope was used to record the current changes acquired by the Rogowski coil during the discharge (Figure 1c).

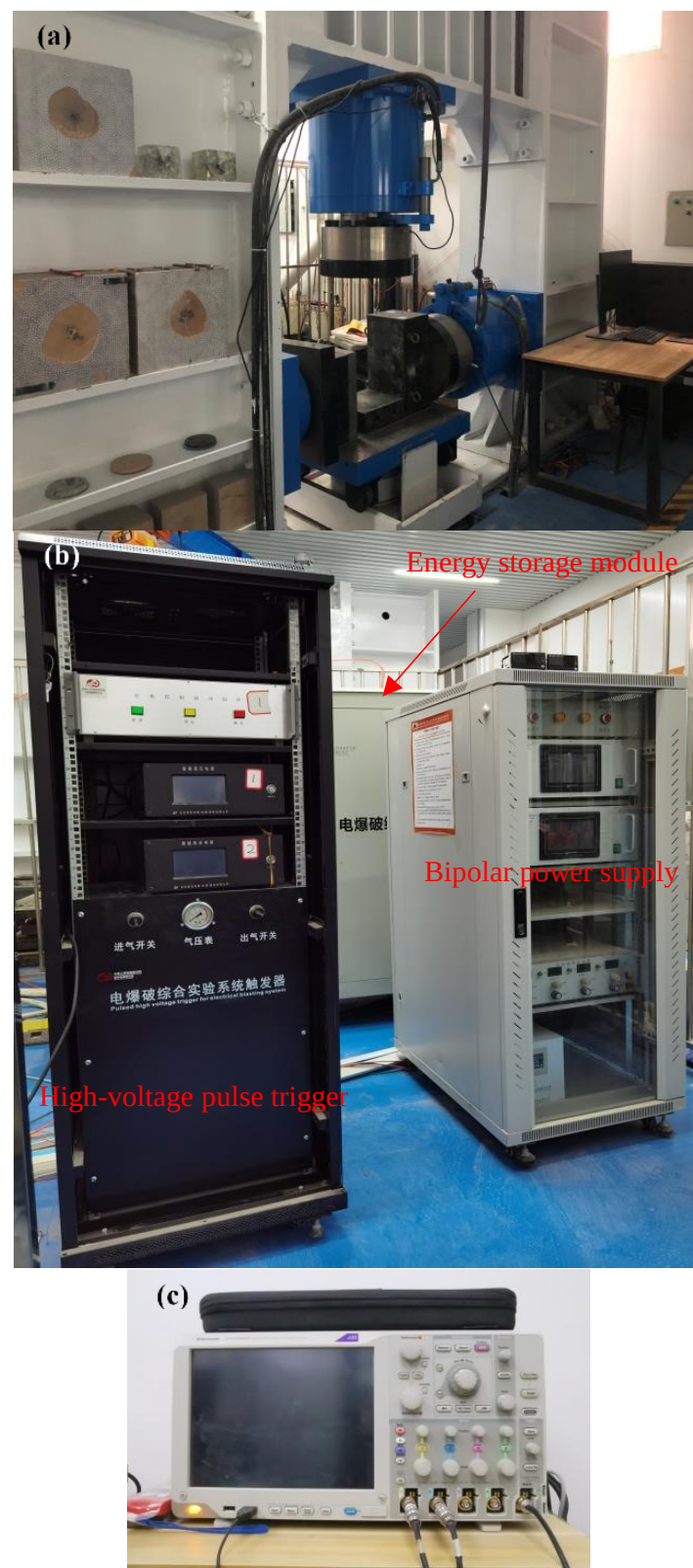


Figure 1. The experimental system: (a) The static pressure loading device; (b) The PHVD device; (c) The oscilloscope.

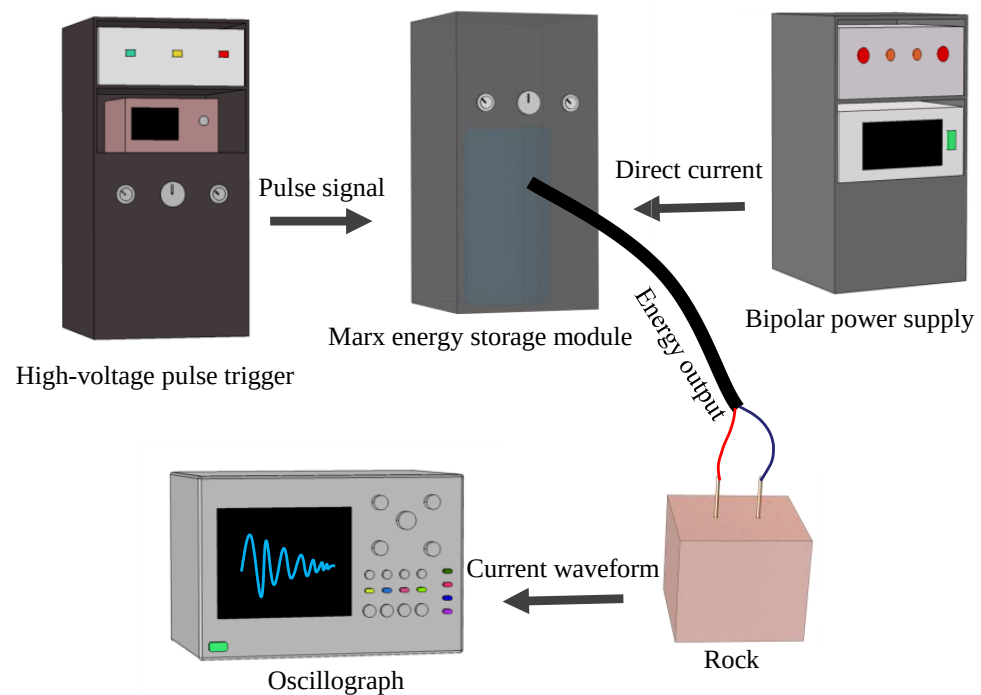


Figure 2. Workflow of the PHVD device.

2.2. Specimens and Electrodes

Specimens were obtained from a large intact sandstone block with the following physico-mechanical parameters: a density of 2108 kg/m^3 , compressive strength of 92.7 MPa , tensile strength of 6.11 MPa , elastic modulus of 20.5 GPa , Poisson's ratio of 0.28 , and a longitudinal wave velocity of 2253 m/s . Specimens measuring $200 \text{ mm} \times 200 \text{ mm} \times 150 \text{ mm}$ were cut therefrom, and their end faces bearing the applied static pressure were polished to have a degree of parallelism below 0.05 mm (Figure 3a). Electrodes used were two copper rods with tips, having diameters of 4 mm and lengths of 130 mm (Figure 3b).

Two boreholes with diameters of 6 mm and depths of 125 mm were opened for installing positive and negative electrodes. The distance between the axes of the two boreholes was 36 mm . The tips of the two electrodes were arranged opposite each other and in close contact with the borehole walls. The distance between the two tips was 30 mm , and the tips were 80 mm from the borehole orifice (Figure 3c). Previous researches indicated that when the pulse rise time was less than 500 ns , the breakdown field strength is: liquids (oil, water, etc.) $>$ solids $>$ air [4,27]. The breakdown field strength of air is lower compared with rock media, i.e., at a given distance, air breakdown occurs earlier than that of rock; while liquids such as oil and water are the most difficult to be broken down. Hence, many PHVD-induced rock fracturing tests were conducted in liquid environment [14,16,22,23]. In this research, the distance between the two electrodes' tips, from air and rock interface, was far larger than the linear distance between them (Figure 3c). The electric impedance in the case of breakdown by surface discharge was enhanced by using an inter-hole discharge method. Additionally, polyimide tape was used to insulate each electrode, with only their tips exposed to the air. In other words, the specimen and the electrodes' tips were exposed to air during the experiment, not in the liquid. Therefore, a discharge channel is more likely to be formed inside rock, avoiding surface discharge.

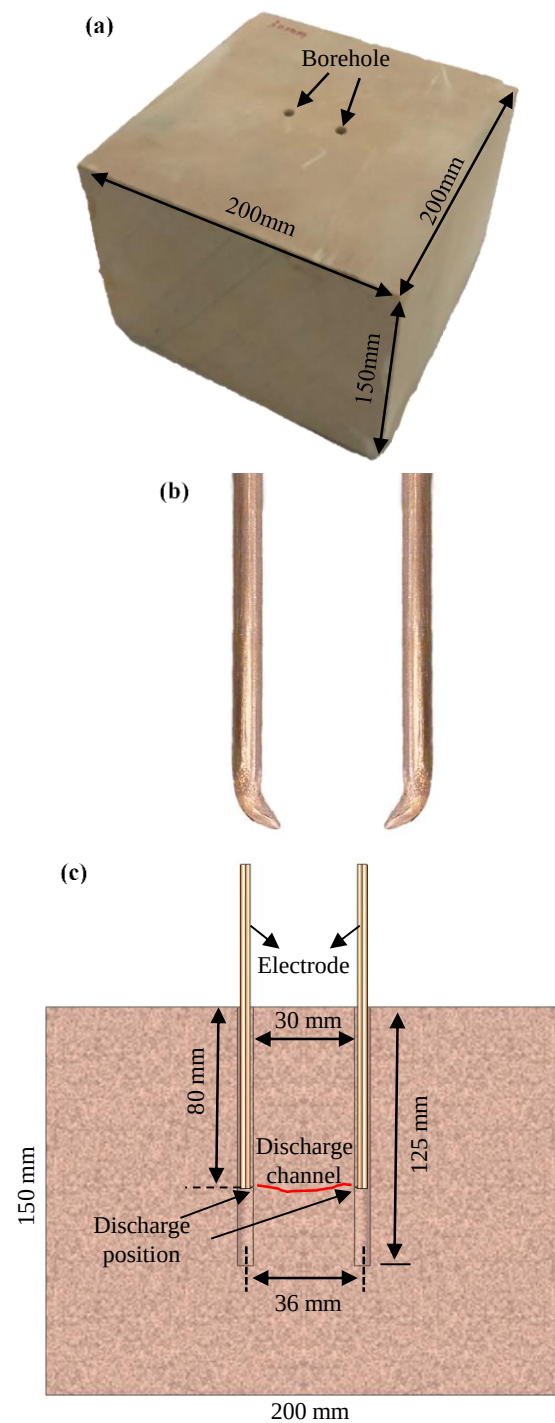


Figure 3. The specimen and electrodes: (a) Sandstone specimen; (b) Electrodes; (c) The layout of electrodes in the specimen.

2.3. Experimental Scheme

It should be noted that there is no connection between the static pressure device and the PHVD device. However, the two devices were used in a certain order during the experiment. Before the experiment, two electrodes were put into the boreholes, which were connected to the positive and negative electrodes of the PHVD system. In the testing process, the static pressure loading device was first used to apply static load on the specimens according to need. Then, the PHVD system was turned on to allow the tips of the two electrodes to

form a discharge channel in the specimen, which releases the energy stored, thus fracturing the rock.

For the sake of subsequent analysis, a coordinate system was established (Figure 4). The x -axis extends along the borehole axis and points to the direction of the borehole orifice. The normal to a plane determined by the axes of two boreholes is the y -axis. The discharge channel forms along the z -axis.

Two groups of electric breakdown tests on sandstone under static loading were designed. The static pressure P in each group was applied at each of 5, 10, 15, and 20 MPa; the discharge voltage was set to a constant value (45 kV). As displayed in Figure 4a, the static pressure in the first group (Group I) is applied normal to the discharge channel (along the y -axis). The specimens corresponding to four static pressures are numbered S1-1 ($P = 5$ MPa), S1-2 ($P = 10$ MPa), S1-3 ($P = 15$ MPa), and S1-4 ($P = 20$ MPa). As illustrated in Figure 4b, static pressure in the second group (Group II) is applied parallel to the discharge channel (along the z -axis). The specimens corresponding to four static pressures are numbered S2-1 ($P = 5$ MPa), S2-2 ($P = 10$ MPa), S2-3 ($P = 15$ MPa), and S2-4 ($P = 20$ MPa). Furthermore, a PHVD test when there is no static pressure ($P = 0$ MPa) was conducted, with the specimen numbered S0.

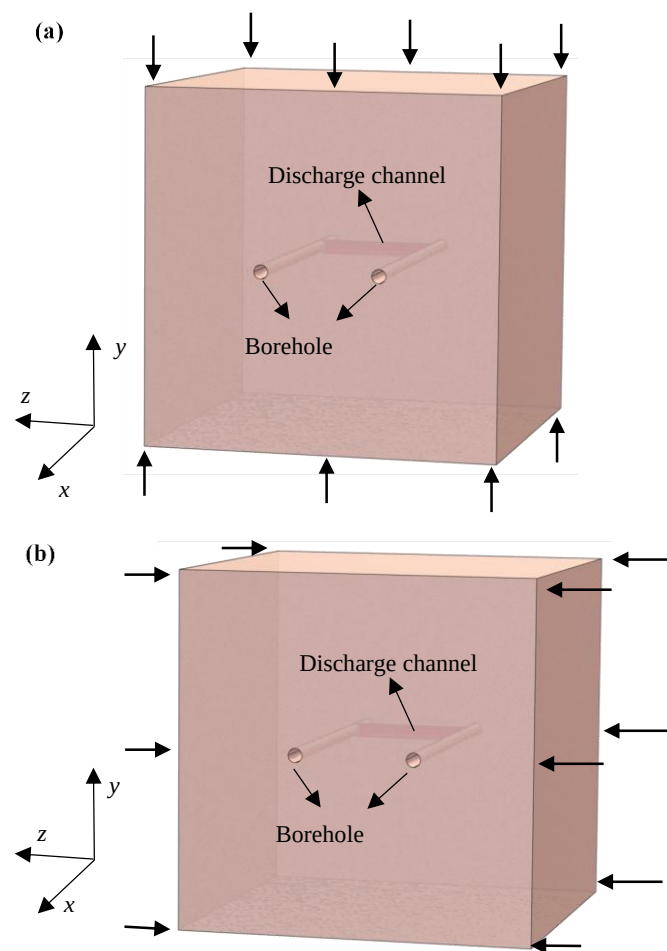


Figure 4. The coordinate system and static pressure loading mode: (a) Loading along the y -direction; (b) Loading along the z -direction.

3. Rock Fracture Mechanism under PHVD

The process of using PHVD to induce rock fracture can be described as: under the effect of high voltage, a discharge leader forms at the zone around the anode tip; afterwards, the discharge trunk can rapidly reach the cathode, a conducted discharge channel forms inside rock, which is a plasma channel [4,14,15]. During this process, rock is converted

into an electric conductor from a dielectric medium. The electrical energy stored in the high-voltage pulse device can be released rapidly to the channel, explosive expansion then occurs to the channel, consequently, leading to the fracturing of the rock.

Figure 5 displays a typical current waveform measured using the Rogowski coil. A steep current surge appears in the current waveform at the moment when the electric switch is turned on. Then, the current increases from 0 to a peak value of 28.8 kA in the form of sine waves, and attenuates in the form of damped oscillation. It is noteworthy that there is no interval between current surge and the starting point of the sine wave. This implies that the sandstone is instantaneously broken down, meanwhile, a discharge channel is formed inside the specimen, indicating no breakdown delay occurs in this process.

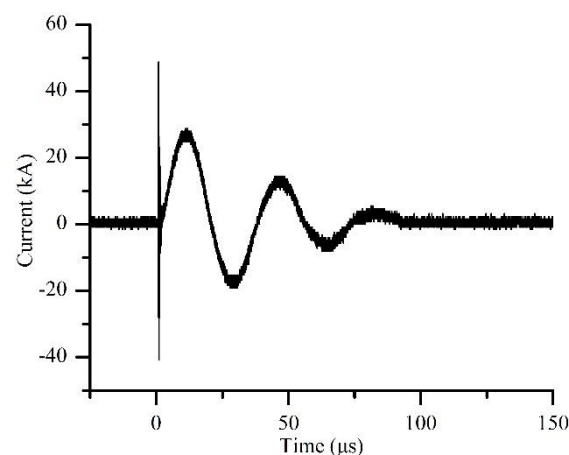


Figure 5. Current waveform of rock fracturing by PHVD.

4. Macro Crack Acquisition and Micro Analysis

4.1. The Cutting and Fluorescent Staining Method

As the sandstone is opaque, the fracturing state of the sandstone subjected to PHVD is difficult to observe. The cutting and fluorescent staining (CFS) method was used to obtain the macroscopic cracks in rock by referring to the method in the literature [28,29]. Thereafter, a MATLAB image recognition program was adopted to process fluorescent stained pictures (Figures 6 and 7). This process comprises four steps: (1) cutting the specimens along the direction of the vertical discharge channel to get the raw image at the center of the specimen; (2) staining with fluorescent powder on the crack zone and then conducting strong light illumination on the crack zone to get the image after staining treatment; (3) by means of implementing steps such as denoising and enhancement, the MATLAB program is used to obtain the binary image of the cracks; (4) calculating the crack length, fractal dimension, etc., to quantify the fracturing state of the specimen.

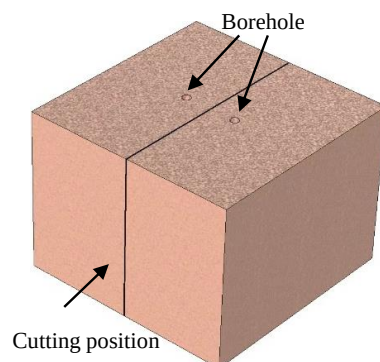


Figure 6. Specimen cutting diagram.

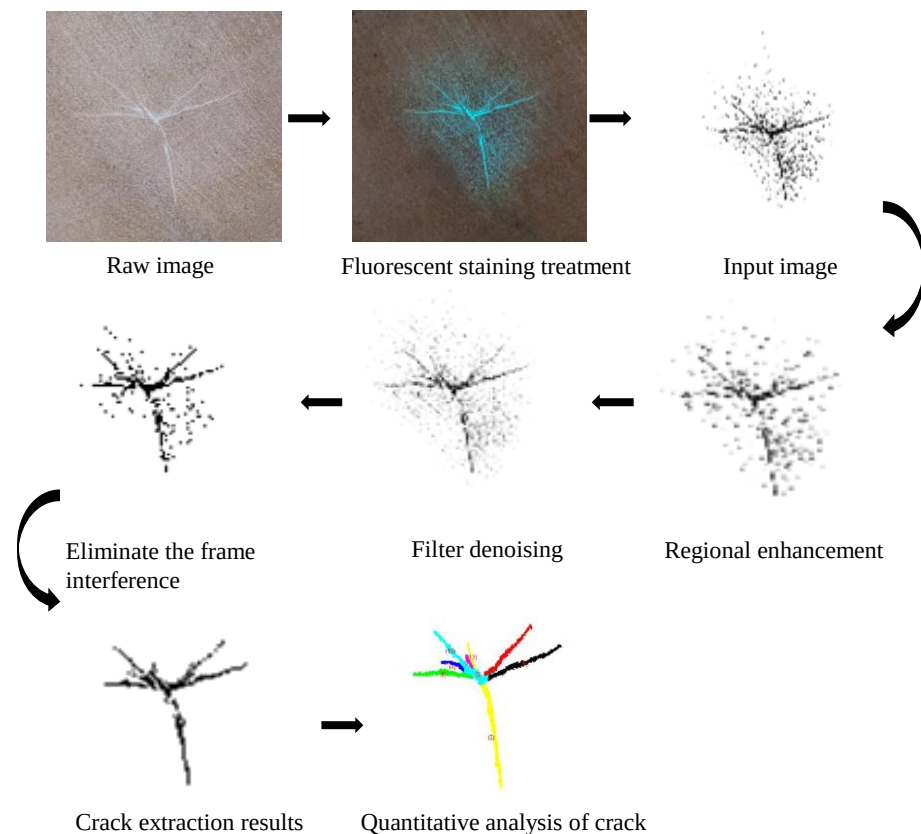


Figure 7. Identification of crack images.

4.2. The Reliability of the CFS Method

To verify the reliability of the CFS technique, industrial CT was used to scan the sample after electric breakdown, followed by cutting and staining. Figure 8 displays the comparison of CT scanned slice at the same position and the fluorescent stained image. It can be found that subjected to PHVD, a breakdown channel formed in the center of the rock and radial cracks formed around the channel. The morphology, number, and distribution obtained using the two methods are generally consistent, which verified the reliability of the CFS method. Thus, this method can capture the fracturing state of the rock. In addition, the CFS method shows merits including low cost and having more distinct contrast with the image background, which can be beneficial for displaying the crack morphology.

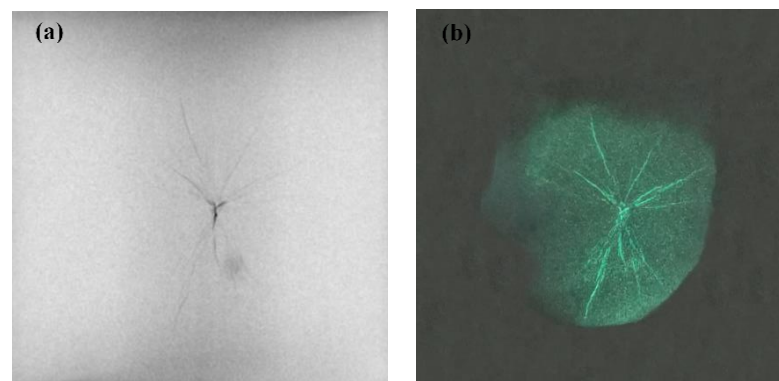


Figure 8. Comparison between CT scanned results and the result obtained using CFS technique: (a) CT scanned image; (b) Fluorescent stained image.

4.3. Microscopic Analysis

An important method to study the microscopic characteristics of mineral particles is to analyze the images obtained by scanning electron microscope (SEM) [30,31]. The fracture surfaces of the sandstone after electric breakdown were examined using a SEM (Apreo 2, Thermo Scientific, Waltham, MA, USA) equipped with a backscattered electron (BSE) detector. The accelerating voltage used for analysis was 5 kV, and a working distance of 8 to 11 mm was used.

The existing studies show that high-temperature melting and shock waves are the dominant factors of PHVD-induced rock fracture [15,16,18,20]. The high temperature causes the mineral grains inside sandstone to melt and fill many of the holes and micro-cracks [32–34]. Under the action of shock waves, the microscopic fracture modes observed by SEM included intergranular fracture (located at the boundary of grains) and transgranular fracture (passing through grains) [35]. As shown in Figure 9, four points are selected from near to far with the discharge channel as the starting point. The micromorphology of point A is shown in Figure 10a, from which it can be observed that there are many micro-cracks and holes with different sizes on the surface of the grains around the discharge channel, and the boundaries between the grains are blurred. These features are typical marks resulted from high-temperature burning. As the observation points move away from the discharge channel, the microscopic morphology of grains changes. It can be seen from Figure 10b that the microscopic morphology on the right side of point B is similar to that of point A, but the left side is dominated by transgranular fracture. Therefore, it can be concluded that the dominant factor of rock fracture transits from high temperature to shock waves. Transgranular fracture, intergranular fracture, and several microcracks can be observed at point C. At the same time, the boundaries between the grains become apparent, showing distinct edges and corners (Figure 10c). As the distance increases, the intensity of the shock wave decays further at point D. In general, the strength of cement between grains is lower than that of grains themselves. Thus, the destroy of cements and intergranular fracture can be found at point D (Figure 10d).

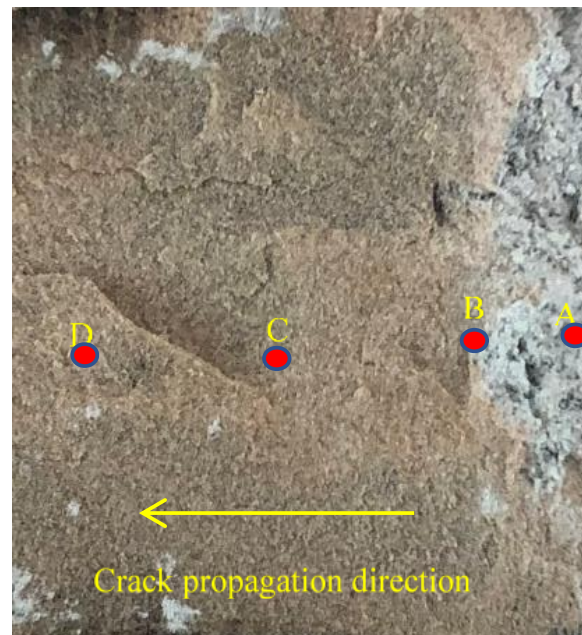


Figure 9. Positions for SEM analysis in sandstone after electric breakdown.

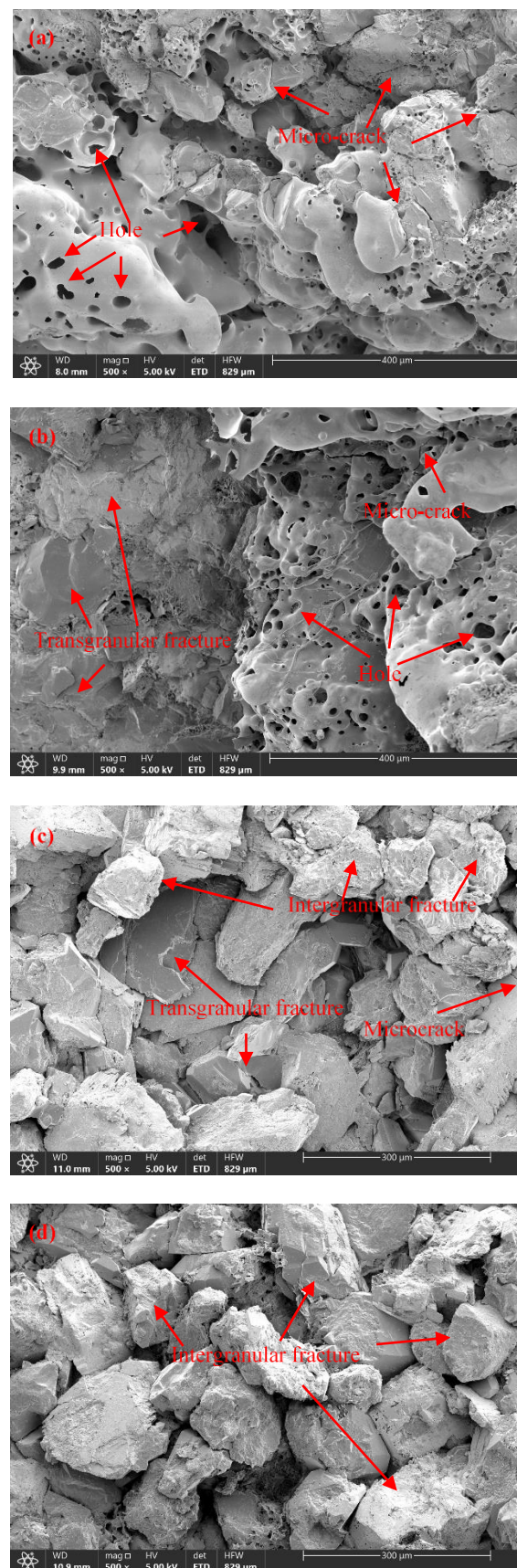


Figure 10. Microscopic characteristics of different fracture positions in sandstone after electric breakdown: (a) Point A; (b) Point B; (c) Point C; (d) Point D.

In studies [36,37], the temperature distribution characteristics and changes in the minerals with the granite under the action of PHVD were studied. Their results indicated that high temperature is an important factor in inducing rock fracturing. The existing studies provided some good insights on the micro-fracture mechanism of rock under the action of PHVD. However, it is difficult to obtain the microscopic fracture morphology of mineral grains due to the numerical simulation methods used in the above literatures. In this research, the failure characteristics of red sandstone under PHVD were studied using the experimental method. According to SEM analysis, the real microscopic morphology of sandstone specimen were obtained.

5. Results and Discussion

5.1. Theoretical Background

5.1.1. Stress and Strain Analysis Method around a Circular Hole under Uniaxial Static Pressure

This section mainly discusses the influence of static pressure on the crack distribution under the effect of high-voltage pulse. The discharge channel inside the rock was simplified into a cylinder, implying that a cylindrical cavity is formed between two electrodes. Owing to the discharge channel having a very small diameter and its formation time being short, in the breakdown process, it exerts little influence on the far-field static pressure. Furthermore, as the discharge voltages of the specimens are the same, the intensity of shock waves acting on the cylindrical cavity is consistent. In addition, the distance between the center of two boreholes and the cutting section is five times larger than the radius of the boreholes, thus, the effect of boreholes on the stress distribution for the cutting section can be neglected. Thereafter, the static stress state of the cutting section after the formation of the discharge channel can be theoretically analyzed.

The static pressure loading condition in Group I is such that:

$$\sigma_y = p, \sigma_x = 0, \sigma_z = 0 \quad (1)$$

The distribution of static stress on the zone surrounding the discharge channel in the polar coordinate system can be obtained using the Kirsch solution [38]:

$$\left. \begin{aligned} \sigma_r &= \frac{p}{2} \left(1 - \frac{a^2}{r^2} \right) - \frac{p}{2} \left(1 - 4\frac{a^2}{r^2} + 3\frac{a^4}{r^4} \right) \cos 2\theta \\ \sigma_\theta &= \frac{p}{2} \left(1 + \frac{a^2}{r^2} \right) + \frac{p}{2} \left(1 + 3\frac{a^4}{r^4} \right) \cos 2\theta \end{aligned} \right\} \quad (2)$$

where: σ_r and σ_θ denote the radial stress and circumferential stress; r refers to the distance between the study point and the center of a circle; a is the radius, and θ represents the angle between the polar diameter and the horizontal axis of the point of interest.

The static pressure loading condition in Group II is such that:

$$\sigma_x = 0, \sigma_y = 0, \sigma_z = p \quad (3)$$

The stress components σ_r and σ_θ for the section in the polar coordinate system are both 0. Then according to Hooke's law, the strain components are expressed as:

$$\left. \begin{aligned} \varepsilon_r &= -\frac{\mu}{E} p \\ \varepsilon_\theta &= -\frac{\mu}{E} p \end{aligned} \right\} \quad (4)$$

where: ε_r and ε_θ represent the radial strain and circumferential strain around the discharge channel inside the cutting section; E denotes the elastic modulus; μ is Poisson's ratio.

5.1.2. Stress and Strain Distribution around the Discharge Channel

Based on Equation (2), the stress distribution on the zone around the discharge channel is shown in Figure 11; circumferential compressive stresses are generated on the left and right sides ($\theta = 0^\circ$ and 180°) of the discharge channel while circumferential tensile stresses appear on the upper and lower sides ($\theta = 90^\circ$ and 270°) of the discharge channel.

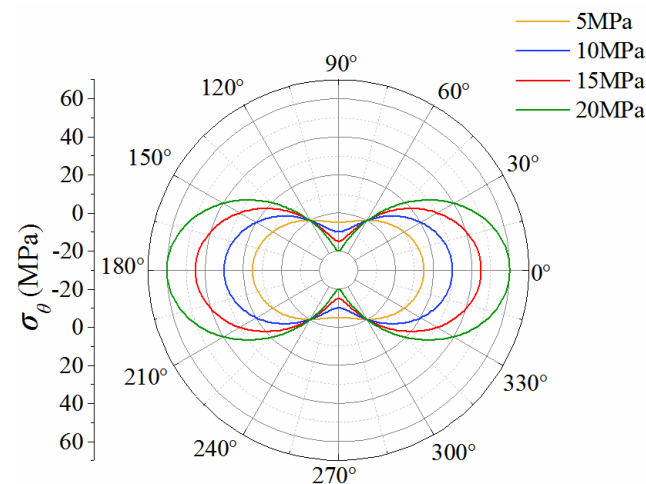


Figure 11. The distribution of circumferential stress around the discharge channel under the static loading applied in Group I.

According to Equation (4), the circumferential strain distribution can be attained (Figure 12). The circumferential tensile strains distributed evenly on the zone around the discharge channel are formed, and such strain distribution is conducive to the propagation of radial cracks.

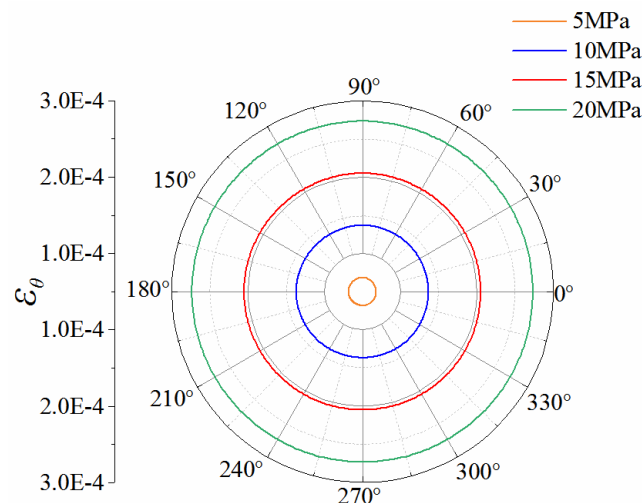


Figure 12. The circumferential strain distribution around the discharge channel under the static loading mode in Group II.

5.2. Analysis of Fracturing Effect

To elucidate the influence of static pressure on the fracturing induced by PHVD, the fracturing state of sandstone was explored from the perspectives of failure modes, the length, and fractal dimensions of cracks.

5.2.1. Failure Modes

Figure 13 shows the crack distribution of specimen S0 after electric breakdown in the absence of static pressure. The several cracks are radially distributed, centered on the discharge channel. The locations of these cracks are random, and the crack lengths are different, as some of the cracks propagate further.



Figure 13. The crack distribution in specimen S0.

The crack distributions of Group I specimens are shown in Figure 14. The cracks are mainly concentrated on the upper and lower parts of the discharge channel, while the left and right sides of the channel contain very few macroscopic cracks, suggesting that the static pressure significantly affects the spatial distribution characteristics of cracks generated by PHVD. The angle between the longest crack and the y -axis is defined as the deflection angle. The deflection angles corresponding to S1-1, S1-2, S1-3, and S1-4 are 11° , 9° , 5° , and 1° , and decrease with increasing static pressure. This shows that cracks tend to propagate along the direction of the applied static pressure. The existing studies provided that fractures caused by dynamic loads such as explosion are easier to propagate in the direction of static pressure. That is to say, static pressure has a guiding role in affecting crack propagation [8,10,13]. Therefore, to some extent, the conclusions drawn in this study are consistent with those researches [8,10,13]. Theoretical analysis indicates the upper and lower parts of the discharge channel are subjected to tensile loading. Hence, the cracks generated by high-voltage pulse are more prone to initiate and propagate along the direction of the y -axis. The left and right sides of the discharge channel suffer the compressive effect, which can inhibit the initiation and propagation of cracks along the x -direction. This finding can explain the experimental phenomena observed.

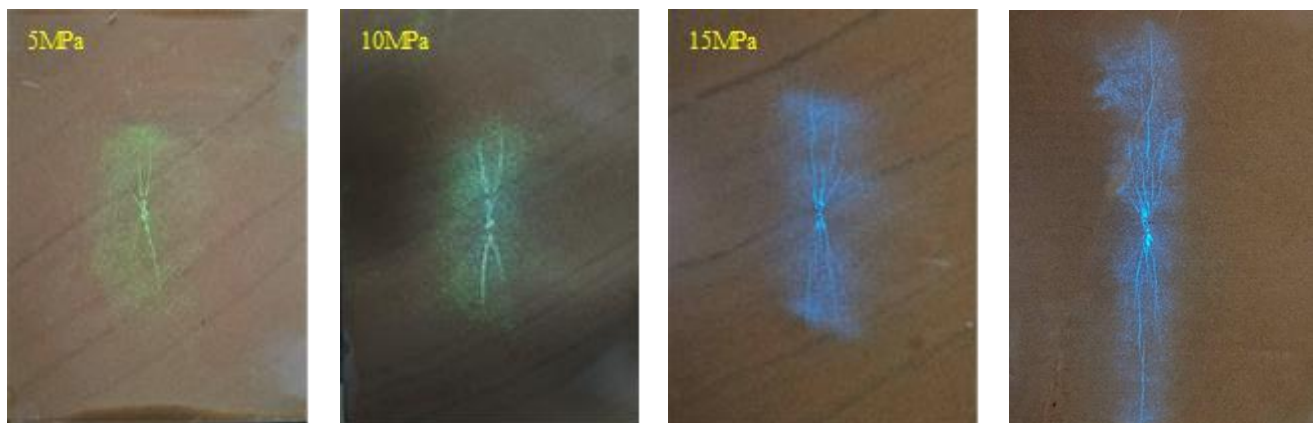


Figure 14. Crack distributions (Group I).

The fracturing state of the specimens in Group II are shown in Figure 15. Cracks are found to be radially and randomly distributed. The spatial morphology and distribution zone of cracks are akin to the case without static pressure. According to the theoretical analysis results, when loading along the direction of the discharge channel, static pressure can form a uniformly distributed circumferential strain field, which cannot change the direction of propagation of radial cracks. Therefore, under such a load regime, the failure modes of the specimens subjected to different stress levels are similar.

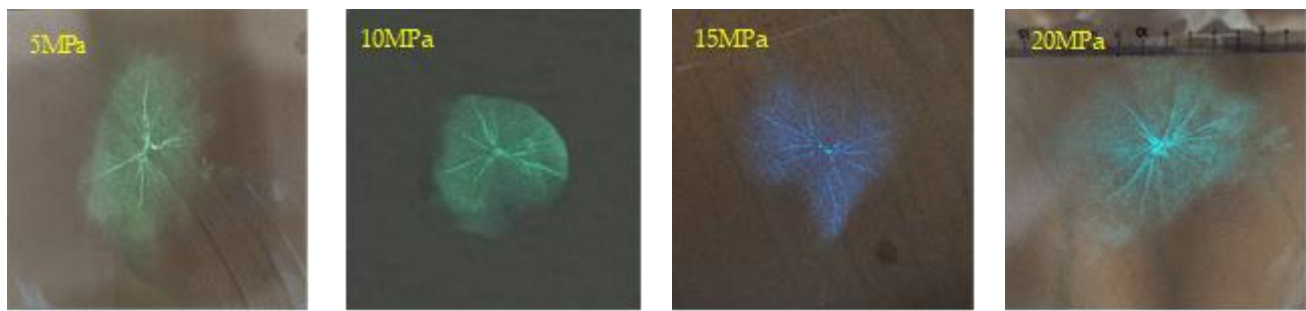


Figure 15. Crack distribution (Group II).

5.2.2. Fractal Dimension

The existing studies show that fractures are well associated with fractals [39,40]. The fractal dimension has been widely used to quantitatively describe complex fractures. The fractures in the rock also exhibit obvious fractal characteristics. A larger fractal dimension implies a more complex crack path. The fractal dimension can be calculated using the box-counting method as follows [41]:

$$D = \lim_{r \rightarrow 0} \frac{\lg Nr}{-\lg r} \quad (5)$$

where: D and r represent the fractal dimension and side length of a square box, respectively; Nr denotes the minimum number of square boxes with the side length of r required to cover the target geometry.

Figure 16 depicts the fitting results of fractal dimension obtained using the box-counting method. It can be found that all fitting lines had $R^2 > 0.98$. The results of fractal dimension suggest that the cracks produced by PHVD present satisfactory fractal characteristics.

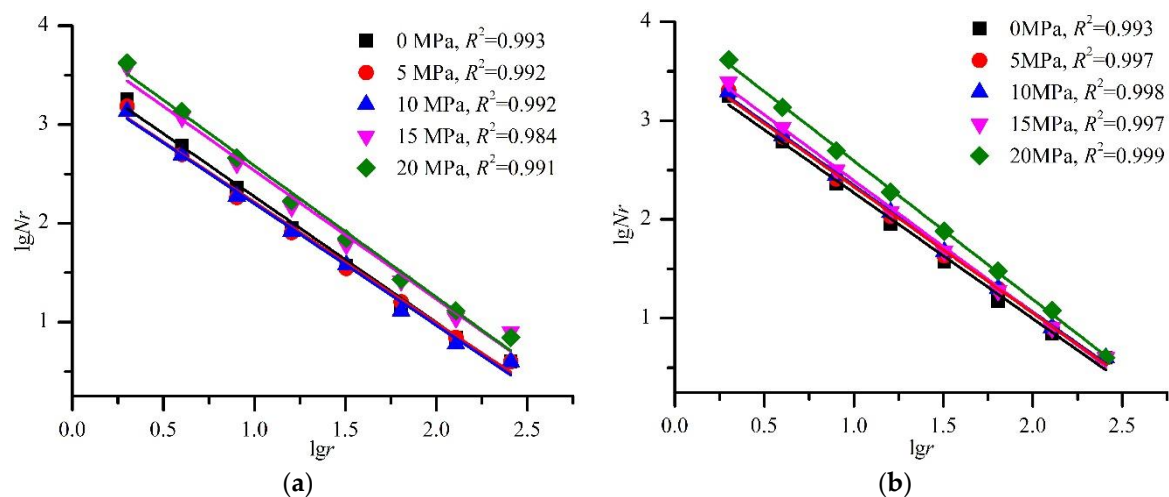


Figure 16. The fractal dimension calculation of the sandstone crack network: (a) Group I; (b) Group II.

The relationship between fractal dimension and static pressure in Group I is displayed in Figure 17a. The fractal dimension corresponding to a static pressure P of 5 and 10 MPa is less than that at 0 MPa; when P is greater than 10 MPa, the corresponding fractal dimension is greater than that at 0 MPa. In other words, after applying static pressure normal to along the y -axis, fractal dimension of cracks is first reduced, then increases. The results may be due to the following reasons: in the case of a relatively low static stress level, the inhibitory effect of crack development along the x -direction reduces the number of cracks, the crack network structure is simplified, and the degree of its complexity is less than that

at 0 MPa. When the applied stress is high, cracks along the x -direction do not propagate as readily, however, secondary cracks appear along the y -direction, and primary cracks show increasing length and deflection degree, increasing the degree of complexity of the crack network.

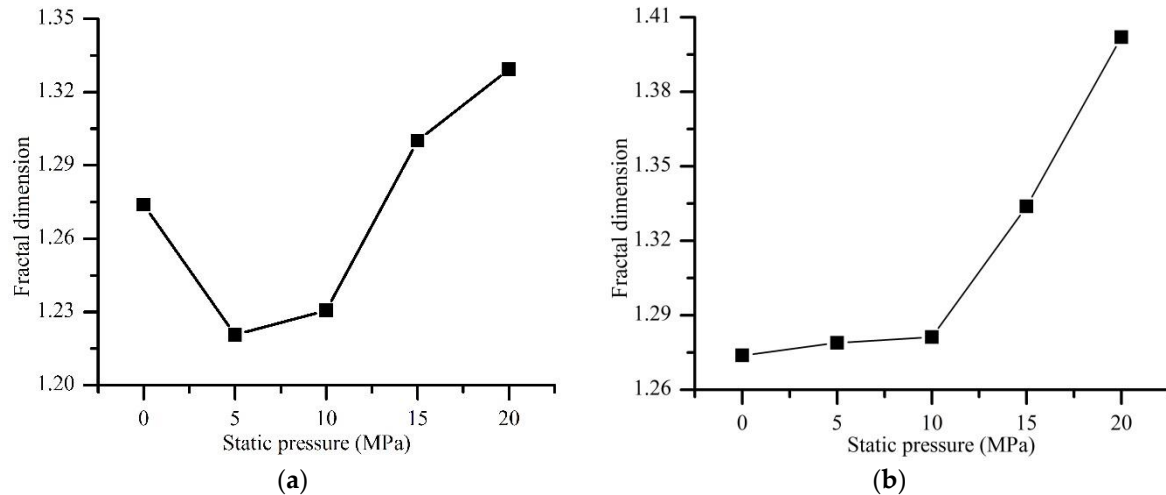


Figure 17. The change of fractal dimension with static pressure: (a) Group I; (b) Group II.

The relationship between fractal dimension and static pressure in Group II is presented in Figure 17b. From the figure, fractal dimensions corresponding to the specimens S0, S2-1, S2-2, S2-3, and S2-4 are 1.2739, 1.2789, 1.2812, 1.3339, and 1.4020. After applying static pressure along the z -direction, the fractal dimension of the cracks rises slowly, then rapidly, with increasing static pressure. When P is less than 10 MPa, the fractal dimension does not change to any significant extent; when P is greater than 10 MPa, the fractal dimension increases rapidly.

5.2.3. Crack Length

The relationship between the crack length and static pressure in Group I is illustrated in Figure 18a; the crack length first decreases, then increases with increasing static pressure P . When P is 5 MPa and 10 MPa, the crack length is below that at 0 MPa; when P is 15 MPa and 20 MPa, the cracks are longer than that at 0 MPa. This result implies that a low static pressure (5 and 10 MPa) can suppress fracturing of the sandstone under the effect of PHVD; while a relatively high static pressure (15 and 20 MPa) can promote fracturing.

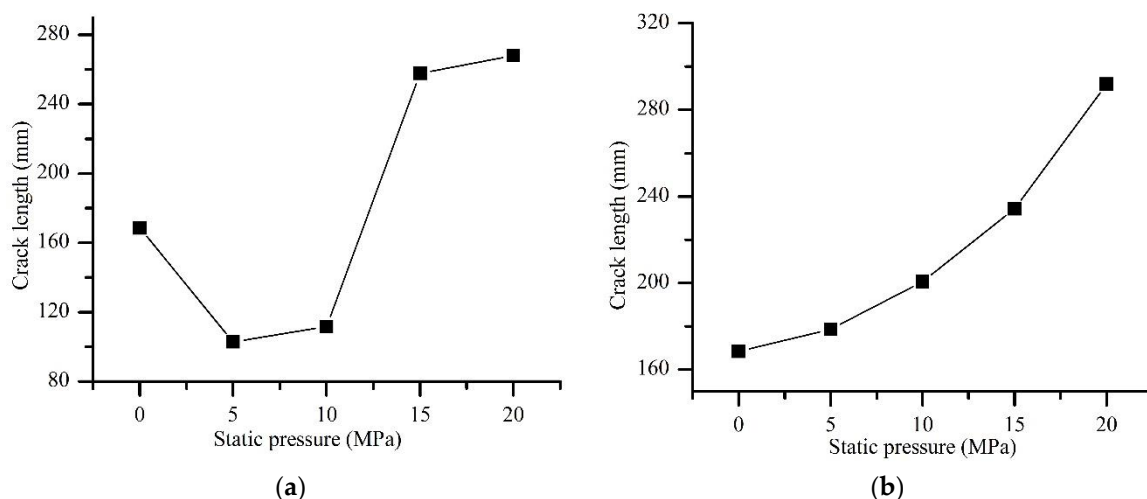


Figure 18. The relationship between the crack length and static pressure: (a) Group I; (b) Group II.

In the condition of applying static pressure along the y -axis, degree of stress concentration increases with increasing static pressure P , that is to say, the promotion and inhibitory effects of static pressure on crack development in different parts of sandstone under PHVD are enhanced. When the applied static pressure is low (5 and 10 MPa), it has no significant effect on crack propagation along the y -axis, however, it can suppress the formation of cracks along the x -axis. This causes the primary cracks in the specimens under the effect of PHVD to develop slowly and leads to the reduction of the crack number. Meanwhile, the inhibitory effects of the static pressure plays a dominant role in crack development. Thus, the total length of crack is smaller than that at 0 MPa. When static pressure is increased (to 15 or 20 MPa), the primary cracks along the y -direction are more likely to initiate, and energy release in this zone should be given first priority, causing increasing crack propagation length. The static pressure exerts the dominant role in promoting crack development along the y -direction, increasing the crack lengths.

The relationship between the crack length and static pressure P in Group II is demonstrated in Figure 18b. The crack lengths corresponding to the specimens S0, S1-1, S1-2, S1-3, and S1-4 are 168.55, 178.70, 200.80, 234.39, and 291.94 mm. As the static pressure increases to 20 MPa (in increments of 5 MPa), the crack length continues to grow. This finding means that the larger the static pressure, the more favorable the fracturing effect of sandstone; among the specimens, the crack length of S1-2 is 1.19 times greater than that of S0, while the crack length in specimen S1-4 is 1.73 times greater than that in S0. This suggests that a low static stress can improve the fracturing effect, to a limited extent, while a high static pressure can significantly improve the fracturing effect.

According to the theoretical analysis, loading along the z -direction will generate circularly distributed hoop tensile strains. This is beneficial for the propagation of radial cracks generated by PHVD, causing the increase in the crack length. Furthermore, the circumferential tensile strain grows with the increase of static pressure P , which triggers the increasing length of cracks. This can explain the trend in the change in crack lengths in Group II specimens.

The findings of this investigation imply that a relatively high static pressure can significantly promote fracturing under the effect of PHVD. In other words, rock is more easily fractured in this way. Deep rock engineering projects, such as drilling, mining, and tunnels, are gradually increasing. With the increase of rock depth, the in situ stress increases gradually. In practical applications, the distribution of the in situ stress should be fully considered to improve the efficiency of rock breaking by high-voltage pulses. Thus, less electric energies are possibly consumed when breaking rock with the same volume.

6. Conclusions

The electrical breakdown tests of sandstone under different directions and levels of static pressure were conducted. Then, image recognition technique was used to explore the influences of static pressure on the failure modes and degree of fracturing of cracks in sandstone under PHVD. The following conclusions were drawn:

- (1) In the absence of static pressure, red sandstone, after breakdown, forms a discharge channel and the macroscopic cracks around the discharge channel are radially distributed. Microscopic analysis indicates that the grains around the discharge channel are shown to be in a burning state under the effect of high temperature, and radial crack zones demonstrate intergranular fracture, transgranular fracture, and destroy of cements under the action of the shock wave.
- (2) The direction of static pressure has a significant effect on the distribution of cracks in sandstone under the effect of PHVD. When the applied static pressure is normal to the discharge channel, the cracks concentrate on the tensile stress zone around the discharge channel and tend to propagate along the direction of the applied static pressure. Cracks are difficult to initiate and propagate in the zone of compressive stress concentration. When the applied static pressure is parallel to the discharge

channel, it can induce uniformly distributed tensile strains, and the cracks present a radial distribution, which matches the case without an applied static pressure.

- (3) The degree of fracturing of sandstone under the effect of PHVD can be influenced by the level of static pressure. When a low static pressure (5 and 10 MPa) is applied normally to the discharge channel, the total length and fractal dimension of cracks are less than that in specimens under no static pressure, which is detrimental to the fracture of sandstone. However, a high static pressure (15 and 20 MPa) can increase the total length and fractal dimension of cracks and promote fracturing of the sandstone. When static pressure is applied parallel to the discharge channel, the crack length and fractal dimension increase with increasing static pressure.

In this research, the effects of uniaxial static pressures on the fracture behaviors of sandstone specimen subjected to PHVD are analyzed, however, the biaxial static loading conditions should be further considered. In addition, it is necessary to simulate the dynamic fracture process of rock by phase field approach in the future.

Author Contributions: Conceptualization, J.P. and F.Z.; Methodology, J.P.; Software, H.X. and H.W.; Validation, H.X., H.W. and J.L.; Investigation, J.P.; Resources, J.P. and F.Z.; Data Curation, H.X. and H.W.; Writing—Original Draft Preparation, J.P.; Writing—Review and Editing, F.Z.; Supervision, F.Z.; Project Administration, J.P. and F.Z.; Funding Acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Fundamental Research Funds for the Central Universities (N2101030), and the National Natural Science Foundation of China (52104119).

Data Availability Statement: That data that support the findings of this study are available from the corresponding author, [F.Z.], upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Ahmadi, M.; Erfan, M.R.; Erfan, M.R.; Torkamany, M.J.; Safian, G.A. The effect of interaction time and saturation of rock on specific energy in ND: YAG laser perforating. *Opt. Laser Technol.* **2011**, *43*, 226–231. [\[CrossRef\]](#)
- Li, Q.; Chen, G.; Luo, D.; Ma, H.; Liu, Y. An experimental study of a novel liquid carbon dioxide rock-breaking technology. *Int. J. Rock Mech. Min. Sci.* **2020**, *128*, 104244. [\[CrossRef\]](#)
- Hassani, F.; Shadi, A.; Rafezi, H.; Sasmito, A.P.; Ghoreishi-Madiseh, S.A. Energy analysis of the effectiveness of micro-wave-assisted fragmentation. *Miner. Eng.* **2020**, *159*, 106642. [\[CrossRef\]](#)
- Zhu, X.; Luo, Y.; Liu, W.; He, L.; Gao, R.; Jia, Y. On the mechanism of high-voltage pulsed fragmentation from electrical break-down process. *Rock Mech. Rock Eng.* **2021**, *54*, 4593–4616. [\[CrossRef\]](#)
- Fukushima, K.; Kabir, M.; Kanda, K.; Obara, N.; Fukuyama, M.; Otsuki, A. Equivalent circuit models: An effective tool to simulate electric/dielectric properties of ores—An example using granite. *Materials* **2022**, *15*, 4549. [\[CrossRef\]](#)
- Andres, U.; Timoshkin, I.; Jirestig, J.; Stallknecht, H. Liberation of valuable inclusions in ores and slags by electrical pulses. *Powder Technol.* **2001**, *114*, 40–50. [\[CrossRef\]](#)
- Rajmeny, P.K.; Singh, U.K.; Sinha, B.K.P. Predicting rock failure around boreholes and drives adjacent to stopes in Indian mines in high stress regions. *Int. J. Rock Mech. Min. Sci.* **2002**, *39*, 151–164. [\[CrossRef\]](#)
- Saharan, M.R.; Mitri, H. Destress blasting as a mines safety tool: Some fundamental challenges for successful applications. *Procedia Eng.* **2011**, *26*, 37–47. [\[CrossRef\]](#)
- Shou, Y.D.; Zhou, X.P.; Qian, Q.H. A critical condition of the zonal disintegration in deep rock masses: Strain energy density approach. *Theor. Appl. Fract. Mech.* **2018**, *97*, 322–332. [\[CrossRef\]](#)
- Yang, R.; Ding, C.; Li, Y.; Yang, L.; Zhao, Y. Crack propagation behavior in slit charge blasting under high static stress conditions. *Int. J. Rock Mech. Min. Sci.* **2019**, *119*, 117–123. [\[CrossRef\]](#)
- Li, X.; Gu, H.; Tao, M.; Peng, K.; Cao, W.; Li, Q. Failure characteristics and meso-deterioration mechanism of pre-stressed coal subjected to different dynamic loads. *Theor. Appl. Fract. Mech.* **2021**, *115*, 103061. [\[CrossRef\]](#)
- Li, X.; Zhu, Z.; Wang, M.; Wan, D.; Zhou, L.; Liu, R. Numerical study on the behavior of blasting in deep rock masses. *Tunn. Undergr. Space Technol.* **2021**, *113*, 103968. [\[CrossRef\]](#)
- Yang, L.; Chen, S.; Yang, A.; Huang, C.; Xie, H. Numerical and experimental study of the presplit blasting failure characteristics under compressive stress. *Soil Dyn. Earthq. Eng.* **2021**, *149*, 106873. [\[CrossRef\]](#)
- Andres, U.; Jirestig, J.; Timoshkin, I. Liberation of minerals by high-voltage electrical pulses. *Powder Technol.* **1999**, *104*, 37–49. [\[CrossRef\]](#)

15. Yan, F.; Lin, B.; Zhu, C.; Zhou, Y.; Liu, X.; Guo, C.; Zou, Q. Experimental investigation on anthracite coal fragmentation by high-voltage electrical pulses in the air condition: Effect of breakdown voltage. *Fuel* **2016**, *183*, 583–592. [\[CrossRef\]](#)
16. Li, C.; Yang, W. Prediction model of high-voltage pulse boring rock-breaking process and intelligent identification of model parameters. *J. Pet. Sci. Eng.* **2022**, *210*, 110066. [\[CrossRef\]](#)
17. Razavian, S.M.; Rezai, B.; Irannajad, M. Investigation on pre-weakening and crushing of phosphate ore using high voltage electric pulses. *Adv. Powder Technol.* **2014**, *25*, 1672–1678. [\[CrossRef\]](#)
18. Li, C.; Duan, L.; Tan, S.; Chikhotkin, V.; Fu, W. Damage model and numerical experiment of high-voltage electro pulse boring in granite. *Energies* **2019**, *12*, 727. [\[CrossRef\]](#)
19. Ezzat, M.; Adams, B.M.; Saar, M.O.; Vogler, D. Numerical modeling of the effects of pore characteristics on the electric breakdown of rock for plasma pulse geo drilling. *Energies* **2022**, *15*, 250. [\[CrossRef\]](#)
20. Cho, S.H.; Cheong, S.S.; Yokota, M.; Kaneko, K. The dynamic fracture process in rocks under high-voltage pulse fragmentation. *Rock Mech. Rock Eng.* **2016**, *49*, 3841–3853. [\[CrossRef\]](#)
21. Kencanawati, N.N.; Shigeishi, M. Acoustic emission sources of breakdown failure due to pulsed-electric discharge in concrete. *Constr. Build. Mater.* **2011**, *25*, 1691–1698. [\[CrossRef\]](#)
22. Bao, X.; Guo, J.; Liu, Y.; Zhao, G.; Cao, J.; Ju, W.; Zhao, J. Damage characteristics and laws of micro-crack of underwater electric pulse fracturing coal-rock mass. *Theor. Appl. Fract. Mech.* **2021**, *111*, 102853. [\[CrossRef\]](#)
23. Duan, L.; Xiao, Y.; Li, C.; Li, A.; Kang, J. Simulation and experimental study on the influence of bit structure on rock-breaking by high-voltage electro-pulse boring. *J. Pet. Sci. Eng.* **2022**, *214*, 110556. [\[CrossRef\]](#)
24. Sun, Y.; Fu, R.; Fan, A.; Gao, Y.; Yan, P. Study of rock fracturing generated by pulsed discharging under confining pressure. In Proceedings of the 2015 IEEE Pulsed Power Conference (PPC), Austin, TX, USA, 31 May–4 June 2015; pp. 1–4.
25. Li, C.; Duan, L.; Tan, S.; Chikhotkin, V.; Wang, X. An electro breakdown damage model for granite and simulation of deep drill-ing by high-voltage electropulse boring. *Shock Vib.* **2019**, *2019*, 7149680.
26. Ezzat, M.; Börner, J.; Vogler, D.; Wittig, V.; Kammermann, B.; Biela, J.; Saar, M.O. Lithostatic pressure effects on the plasma-pulse geo-drilling (PPGD). In Proceedings of the 48th European Conference on Plasma Physics, Online, 27 June–1 July 2022.
27. Bluhm, H.; Frey, W.; Giese, H.; Hoppe, P.; Schultheiss, C.; Strassner, R. Application of pulsed HV discharges to material fragmen-tation and recycling. *IEEE Trans. Dielectr. Electr. Insul.* **2000**, *7*, 625–636. [\[CrossRef\]](#)
28. Hamdi, E.; Romdhane, N.B.; Le Cléc'h, J.M. A tensile damage model for rocks: Application to blast induced damage assessment. *Comput. Geotech.* **2011**, *38*, 133–141. [\[CrossRef\]](#)
29. Dehghan Banadaki, M.M.; Mohanty, B. Numerical simulation of stress wave induced fractures in rock. *Int. J. Impact Eng.* **2012**, *40–41*, 16–25. [\[CrossRef\]](#)
30. Zaaferani, N.; Raabe, D.; Singh, R.N.; Roters, F.; Zaefferer, S. Three-dimensional investigation of the texture and microstructure below a nanoindent in a Cu single crystal using 3D EBSD and crystal plasticity finite element simulations. *Acta Mater.* **2006**, *54*, 1863–1876. [\[CrossRef\]](#)
31. Pereira Gonçalves, P.; Otsuki, A. Determination of liberation degree of mechanically processed waste printed circuit boards by using the digital microscope and SEM-EDS analysis. *Electronics* **2019**, *8*, 1202. [\[CrossRef\]](#)
32. Zhang, H.; Sun, Q.; Jia, H.; Dong, Z.; Luo, T. Effects of high-temperature thermal treatment on the porosity of red sandstone: An NMR analysis. *Acta Geophys.* **2021**, *69*, 113–124. [\[CrossRef\]](#)
33. Yang, S.Q.; Hu, B. Creep and long-term permeability of a red sandstone subjected to cyclic loading after thermal treatments. *Rock Mech. Rock Eng.* **2018**, *51*, 2981–3004. [\[CrossRef\]](#)
34. Xiao, W.; Yu, G.; Li, H.; Zhan, W.; Zhang, D. Experimental study on the failure process of sandstone subjected to cyclic loading and unloading after high temperature treatment. *Eng. Geol.* **2021**, *293*, 106305. [\[CrossRef\]](#)
35. Zhang, Q.B.; Zhao, J. Quasi-static and dynamic fracture behaviour of rock materials: Phenomena and mechanisms. *Int. J. Fract.* **2014**, *189*, 1–32. [\[CrossRef\]](#)
36. Walsh, S.D.; Vogler, D. Simulating electropulse fracture of granitic rock. *Int. J. Rock Mech. Min. Sci.* **2020**, *128*, 104238. [\[CrossRef\]](#)
37. Fukushima, K.; Kabir, M.; Kanda, K.; Obara, N.; Fukuyama, M.; Otsuki, A. Simulation of electrical and thermal properties of granite under the application of electrical pulses using equivalent circuit models. *Materials* **2022**, *15*, 1039. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Kirsch, C. Die theorie der elastizität und die bedürfnisse der festigkeitslehre. *Z. Ver. Dtsch. Ing.* **1898**, *42*, 797–807.
39. Husain, A.; Nanda, M.N.; Chowdary, M.S.; Sajid, M. Fractals: An Eclectic Survey, Part-I. *Fractal Fract.* **2022**, *6*, 89. [\[CrossRef\]](#)
40. Husain, A.; Nanda, M.N.; Chowdary, M.S.; Sajid, M. Fractals: An Eclectic Survey, Part II. *Fractal Fract.* **2022**, *6*, 379. [\[CrossRef\]](#)
41. Zhang, T.; Liu, B.; Wei, Z.; Jiao, Z.; Song, Z.; Zhang, H. Dynamic mechanical responses and crack evolution of burst-prone coal with a single prefabricated fissure. *Theor. Appl. Fract. Mech.* **2022**, *121*, 103494. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.