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Research Article

Influences of Microwave Irradiation on the Physicomechanical Properties and Cerchar Abrasivity Index of Rocks

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The research is aimed at exploring the influences of microwave irradiation on the physicomechanical properties and Cerchar abrasivity index (CAI) of rocks. For this purpose, basalt collected in Chifeng (the Inner Mongolia Autonomous Region, China) was taken as research objects to carry out microwave irradiation tests for different durations in a multimode cavity. By using the MTS815 mechanical testing machine and the abrasion servo tester of rocks, mechanical tests and Cerchar abrasion tests were conducted before and after microwave irradiation. Changes in the mass, volume, surface fractures, surface temperature, ultrasonic wave velocity, uniaxial compressive strength (UCS), and CAI of the basalt samples before and after microwave irradiation were analyzed. Results show that the surface temperature of basalt samples linearly increases with the duration of microwave irradiation. The volume and fracture coalescence of the rock samples both increase with the prolonging duration of microwave irradiation. The mass, ultrasonic wave velocity, UCS, and CAI of the basalt samples all decrease with the increase in the duration of microwave irradiation. The reduction of the physicomechanical properties and CAI of rocks indicates that microwave irradiation can reduce the wear of rock-breaking tool and thus improve the efficiency of rock breaking.

1. Introduction

With the constant development of tunnels and underground engineering, tunnel boring machines (TBMs) are used more and more widely. However, tool wearing in the mechanical excavation process under a complex and varying geological environment has become an important factor that restricts the construction schedule and affects the construction cost [1, 2]. How to reduce tool wearing and improve the efficiency of mechanical rock breakage has become a research focus during tunnel excavation in hard rocks [3, 4].

Microwaves generally refer to ultra-high-frequency electromagnetic waves with a wavelength of 0.001~1 m at a frequency of 0.3~300 GHz. They are characterized by a short wavelength and a high frequency, and the commonly used microwave heating frequencies are 0.915 and 2.45 GHz [5]. The heating effect of microwaves was found by a radar engineering in the United States in 1945 by accident [6]. In mining and metallurgy, Chen et al. [7] and Walkiewicz et al. [8] found that most natural minerals are changed after microwave irradiation. The minerals sensitive to microwave absorption are heated and expanded after absorbing microwaves, thus producing thermal expansion stress under the confinement of external materials, so the rock develops cracks and is even broken under microwave irradiation [9]. Based on the principle, microwave-assisted rock breakage has become a new rock breakage method. It refers to weakening rocks through microwave irradiation before mechanical rock breakage. Particularly for hard and highly abrasive strata encountered during excavation, microwave-assisted rock breakage can effectively reduce tool wearing in mechanical rock breakage and therefore improve the efficiency of mechanical rock breakage. Through research, the United States Bureau of Mines has found that compared with pure mechanical rock breakage, microwave-assisted rock breakage can improve the intrusion rate in rocks by a factor of three [10].

Up to now, the majority of research on microwave-assisted rock breakage was carried out using a multimode cavity. Hassani et al. [11, 12] and Teimoori et al. [13] used a multimode microwave cavity to conduct uniaxial compression tests and tensile tests on different types of rocks under different microwave powers. Through comparison of tests and numerical research, the influences of the microwave irradiation distance on the surface temperature of hard rocks were studied. The Railway Technical Research Institute (RTRI) in Japan carried out experimental research on microwave-assisted rock breakage using the induction heating method [14]. The frequency, wavelength, and maximum power of the test device were 915 ± 25 Hz, 30 cm, and 60 kW, respectively. The research revealed that the larger the microwave power is, the better the rock breakage effect. Hartlieb et al. [15, 16], Peinsitt et al. [17], Meisels et al. [18], and Toifl et al. [19] in Montanuniversitaet Leoben, Austria, performed experimental research on microwave irradiation on basalt, granite, and sandstone. They analyzed changes in thermophysical properties and water contents in rocks after microwave irradiation and discussed the propagation characteristics and thermal-dynamic properties of microwaves in heterogeneous hard rocks by combining experiments and numerical research. Kingman et al. [20] considered that the bond work index of rocks decreases obviously after microwave irradiation, which means that the energy needed for rock breakage reduces apparently.

Generally, increases in microwave power and irradiation duration may rise the surface temperature of rocks, generate more fractures, and constantly decrease ultrasonic velocity and strength indicators including uniaxial compressive strength (UCS), tensile strength, point-load strength, and fracture toughness [4, 21]. The wing cracks are usually the first crack that appears in the loading process in studies about fractured rocks, and a certain correlation exists between the wing crack propagation process and the peak strength of fractured specimens [22]. The failure criterion of rocks is a critical factor involved in reliability design and stability analysis of geotechnical engineering; the conventional triaxial compressive strength of rocks also decreases after microwave irradiation [23, 24]. In other words, the reduction in rock strength after microwave irradiation can also be explained by the correlation between the crack propagation process and the peak strength for the specimen containing preexisting flaws made of rock-like material [25].

Lu et al. [24, 26] considered that the temperature-rising characteristic of rocks is determined by comprehensive dielectric properties of mineral components in rocks and the fracture effect is determined by the temperature-rising characteristic and heat expansibility of various minerals in rocks. Under uniaxial compression, the elastic modulus and Poisson's ratio of basalt quasilinearly decrease with the prolonged duration of microwave irradiation [24]. Different heating paths exert different effects on rock breakage. When rocks are continuously heated under high power, the minerals therein expand nonuniformly so that high thermal stress is generated inside the rocks, which facilitates damage to the rocks after a short treatment time at a low temperature. The simulations show that the resultant sample temperature, and therefore damage, is higher in samples with high ratios of compressive to tensile strength under the same microwave radiation conditions [27].

There is less research on rock abrasivity, which, however, has great influences on the wearing of machines. Previous research generally judges rock abrasivity only from a certain physical index, which fails to consider the topic from the perspective of rock-machine interaction. The Cerchar Institute in France designed a method specific for testing rock abrasivity to solve the above problem. The method is simple and has been widely used, termed as the Cerchar test [28], the result of which, that is, Cerchar abrasivity index (CAI) value is acknowledged as an international quantitative index for evaluating the rock abrasivity. The State Key Laboratory of Shield Machine and Boring Technology in China [29] also developed a new test method for rock abrasivity. Gong et al. [30] collected and analyzed the grading standards used by various international laboratories and organizations and provided the range of CAI of common lithology. Zhu [31] found that the compressive strength of hard rocks is positively correlated with the CAI. Deyab et al. [32] discussed the effect of irradiation on kimberlite and granite rocks of abrasivity using the CAI; they found that the CAI values were basically unchanged because the specimens could not be treated in a microwave at 15 kW of power for more than 30 s due to disintegration and melting in some cases.

Despite the ample research on the influences of microwave irradiation on rocks, the CAI of rocks has not been sufficiently studied by combining microwave irradiation. Therefore, it is critical to explore the influences of microwave irradiation on physicomechanical properties and CAI of rocks. Basalt collected in Chifeng (the Inner Mongolia Autonomous Region, China), a high-strength rock, was selected to conduct microwave irradiation and Cerchar tests. Changes in the mass, volume, surface fractures, surface temperature, ultrasonic wave velocity, UCS, and CAI of the rock after tests were analyzed to explore the rock breakage effect of microwave irradiation and the influences of microwave irradiation on tool wearing of rocks.

2. Test Apparatuses, Samples, and Test Methods

2.1. Test Apparatuses. Microwave irradiation tests were conducted using an EMB17G4V-SS commercial microwave oven (Midea), with a rated voltage and frequency of 220 V and 50 Hz and rated input power of 3,200 W. The working frequency and maximum output power of microwaves are separately 2,450 MHz and 2,100 W, and the power is continuously adjustable within 100~2,100 W. An infrared temperature-measuring device and a data acquisition unit were installed outside the microwave oven, which enabled real-time measurement and acquisition of surface temperatures of samples, as shown in Figure 1.

The mechanical tests were conducted using an MTS815 mechanical testing machine of rocks in the State Key Laboratory of Shield Machine and Boring Technology

Figure 1: The modified commercial microwave oven.

Figure 2: The MTS815 mechanical testing machine of rocks.

(Figure 2). It is a servo triaxial rigid testing machine specific for rocks and concrete produced by MTS company in the United States, with three independent sets of closed-loop servo control functions for axial pressure, confining pressure, and pore water pressure. The testing machine can be used to perform uniaxial and triaxial compression tests, creep and relaxation tests, and fluid-structure interaction tests on rocks and concrete.

The Cerchar abrasion tests on rocks were conducted using an ATA-IGG I abrasion servo tester for rocks, which can test the CAI of rocks [29]. Using servo control in the tests, the tester can analyze the rock-machine interaction in the whole abrasion process. The test method is simple and nondestructive, and the test results favorably reflect the abrasivity of rocks for tools. The abrasion servo tester is composed of an abrasion tester and a measuring and recording part, and its principle and devices are shown in Figures 3 and 4. The abrasion tester consists of a frame, a vise, a lower fixture, a stylus (HRC 55), a gearbox, a servo motor, and a drive system; the measuring and recording part includes a vertical grating displacement sensor, a horizontal grating displacement sensor, a stress sensor, an EDC controller, a computer, and a measuring device for the width of wear tracks on the stylus (high-definition digital microscope).

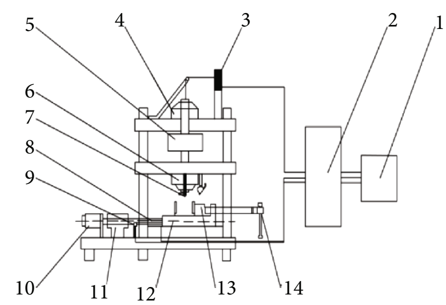


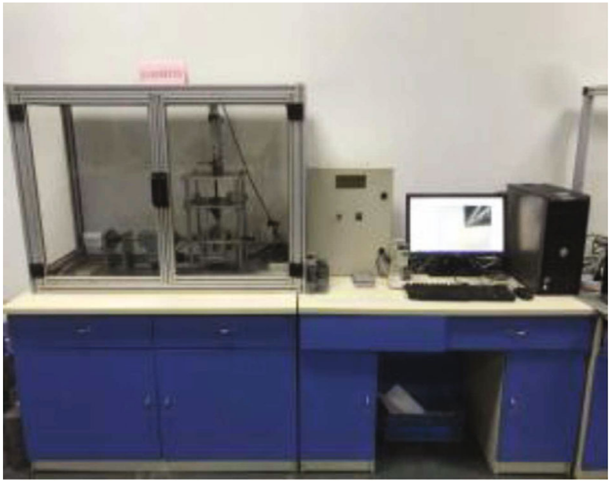
Figure 3: Schematic diagram of the abrasion servo tester of rocks [29]. 1-Computer; 2-EDC controller; 3-vertical grating displacement sensor; 4-upper fixture; 5-steel block; 6-lower fixture; 7-stylus; 8-stress sensor; 9-horizontal grating displacement sensor; 10-Panasonic AC servo motor; 11-gearbox; 12-slide rail; 13-vise; 14-vise handle.

2.2. Samples and Test Methods. Test samples were Chifeng basalt [21] that was divided into two types according to specifications, that is, cylindrical samples measuring $\Phi 50 * 50$ mm and $\Phi 50 * 100$ mm, respectively. The samples were machined through drilling, cutting, and grinding following the standard recommended by the International Society for Rock Mechanics (ISRM) [33]. The nonparallelism of the two ends of the samples was lower than 0.05 mm, the height and diameter errors were smaller than 0.3 mm, and the perpendicularity deviation of ends with the axis was smaller than 0.25 mm. The X-ray diffraction (XRD) analysis indicates that the Chifeng basalt mainly comprises plagioclase, pyroxene, and olivine, as well as a small amount of ilmenite (Figure 5). The major oxide concentrations of the basalt are shown in Table 1. The average UCS, density, and P-wave velocity of the basalt were 212.50 MPa, 2.89 g/mm^3, and 5,793.01 m/s, respectively. The samples were dried in the drying oven at 105°C for 48 hours before microwave irradiation.

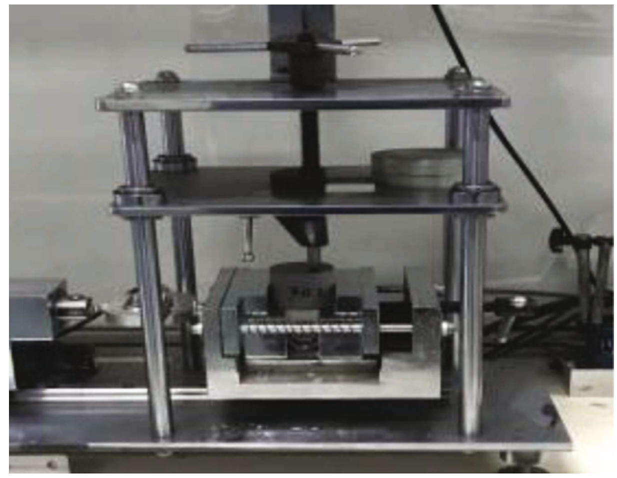
The microwave heating tests were performed in the modified commercial microwave oven. A mullite was placed in the microwave oven (not absorbing microwaves) as a pad, on which the basalt sample was put and heated with microwaves. The microwave heating power was 2,100 W and the heating lasted separately for 10, 20, 30, 40, and 50 s. Afterward, the sample was taken out and cooled to room temperature.

The uniaxial compression tests were carried out on the MTS815 mechanical testing machine of rocks. An axial extensometer and a circumferential extensometer were installed on the basalt sample, which was placed at the center of the test bench. The axial and circumferential extensometers were connected to the data acquisition unit on the test bench to measure the axial and circumferential deformation of the sample in the failure process. The compression rate was set to be 1 kN/s, and data acquisition stopped after the strength was reduced by 20%. The measurement ranges of the axial and circumferential deformation were separately set to be ±4 mm and 12.5 mm.

The Cerchar abrasion tests were performed on the abrasion servo tester of rocks [29]. Before the test, the stylus was



(a) Abrasion servo tester of rocks



(b) Abrasion tester

(c) Stylus (HRC 55)

(d) High-definition digital microscope

Figure 4: The abrasion servo tester of rocks and its components [29].

observed under the high-definition digital microscope to ensure whether it was intact or not and whether the conicity at the tip was 90° or not and to record the original typical microscopic images of the stylus. Then, the EDC controller was turned on and linked with the operational software in the computer, and whether the whole operating system ran normally or not was checked. After tightly clamping the stylus with the fixtures, the sample was placed in the vise and tightly clamped by rotating the vise handle. Afterward, the load of the tester was moved downward to enable contact between the tip of the stylus and the sample surface. As the test started, the stylus was moved horizontally for 10 mm at a rate of 60 mm/min. The stylus after sliding was observed under the high-definition digital microscope to measure the radiometer of wear tracks. The CAI is a dimensionless unit value and is calculated by multiplying the wear surface stated in units of 0.01 mm by 10, which was calculated using [34].

$$\mathrm{CAI} = d \times 10, \tag{1}$$

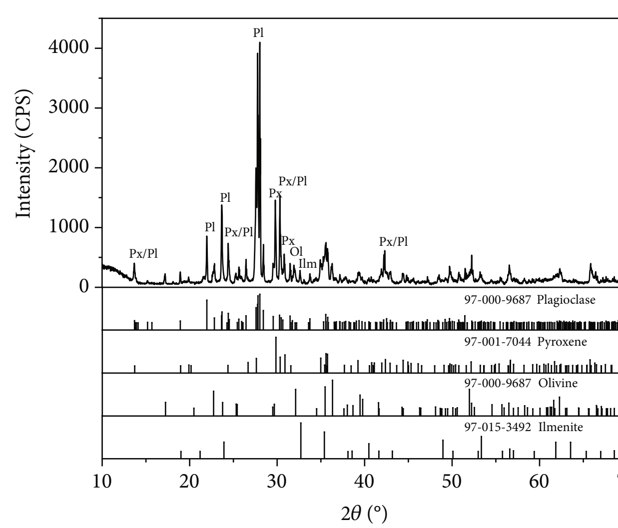


Figure 5: X-ray diffraction pattern of the basalt specimen from Chifeng, China (θ is the diffraction angle).

Table 1: Major oxide concentrations of the basalt (wt.%).

Major oxides	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO
CFXW-3	50.70	2.07	14.06	2.0282	9.38	0.17	7.62
Major oxides	CaO	Na_2O	K_2O	P_2O_5	LOI	Sum	
CFXW-3	8.65	3.25	1.14	0.40	0.06	99.53	

where d is the wear tip surface measured to an accuracy of 0.01 mm. The wear tracks produced by each group of samples on the stylus were measured for three times, each by rotating the stylus for 120°, and the average was taken as the CAI of the sample.

3. Test Results and Analysis

3.1. Crack Propagation. As shown in Table 2, the basalt samples change slightly on the whole after microwave irradiation for 10 s under macroscopic observation, with only small cracks seen on the surface of samples. The number of fractures on the surface of basalt samples grows after microwave irradiation for 30 s; coalesced fractures appear on the surface of the samples after microwave irradiation for 50 s. Under microscopic observation at 100- and 400-fold magnifications, the width of fractures on the surface of basalt samples after microwave irradiation is found to linearly increase with the irradiation duration. After microwave irradiation for 10, 30, and 50 s, the widths of surfaces on the basalt samples are 0.049, 0.080, and 0.109 mm, respectively. The cracking modes on the surface of the basalt samples mainly include intergranular fracture and transgranular fracture [35] that separate along and pass through mineral grains in the rock. This is mainly because the minerals of strong microwave absorption and those of high thermal expansibility in basalt samples thermally expand after absorbing microwaves.

3.2. Changes in Physical Properties. Changes in the surface temperature of basalt samples with the duration of microwave irradiation are shown in Figure 6. Under a fixed microwave power, the temperature at a certain point on the sample surface constantly linearly rises as the duration of microwave irradiation prolongs. The mass of basalt samples constantly reduces with the increasing duration of microwave irradiation, as displayed in Table 2 and Figure 7. The mass of the sample remains basically unchanged after microwave irradiation for 10 and 20 s; after being irradiated with microwaves for 30, 40, and 50 s, the mass of the basalt sample reduces by 0.12%, 0.20%, and 0.35%, respectively. The longer the duration of microwave irradiation is, the larger the mass reduction of the sample. The mass of the sample decreases abruptly after microwave irradiation for 50 s.

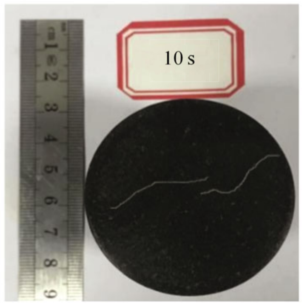
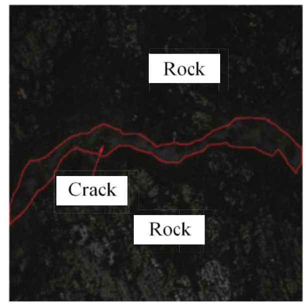
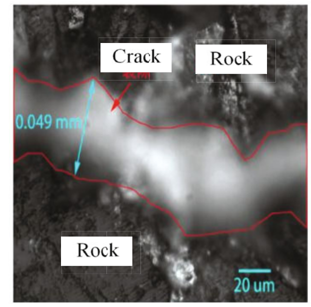
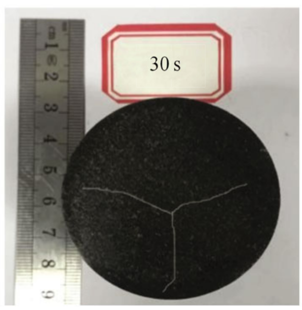
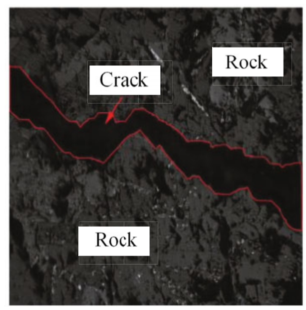
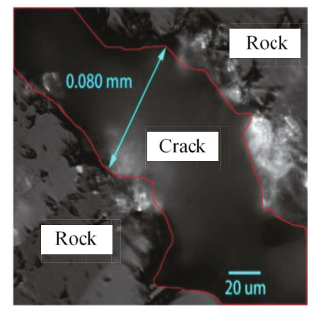
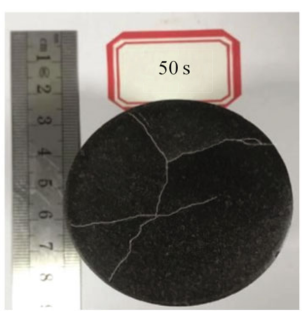
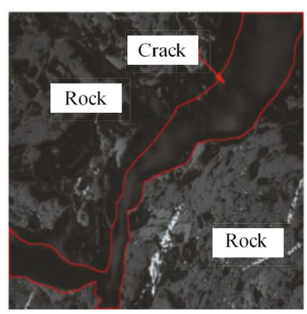
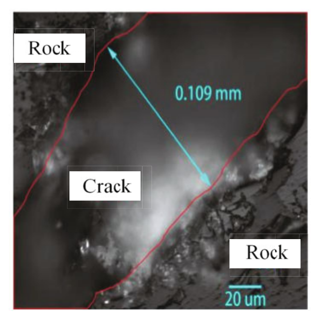
The mass change of the basalt sample is mainly related to the escape of water in minerals under different temperatures. According to mineralogy, water in minerals includes hydroscopic water, interlayer water, confined water, microporous water, and constitution water. As the samples were dried under 105°C for 48 h in advance, free water, hydroscopic water, and interlayer water in rock have already escaped before the microwave irradiation test. However, the confined water and microporous water will escape at 110-500°C. Due to microwave heating caused by the sample, internal temperature is much higher than the surface temperature [35], so from 20 s, the mass began to occur significantly reduced. Therefore, the mass of the basalt sample decreases mainly due to the confined water and microporous water escape after microwave irradiation.

The volume of the basalt samples enlarges constantly with the prolonged duration of microwave irradiation, as displayed in Table 3 and Figure 7. After 10 s of microwave irradiation, the basalt sample basically does not change in terms of volume. After microwave irradiation for 20, 30, 40, and 50 s, the volume of the samples increases separately by 0.11%, 0.32%, 0.69%, and 0.81% compared with that before microwave irradiation. The increase of volume with microwave irradiation duration is due to the propagation of internal cracks caused by microwave heating. The longer the microwave irradiation duration, the more serious the crack propagation inside the sample, so the larger the volume increase of the sample.

Figure 8 illustrates changes of the P-wave velocity of the basalt sample before and after microwave treatment. When the duration of microwave irradiation is 10, 20, and 30 s, the P-wave velocity of the sample constantly reduces with the increasing duration, while at a slow rate. After microwave irradiation for 40 s, the decreased rate of P-wave velocity obviously accelerates compared with the above three durations; when the duration of microwave irradiation is 50 s, the P-wave velocity declines abruptly. On the whole, the P-wave velocity constantly declines with the growing duration of microwave irradiation and the decrease rate constantly rises as the duration prolongs. The lower the P-wave velocity of rocks is, the greater the damage inside the rocks, which indicates that the increasing duration of microwave irradiation aggravates the damage in the rock.

3.3. Compression Strength and Failure Time. The failure effect and test results of the basalt samples under uniaxial compression are separately shown in Figures 9 and 10. With the increasing duration of microwave irradiation, the UCS of the basalt sample constantly decreases [35]. The UCS of rocks reflects the ultimate failure strength of rocks under axial compression. For the same type of rocks, the higher the UCS is, the larger the abrasivity and the greater the wearing for tools for mechanical rock breakage. After microwave irradiation, the decrease in the UCS proves that the energy needed for reaching the failure limit of rocks constantly reduces. In addition, the time taken by the MST testing machine for the failure of the basalt samples constantly shortens as the duration of microwave irradiation increases. This proves that microwave irradiation to some extent can

Table 2: Comparison of macroscopic and microscopic changes on the surface of the basalt samples after microwave irradiation.

Serial no.	Macroscopic observation	The 100-fold magnification	The 400-fold magnification
1-1			
1-3			
1-5			

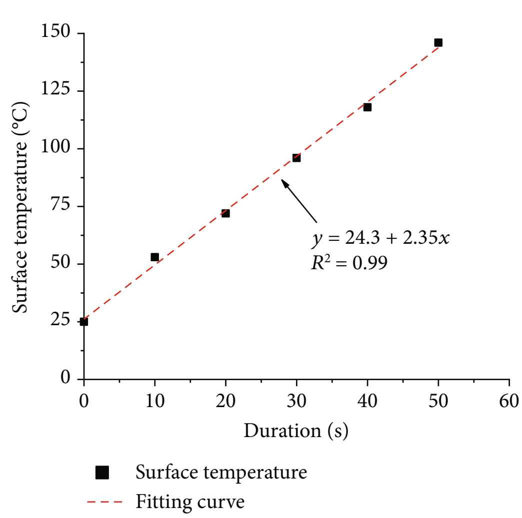


Figure 6: Changes of the surface temperature of the basalt samples with the duration of microwave irradiation.

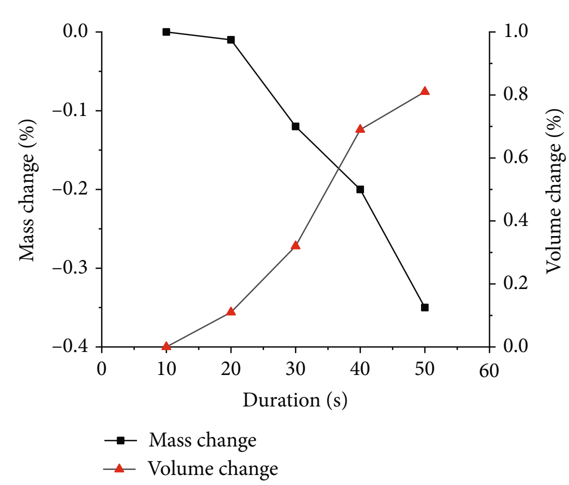


Figure 7: Changes of the mass and volume of the basalt samples with the duration of microwave irradiation.

Table 3: Changes of the mass and volume of the basalt samples with the duration of microwave irradiation.

Duration (s)	Mass (g) Before microwave	Mass (g) After microwave	Mass (g) Change (%)	Volume (cm^3) Before microwave	Volume (cm^3) After microwave	Volume (cm^3) Change (%)
10	253.601	253.598	0	89.11	89.11	0
20	262.632	262.610	-0.01	92.40	92.51	0.11
30	270.712	270.382	-0.12	94.73	95.04	0.32
40	268.925	268.376	-0.20	94.28	94.94	0.69
50	270.512	269.608	-0.35	94.86	95.63	0.81

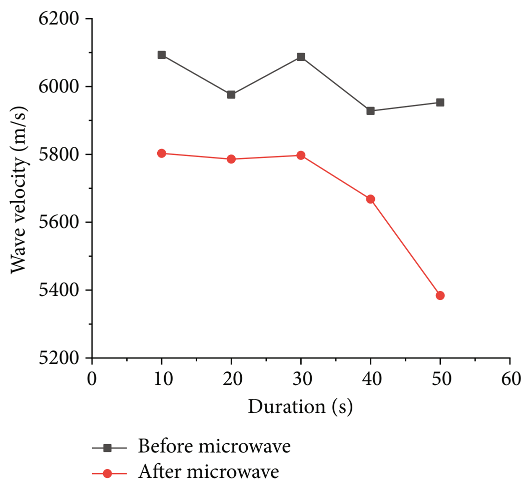


Figure 8: Changes of the ultrasonic wave velocity with the duration of microwave irradiation.

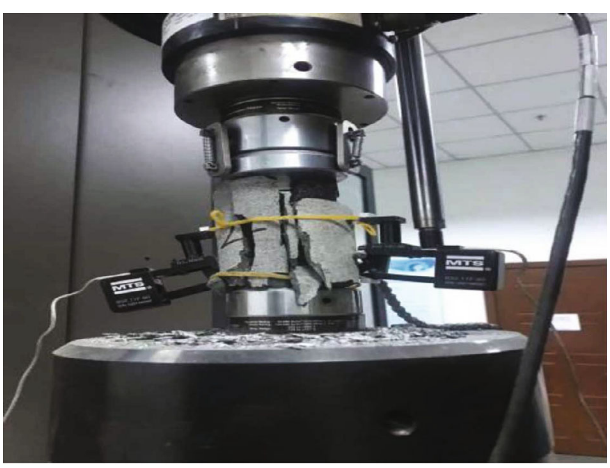


Figure 9: Uniaxial compression effect of the basalt sample.

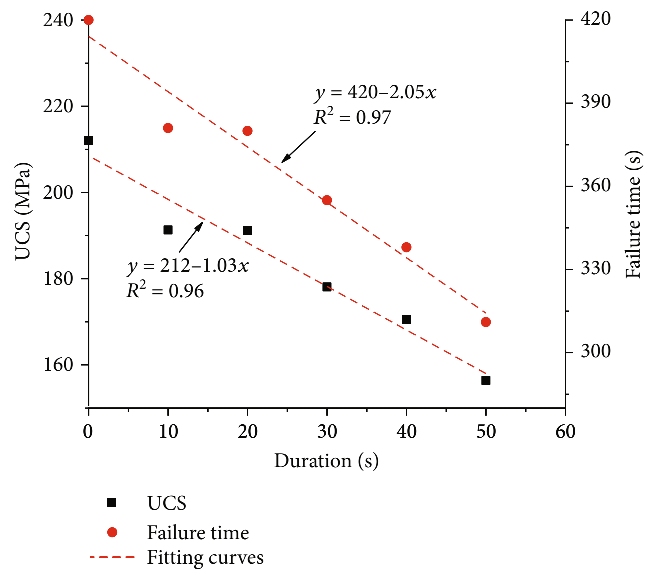


Figure 10: Changes of the UCS and time for failure of the rock with the duration of microwave irradiation.

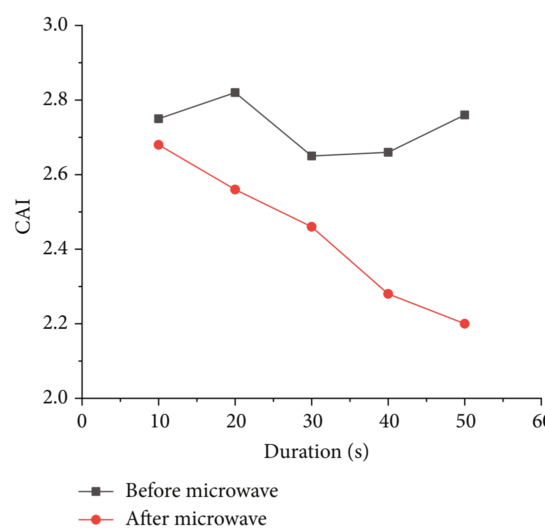


Figure 11: Changes of the CAI with the duration of microwave irradiation.

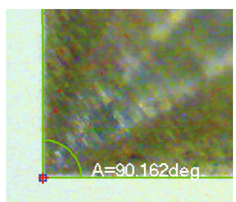
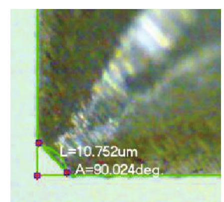
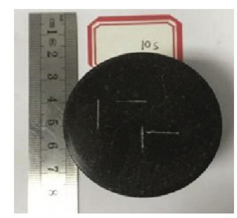
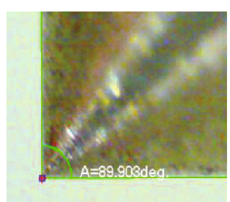
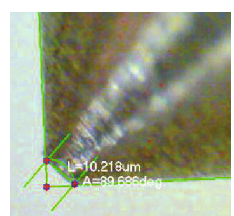
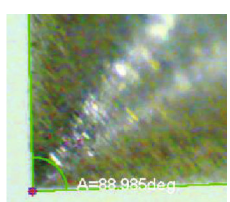
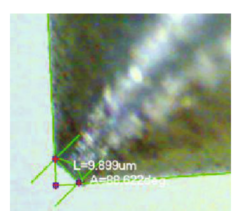
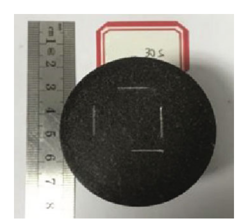
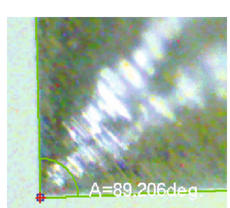
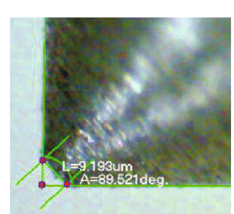
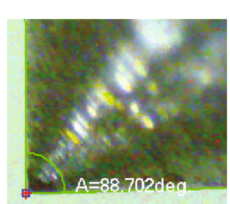
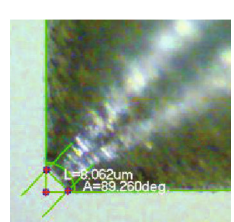
accelerate damage in the rock and shorten the time required for the failure of the rock, thus improving the rock breakage efficiency.

After microwave irradiation, the failure time of UCS decreases gradually with the increase of microwave irradiation time, showing a linear decreasing relationship. The relationship between failure time and microwave irradiation time is similar to that between UCS and microwave irradia-

Table 4: Comparison of CAI values of the basalt samples before and after microwave irradiation.

Serial no. of samples	Scratch direction	Measurements after rotating for 120°			Average CAI	Duration (s)	Measurements after rotating for 120°			Average CAI
1-1	Horizontal	2.72	2.68	2.72	2.75	10	2.67	2.61	2.58	2.68
	Vertical	2.83	2.86	2.76			2.62	3.00	2.61	
1-2	Horizontal	2.9	2.83	2.82	2.82	20	2.65	2.41	2.72	2.56
	Vertical	2.86	2.72	2.79			2.54	2.54	2.54	
1-3	Horizontal	2.58	2.51	2.51	2.65	30	2.47	2.54	2.51	2.46
	Vertical	2.75	2.72	2.86			2.44	2.40	2.47	
1-4	Horizontal	2.72	2.58	2.58	2.66	40	2.40	2.44	2.43	2.28
	Vertical	2.79	2.65	2.68			2.07	2.29	2.09	
1-5	Horizontal	2.69	2.62	2.62	2.76	50	1.98	1.98	2.01	2.00
	Vertical	2.86	2.93	2.90			2.01	1.98	2.01	

Table 5: Images of stylus and rock scratches before and after microwave irradiation.

Serial no.	Duration (s)	Original images of the stylus	Images of the worn stylus	Images of scratches on the rock
1-1	10			
1-2	20			
1-3	30			
1-4	40			
1-5	50			

tion time. On the one hand, the control method used in the uniaxial compression test is load control because the peak strength of rock decreases after microwave irradiation. When the loading rate is constant, the failure time is directly proportional to the peak intensity, which leads to the reduction of the failure time. On the other hand, microwave irradiation leads to the reduction of rock strength and failure time, which indicates that microwave irradiation can improve the efficiency of rock breaking.

3.4. CAI Analysis. The Cerchar abrasion test results of the rock are shown in Figure 11 and Tables 4 and 5. Before microwave irradiation, the CAI of the basalt is about 2.7 on average and the tip of the stylus is seriously worn, which indicates the large wearing of mechanical tools in the process of rock breakage. After microwave irradiation for 10 s, the CAI of the rock changes slightly. As the duration of microwave irradiation prolongs, the CAI decreases slowly after microwave irradiation for 20 and 30 s. The decreased rate of the CAI grows after microwave irradiation for 40 s, while it slows down again when the duration of microwave irradiation reaches 50 s. The CAI of the basalt sample shows a slow decrease trend on the whole with the increasing duration of microwave irradiation.

The CAI measures the degree of wearing of the stylus due to rocks and also reflects the rock abrasivity [32]. The larger the CAI is, the more unlikely the rock is abrased and the more serious the tool wearing in the mechanical excavation. The CAI constantly reduces with the increasing duration of microwave irradiation, which suggests that microwave irradiation decreases the rock abrasivity and therefore reduces the wearing of rock breakage tools in the mechanical excavation. As a result, this lowers the maintenance time and cost of rock breakage equipment and improves the rock breakage efficiency.

4. Conclusions

The surface temperature of the rock subjected to microwave irradiation linearly rises with the duration of microwave irradiation. As the duration of microwave irradiation prolongs, the number and width of surface fractures on the rock constantly grow. The fractures are mainly generated due to cracking along and passing through wave-absorbing minerals inside the rock, accompanied by a constant decrease in the mass while an increase in the volume of the basalt sample. After microwave irradiation, the ultrasonic wave velocity of the rock constantly decreases with the increasing duration of microwave irradiation. This indicates that the damage inside the rock constantly expands with the increasing duration and proves that microwave irradiation to some extent can aggravate the damage inside the rock. The UCS of the rock experiencing microwave irradiation declines to some extent, and the longer the microwave irradiation is, the more substantially the UCS decreases and the shorter the time taken for rock breakage. The result indicates that microwave irradiation to some extent can effectively reduce the UCS of the rock and lower the energy needed for rock breakage. After microwave irradiation, the CAI of the rock is found to decrease and the longer the microwave irradiation is, the more greatly the CAI decreases. The result suggests that microwave irradiation can lower the rock abrasivity, thus reducing the wearing of rock breakage tools during mechanical excavation and improving the rock breakage efficiency.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors wish to confirm that there are no known conflicts of interest associated with this manuscript.

Acknowledgments

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