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Mechanistic Study of a Microwave Field-Controlled Static Crushing Agent for Efficient Rock Breaking

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Cite This: *ACS Omega* 2022, 7, 29344−29355

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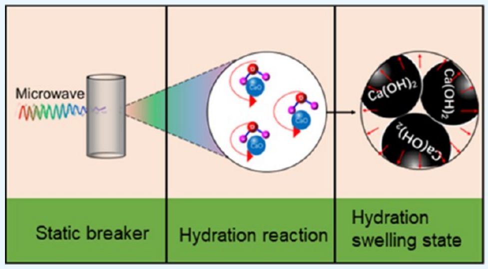


ABSTRACT: The long reaction time and uncontrollable reaction process of the swelling agent in the process of rock breaking by static crushing agent lead to unsatisfactory efficiency and effect of rock breaking. This paper uses physical experiments to compare and analyze the changes in temperature and pressure of the hydration reaction under different microwave conditions; utilizes microscopic analysis of the hydration reaction products under each condition, combined with numerical calculations to elucidate the mechanism of the effect of microwave field on the hydration reaction of the expansion agent; and proposes a microwave field-controlled static crushing agent rock-breaking method. The study reached the following main conclusions: (1) microwave heating is better than conventional heating in terms of heating rate, peak temperature, and peak pressure; (2) using static crushing agent rock breaking is preferable to use a low-power microwave field to control the reaction process, and to ensure that the initial temperature is not higher than the local water boiling point; (3) microwave heating to promote the reaction mechanism lies in its deep heating of the system, faster heating rate, and higher energy utilization, and is more conducive to hydration expansion reaction; (4) selective heating of microwaves can enhance the hydration reaction of calcium oxide and inhibit the production of hydrated tricalcium silicate, making the reaction more complete, while microwave heating will also improve the microstructure of hydration products.

1. INTRODUCTION

Static crushing agent is a kind of powder material with high expansion characteristics and nonblasting properties prepared by grinding inorganic compounds with high-temperature-calcined CaO as the main component and corresponding additives such as cement, which is noncombustible, nonexplosive, natural nontoxic.[1] Static blasting technology is a fast-developing blasting technology in recent years, where static crushing agents are mixed with water to form a slurry and then poured into the rock or cement borehole, resulting in a new product $Ca(OH)_2$ as the hydration reaction advances, thereby increasing the solid phase content by 2 or 3 times in volume.[2] Compared with the traditional explosive blasting process, it has the advantages of wide applicability, high safety, and stability.

Research on static crushing agents began in Japan in the 1970s. Toshio Kono was the first to conduct theoretical research on expansion agents, pointing out that the magnitude of expansion pressure depends on the growth of $Ca(OH)_2$ crystals and finding that the ambient temperature and the thermal conductivity of the crushed material are the main factors affecting their growth.[3] A large number of scholars at home and abroad have conducted a large number of experimental studies and found that the ratio of water agent, temperature, and pore size are the main factors affecting the expansion pressure of the static crushing agent.[4−8] Among them, temperature is the key factor affecting the speed and peak pressure of static crushing agent, and many other studies have shown that the higher the temperature, the faster the peak pressure is reached, and the peak expansion pressure can be increased by increasing the pore size and suitable water agent ratio.[9,10] The peak expansion pressure can be increased by increasing the pore size and suitable water agent ratio. Some scholars focused on the improvement of temperature on the reaction efficiency of static breakers, indicating that the reaction rate can be changed by increasing the temperature.[11,12]

As a heating method, microwave can control the hydration reaction more effectively through selective heating.[13,14] The strong vibration of the dipole moment of the water molecules interacting with the microwave field is described in Figure 1. The diffuse motion of the water molecules absorbs electromagnetic energy and generates huge energy by oscillating at a high speed of billions of times per second.[15] The increase in the volume of each CaO is accompanied by an exponential increase in the intermolecular gap, resulting in a significant increase in the macro-level volume of the reaction.Since the reactive molecules are bound by the pore walls, they are constantly squeezed against

Received: June 9, 2022
Accepted: August 4, 2022
Published: August 12, 2022

https://doi.org/10.1021/acsomega.2c03598
ACS Omega 2022, 7, 29344−29355

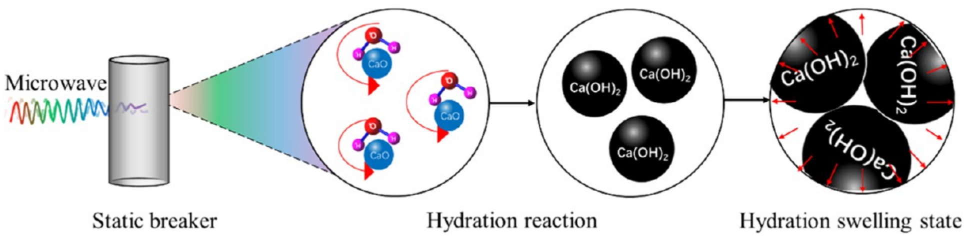


Figure 1. Microwave irradiation mechanism of the static crushing agent.

each other to form expansion pressure.[16] When the pressure reaches the tensile strength of the material, the material can develop voids and crack. Therefore, using microwave to improve the hydration rate of the static crushing agent is a feasible idea.

The above scholars have done in-depth research on the theory of static crushing agent and the influence of conventional heating on static crushing agent, but the research on the influence of microwave field on static crushing agent and the mechanism has not been reported, based on this paper, taking a static crushing agent as the research object, comparing and analyzing the characteristics of microwave heating compared with conventional heating, summarizing the macroscopic changes of expansion force under different microwave conditions, and analyzing the microscopic components and structural evolution characteristics of the static crushing agent after microwave irradiation, so as to reveal the influence mechanism of microwave power and irradiation duration on the hydration phase change process and propose a method to achieve efficient rock breaking of microwave field-controlled static crushing agent, providing theoretical support for controlling the process of swelling pressure of static crushing agent and improving rock-breaking efficiency.

2. EXPERIMENTAL PROGRAM AND PROCEDURE

To investigate the different effects of the hydration reaction of static crushing agent between microwave heating and conventional heating, under the premise of ensuring the same total energy output of conventional heating and microwave heating, three sets of experiments were designed as given in Table 1 to compare and analyze the changes in the hydration reaction temperature and expansion pressure of static crushing agent under different heating methods.

Table 1. Experimental Protocols for Different Heating Methods

group	heating method	heating power (w)	time (s)
group 1	conventional heating	400	20
group 2	microwave heating		
group 3	no heating		

To further investigate the effect of microwave conditions on the hydration reaction of static crushing agent, by studying the effect of different microwave radiation power and heating time on the reaction temperature and pressure, we designed as shown in Table 2 three different power irradiation conditions for each group of experiments and set up three different irradiation times, with five samples per program, totaling 45 sets of experiments.

The experiments involved in this paper used the experimental apparatus and equipment as shown in Figure 2, taking the static crushing agent as the research object and observing the hydration reaction law of the static crushing agent. The specific experimental steps are as follows.

Table 2. Experimental Programs for Different Microwave Conditions

time/s power/w	15	20	25
200	5	5	5
400	5	5	5
800	5	5	5

(i) To ensure the same basic conditions for each group of experiments and ensure better fluidity and expansion pressure, set the ratio of 0.3:1 of aqueous solution and static crushing agent (a),[17] and weigh 12 and 40 g, respectively, by electronic balance (b);

(ii) The static crushing agent solution (c) was mixed thoroughly and then heated using a water bath heater (d) and a microwave oven (e), respectively;

(iii) After heating for the appropriate time, the reaction vessel is taken out of the heating equipment and temperature measurements are made using an HD thermal imager (g), and pressure measurements are made using a homemade pressure sensing device (f).

(iv) XRD test (h) was performed on the stabilized phase change products to obtain the substance composition after the hydration reaction of the static crushing agent, and then SEM (i) was used to obtain its microstructure characteristics;

(v) The concrete samples with the same strength were tested under conventional and microwave conditions to test the feasibility of the static crushing agent with microwave irradiation in practical application.

3. DISCUSSION OF RESULTS

To investigate the effect of different heating methods on the hydration reaction of the static crushing agent, the difference in temperature and pressure of microwave heating compared to the other two methods is summarized and analyzed in Section 3.1 through physical control experiments; to further investigate the effect of different microwave conditions on the hydration reaction of the static crushing agent, the optimal combination of microwave power and heating time is summarized in Section 3.2 through physical control experiments and the selected input heating energy should not cause the static crushing agent solution to boil and evaporate as the basis for the selection of the optimal combination.

3.1. Effect of Heating Method on Reaction Temperature and Pressure. To study the effect of different heating methods on the hydration reaction of the static crushing agent, the temperature and pressure of the hydration reaction of the static crushing agent under the conditions of no heating,

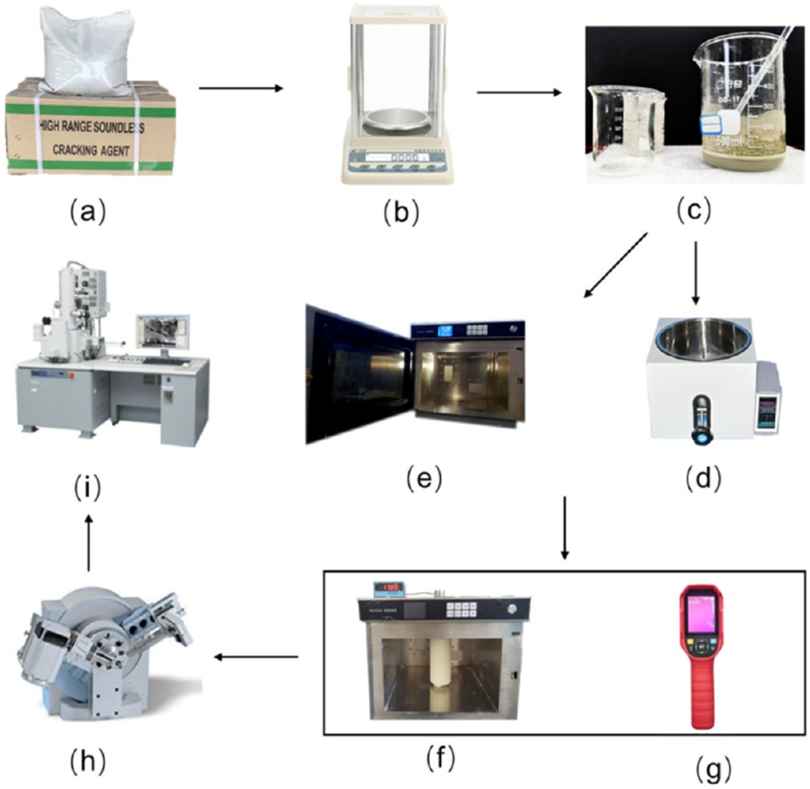
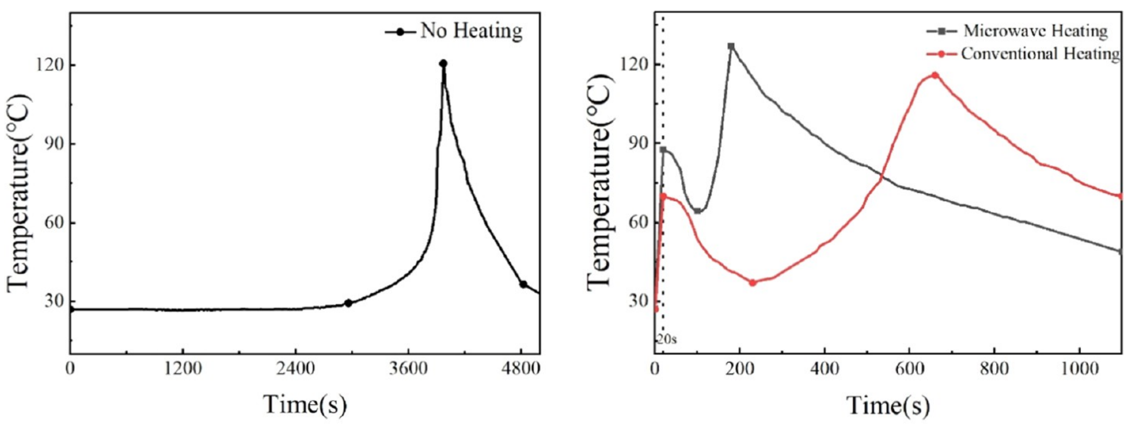


Figure 2. Experimental apparatus and equipment: (a) static crushing agent; (b) high-precision electronic balance; (c) mixed-static crushing agent solution; (d) water bath heater; (e) industrial microwave oven; (f) homemade pressure sensor; (g) UTi260B high-definition thermal imager; (h) Bruker AXS D8 analyzer; and (i) ZEISS Gemini 300 scanning electron microscope.



(a) No heating

(b) Microwave heating and conventional heating

Figure 3. Reaction temperature profiles for different heating methods.

conventional heating, and microwave heating were compared and analyzed with time, as shown in Figures 3 and 4.

As can be seen in Figure 3, the initial reaction temperature under different heating methods is 27 °C. The hydration reaction temperature did not change significantly within 0–3000 s without heating, the temperature increased rapidly within 3000–3970 s, and the reaction temperature decreased after reaching the peak temperature of 120.7 °C at 3970 s. Under conventional heating conditions, the reaction temperature increased from the initial temperature of 27–70 °C, and under microwave heating conditions, the reaction temperature increased from the initial temperature of 27–87.8 °C, after the static crushing agent was heated for 20 s later by microwave and conventional heating methods. Under conventional heating conditions, the temperature of the hydration reaction decreased from 20 to 230 s, increased rapidly from 230 to 660 s, reached the peak temperature of 116 °C at 660 s, and then decreased slowly with time. Under microwave heating conditions, the temperature of the hydration reaction decreased from 20 to 100 s, increased rapidly from 100 to 200 s, reached a peak temperature of 127.2 °C at 200 s, and then decreased slowly with time. This shows that the time for microwave heating to reach the peak temperature is 20 times faster than that without heating and 3.3 times faster than that of conventional heating. The peak temperature of the reaction under microwave heating is also the highest.

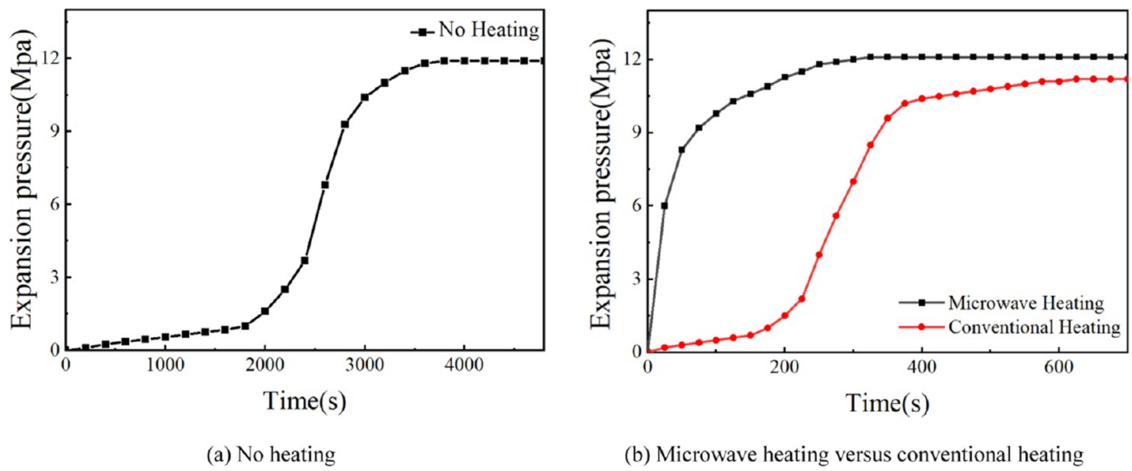


Figure 4. Curve of reaction pressure for different heating methods.

As can be seen from Figure 4, the growth of expansion pressure under nonheating conditions is "smooth−steep−smooth"; conventional heating and nonheating expansion pressure growth law is about the same, but the former pressure rate is faster; microwave heating lacks a "smooth" phase, with the reaction pressure increasing sharply and then smoothing. Overall, the expansion pressure tends to increase with time for all three heating methods. The preadaptation phase of the microwave heating method is significantly better than the other two methods, and the rate of pressure increase is faster.

3.2. Effect of Microwave Conditions on Reaction Temperature and Pressure. To further investigate the effect of different microwave conditions on the temperature and expansion pressure of the static crushing agent, constant powers of 200, 400, and 800 W were used to heat for 15, 20, and 25 s, respectively. Figure 5 shows the variation of reaction temperature and pressure with time under 200, 400, and 800 W irradiation. Figure 6 compares in detail the relationship between peak temperature and peak pressure under different microwave conditions.

According to Figures 5 and 6, with the increase of microwave power and heating time, the reaction reaches the peak temperature and peak pressure faster, i.e., the higher the input energy, the faster the reaction heating rate and pressure rate; according to the peak temperature curve in Figure 6, as the input energy decreases, the peak temperature rises first, then decreases, and becomes the highest at the reaction condition "400 W 20 s"; according to the peak pressure curve in Figure 6, as the input energy decreases, the peak pressure also decreases gradually. According to the peak pressure curve in Figure 6, the peak pressure decreases with the decrease of the input energy, i.e., the input energy and the peak pressure are positively correlated, and when the microwave input energy is lower than the reaction condition "400 W 20 s", the peak pressure increases significantly with the increase of energy, and when the input energy is higher than reaction condition "400 W 20 s", the peak pressure tends to increase slowly with energy.

A comparison of the weights of the reaction products before and after reaction condition "400 W 20 s" shows a significant decrease in weight, and it can be deduced from the results in Table 3 that the excessive energy provided to increase the temperature above the boiling point of water causes some of the water to evaporate, reducing the reaction with the calcium oxide and causing the final peak reaction temperature and expansion pressure to be affected. Therefore, in the actual use of the product, taking into account economic and energy efficiency, when selecting the microwave input energy, we should ensure that the temperature of the heating phase does not exceed the boiling point of the local water.

4. MECHANISMS AND ANALYSIS

To explore the influence of microwave field on the hydration reaction of the static crushing agent, this section analyzes from macro- and microscopic perspectives. Section 3.1 analyzes the influence of different heating methods on the rate of temperature rise from a macroscopic perspective to verify the accuracy of experimental data and theoretical data. Section 3.2 analyzes the influence of microwave heating on hydration products from a microscopic perspective to analyze the mechanism of microwave action.

4.1. Microwave Heating Mechanism. According to preliminary experiments, in the same input energy, the peak temperature and peak pressure of microwave heating are higher than those of conventional heating methods, which reflects in that the rate of static crushing agent hydration reaction using the microwave heating method is higher than using conventional heating. According to the Arrhenius formula, increasing the temperature can increase the percentage of activated molecules, thus increasing the number of activated molecules, the effective collision between molecules, and the chemical reaction rate.[18]

As shown in Figure 7, with the same energy input, the final temperature of the heating phase of microwave heating is higher than that of conventional heating, using the slope to indicate the heating rate of the two heating methods. The heating rate of microwave heating K_1 = 3.035, and the heating rate of conventional heating K_2 = 2.1. With the same input energy, the higher the heating rate, the faster the rate of hydration reaction, and the better the hydration effect. Therefore, the rate of heating phase is used to characterize the effect of different heating methods on the reaction, i.e., the higher the rate of heating, the better the effect of the heating method used.

To ensure the accuracy of the heating rate obtained from the experiment, this paper uses theoretical numerical calculations to further verify. The mechanism of interaction between the microwave and the material is very complex. The magnitude of the temperature generated is related to the dielectric properties of the heated material itself. Generally, composite permittivity ε

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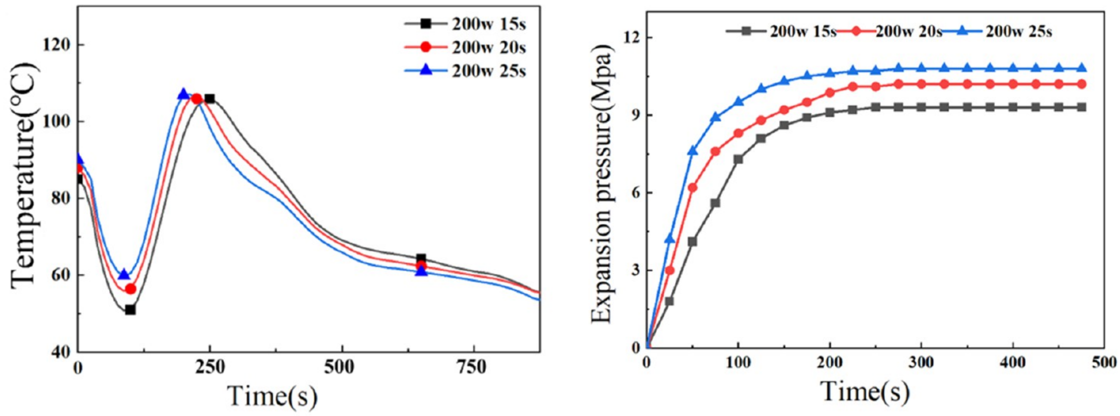
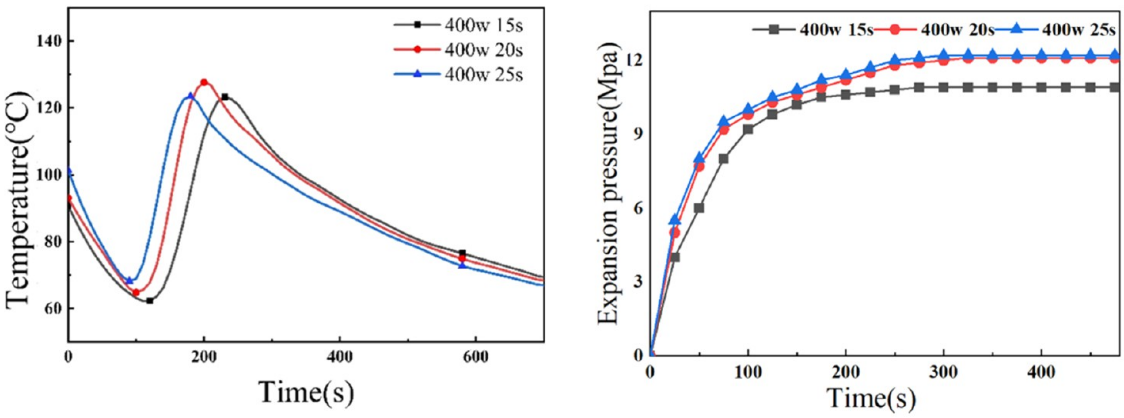
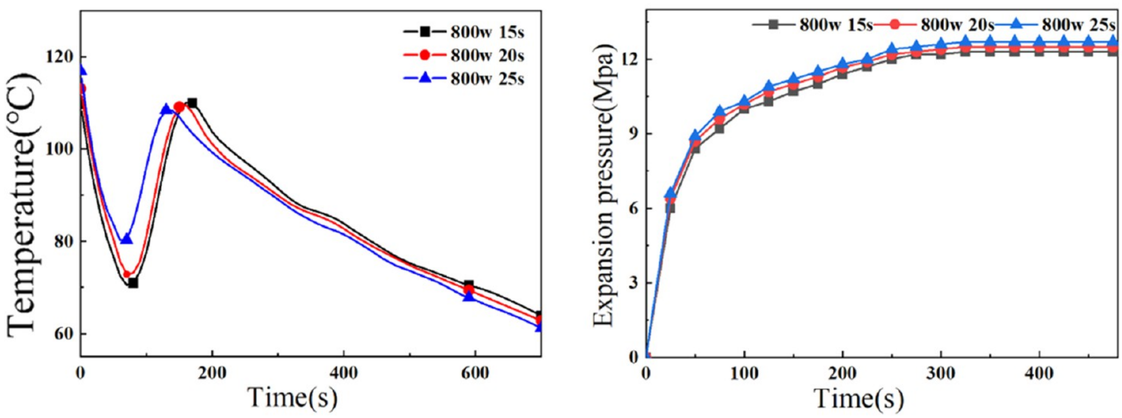


(a) p=200w, reaction temperature and pressure curve



(b) p=400w, reaction temperature and pressure curve



(c) p=800w, reaction temperature and pressure curve

Figure 5. Curve of reaction temperature and pressure for different microwave conditions.

is used to represent the measurement of dielectric absorbing and storing electric field energy,[19] as shown in eq 1

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

where ε' is the real part of the complex dielectric constant, whose size reflects the medium's ability to combine charges; ε'' is the imaginary part of the complex dielectric constant, which reflects the loss of the medium; and j is the imaginary part.

The interaction between the static crushing agent solution and the microwave energy can be derived from Maxwell's equations,[20] which can be expressed as

$$P = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{2}$$

where E is the electric field strength, V/m, E = 4000 V/m; f is the frequency, Hz; and $\varepsilon_0 = 8.85 \times 10^{-12}$ A/s.

Since the static crushing agent is a mixed substance, the virtual part of the mixed relative complex dielectric constant, density, and specific heat capacity of the static crushing agent can be estimated according to the virtual part of the mixed relative complex dielectric constant, density, specific heat capacity, and their volume proportion of each substance,[21] as shown in eq 3

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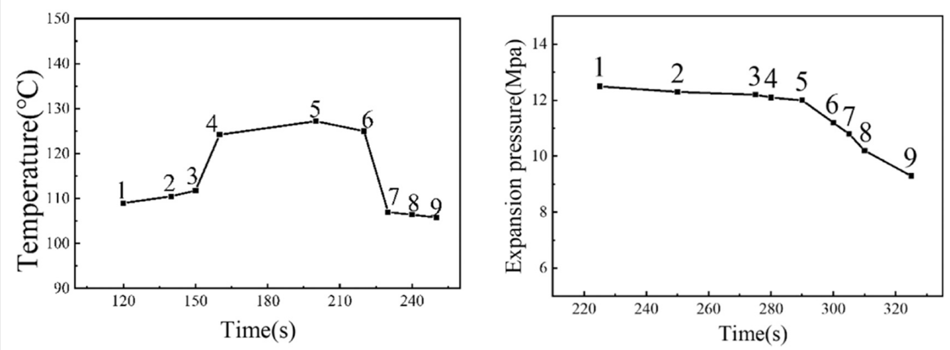

No.	Reaction conditions	Peak temperature (°C)	Time to peak temperature (s)	Peak pressure (Mpa)	Time to peak pressure (s)
1	800w 25s	109	120	12.5	325
2	800w 20s	110.5	140	12.3	310
3	800w 15s	111.8	150	12.2	305
4	400w 25s	124.2	160	12.1	300
5	400w 20s	127.2	200	12.0	290
6	400w 15s	125	220	11.2	280
7	200w 25s	106.8	230	10.8	275
8	200w 20s	106.4	240	10.2	250
9	200w 15s	105.8	250	9.3	225

Figure 6. Relationship between the magnitude of peak temperature and pressure under different microwave conditions.

Table 3. Difference in Mass before and after the Reaction under Different Microwave Conditions

	mass before reaction (g)	mass after reaction (g)	mass difference (g)
200 W 15 s	109.1	104	5.1
200 W 20 s	109.1	104	5.1
200 W 25 s	109.1	103.9	5.2
400 W 15 s	109.1	103.8	5.3
400 W 20 s	109.1	103.8	5.3
400 W 25 s	109.1	102.5	6.6
800 W 15 s	109.1	101.8	7.3
800 W 20 s	109.1	101.5	7.6
800 W 25 s	109.1	101.2	7.9

$$\varepsilon_r'' = \sum_{i=1}^{n} V_i \varepsilon_{ri}''$$

$$\rho = \sum_{i=1}^{n} V_i \rho_i$$

$$C_p = \frac{\sum_{i=1}^{n} V_i \rho_i C_{pi}}{\rho} \quad (3)$$

where V_i is the volume share of a substance, V_{H_2O} = 27.8% and V_{CaO} = 72.2%; ρ is the density of a substance, ρ_{H_2O} =1000 kg/m^3 and ρ_{CaO} = 3350 kg/m^3; and C_p is the heat capacity of a substance, C_{pH_2O} = 4200 J/(kg·°C) and C_{pCaO} = 256 J/(kg·°C).

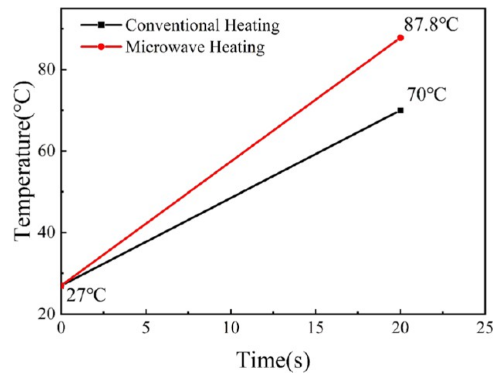

Figure 7. Temperature rise curve for conventional and microwave heating.

According to the thermodynamic formula and electromagnetic loss power,[22,23] the heating rate under the action of microwave can be calculated as shown in eq 4

$$\Delta T = \frac{2\pi f \varepsilon_r'' \varepsilon_0 |E|^2}{\rho C_p} t \quad (4)$$

From eq 4, it can be seen that the rate of heating of a unit volume of static crushing agent depends mainly on the electric field strength of the microwave field, the microwave frequency of the microwave field, and the dielectric properties of the static crushing agent solution. The rate of heating $K_1' = \frac{2\pi f \varepsilon_r'' \varepsilon_0 |E|^2}{\rho C_p}$ is

https://doi.org/10.1021/acsomega.2c03598
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substituted into the known variables to obtain K'_1 = 3.31, which is the theoretical heating rate value under microwave conditions.

The rate of heating under conventional heating can be calculated from the heat calculation formula,[24] as in eq 5

$$\Delta T = \frac{P}{mC_p}t \tag{5}$$

where P is the power, P = 200 W; m is the mass of the object, m = 0.11 kg; and ΔT is the amount of change in temperature after heat absorption.

From eq 5, it can be seen that under conventional heating conditions, the rate of heating $K_2' = \frac{P}{mC_p}$ is substituted into the known variables to obtain K'_2 = 2.68 as the theoretical heating rate value under conventional action conditions.

It can be concluded that the heating rate measured by the experiment is consistent with the theoretical numerical analysis results, and the heating rate of microwave heating is higher than that of conventional heating under the condition of experimental error. Due to the deep heating of the system, without the heat conduction process of conventional heating, microwave heating has lower energy consumption, faster heating rate, and less energy consumption for increasing the same temperature, so we can conclude that microwave heating is a better way to heat.

4.2. Composition and Microstructure Analysis. Quantitative X-ray diffraction studies of dried static crushing agent powders can give an idea of the mineralogical composition of the static crushing agent. Figure 8 shows that the static crushing

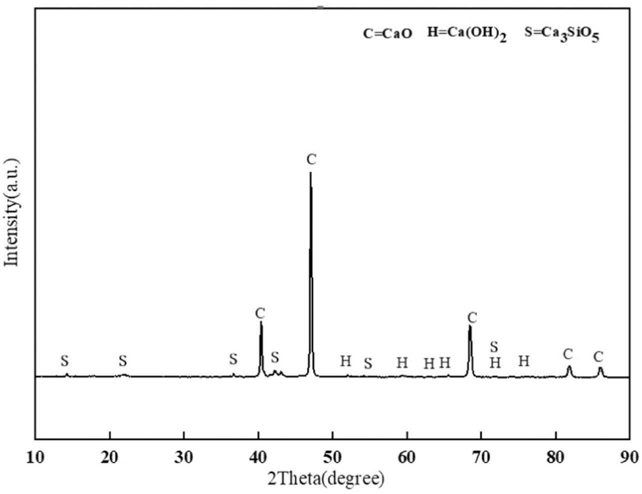

Figure 8. X-ray diffraction pattern of dry static crushing agent powder.

agent raw materials are mainly CaO, SiO_2, and $Ca(OH)_2$. CaO is the predominant elemental component, while SiO_2 is wrapped around CaO to reduce the contact reaction between calcium oxide and air, and the existence of 10.2% Ca $(OH)_2$ is speculated to be due to improper disposal of raw materials during packaging and use, causing some CaO to react. The specific chemical composition weight fractions are shown in Table 4.

To clarify the hydration reaction mechanism of the static crushing agent under different microwave conditions, the hydration products need to be further analyzed. As shown in Figure 9, the sample information of minerals formed in the samples scanned by the hydrated static crushing agent under

Table 4. Calculated Chemical Composition of Static Crushing Agent

ingredients	CaO	SiO_2	$Ca(OH)_2$
weight fraction (%)	80.1	9.6	10.2

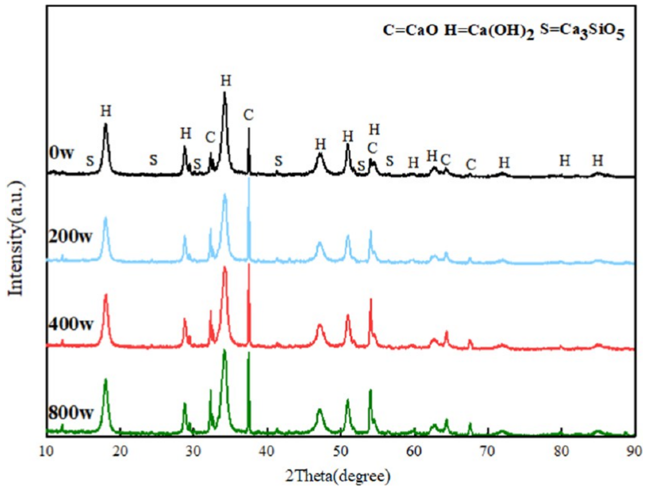

Figure 9. X-ray diffraction patterns of static crushing agent hydration products under different microwave conditions.

normal temperature and microwave heating powers of 200, 400, and 800 W can be clearly observed in the X-ray diffraction pattern.

The hydration products of static expansion include $Ca(OH)_2$ and CSH gel. $Ca(OH)_2$ is the major product, and CSH gel is the minor product. The chemical reaction equations involved are as in eqs 6 and 7.

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{6}$$

$$C_3S + 3H_2O \rightarrow C - S - H + 2Ca(OH)_2 \tag{7}$$

In the hydration products of the above two reactions, $Ca(OH)_2$ is the main reason for its volume expansion. As a cementing material, CSH gel plays a similar role as cement and becomes a strength component of the static crushing agent. As shown in Figure 10, the weight proportion of each component is shown in detail.

As shown in Figure 10, when the microwave power is increased from 0 to 400 W, the CaO content decreases from 14 to 7%. When the microwave power is 800 W, due to the large loss of water molecules, the CaO content increases to 13%, but it is still lower than the normal temperature. The specific gravity content of CSH gel is as high as 17% at room temperature and is lower than this value under microwave heating. The specific gravity content of Ca$(OH)_2$ under normal temperature is 69%, which is higher than this value under microwave heating. Therefore, compared with normal temperature, microwave heating can reduce the specific gravity fraction of CaO and increase the total weight fraction of Ca$(OH)_2$ and CSH gel materials. The greater the weight fraction of $Ca(OH)_2$, the better the hydration degree of the static crushing agent and the more complete the reaction, which means that microwave selective heating can enhance the hydration reaction of main CaO, inhibit the production of secondary products of CSH gel, and make the reaction more complete. The increase of $Ca(OH)_2$ content in the hydration product of the static crushing agent is the main reason for the increase in the swelling pressure.

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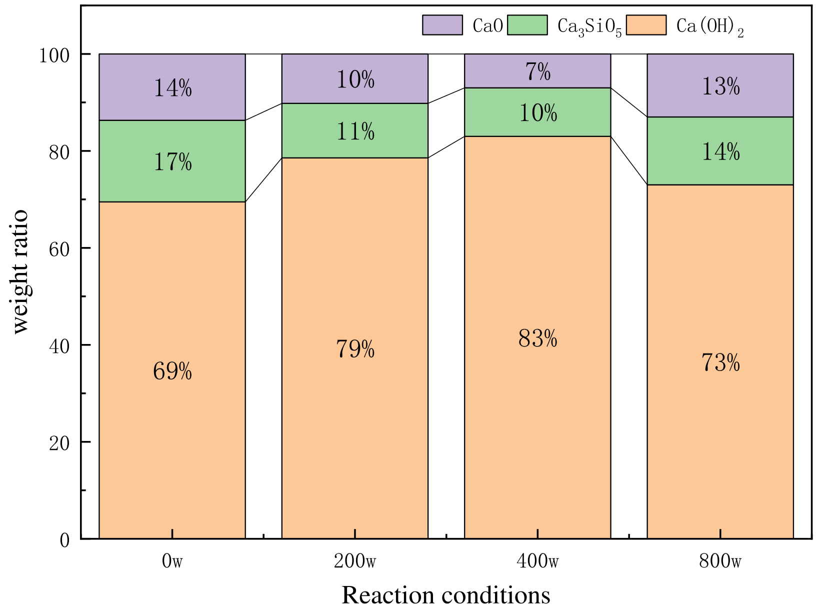

Figure 10. Proportion of material components under each reaction condition.

Comparing the experimental graphs, it is found that there is a positive correlation between the weight fraction of $Ca(OH)_2$ in the reaction product and the peak temperature and swelling pressure of the static crushing agent. The microscopic approach verifies that microwave heating results in a more complete hydration of the reaction and facilitates the generation of higher expansion pressures.

The hydrated material of the static crushing agent was subjected to morphological analysis by the SEM technique, as shown in Figure 11, which is a scanning electron microscope image of the hydrated static crushing agent specimens from two sets of experiments. The hydration products of $Ca(OH)_2$ were found to be mostly lumpy or agglomerated and of larger size in Figure 11a,b. Compared with conventional heating, the degree of hydration by microwave action was more complete and the percentage and volume of $Ca(OH)_2$ hydration products were larger; compared with Figure 11c,d, most of the hydration products of CSH gels showed columnar or spear-like structures, and the coalescence products showed crust-like and bean-like structures; in contrast to Figure 11e,f, the surface morphology of the reacted materials changed significantly after microwave heating, and unlike the fibrous and whisker-like hydration products produced in most areas under conventional heating, the surface grooves of the particles increased significantly under microwave conditions and the surface morphology was rougher and had obvious fissures. The increased contact area is more conducive to the hydration reaction.

As shown in Figure 12, with the increase of microwave power, the hydration products of the static crushing agent changed from lumpy to roll-like, with significantly more surface grooves and rougher surface morphology, indicating more complete hydration. Overall, the microwave heating method has a greater impact on the microstructure of the hydration products of the static crushing agent. As one of the important early hydration products, $Ca(OH)_2$ has a great impact on the concrete rupture.

5. ROCK-BREAKING EFFICIENCY TESTS

To test the feasibility of static crushing agent under microwave irradiation in practical applications, and to verify the enhancement of rock-breaking efficiency by microwaves, the theoretical results of this paper were applied to rock-breaking efficiency tests, using concrete specimens of the same strength in unheated and microwave heating methods for cracking experiments, to observe the cracking time and cracking effect. To clearly describe the laboratory work carried out, the experimental steps of this experiment are summarized in Figure 13.

From the theoretical derivation of eq 8 of the elastic mechanics,[25,26] the concrete cracking equation is

$$(1 + \nu)p_r \geq R_t \cdot B \tag{8}$$

where B represents the cracking coefficient of the material being broken, R_t represents the tensile strength of the material being broken, ν represents Poisson's ratio of the ruptured material, and p_r represents the expansion pressure in the borehole, MPa.

The empirical coefficient of cracking of the concrete in this study was 0.5−0.7, the Poisson's ratio of the concrete was 0.2, and the tensile strength of the concrete was 10.2, as shown in Table 5. For the average load strength, the maximum expansion pressure of the amount of static crushing agent configured under microwave irradiation was 12.0 MPa according to the preliminary experiments, which was brought into eq 8, and the conditions for concrete cracking were met, verifying that the static crushing agent configured was sufficient to crack the concrete specimens and ensure that the experiment could be carried out effectively.

In the rock-breaking efficiency test experiment, the size of the concrete test block is designed as shown in Figure 14. The average load pressure of the prepared concrete test block is 10.2 MPa. The ratio of microwave heating equipment and static crushing agent mixed solution is the same as that in the previous experiment. Rapid-setting cement is used for sealing, and the experiment is carried out only after the sealing cement has hardened to a certain strength. When selecting the microwave input energy, according to the principle that the selected input heating energy does not make the static crushing agent solution boil and volatilize, based on the preliminary experiment, the concrete cracking experiment selects the heating combination of microwave power 400 W and heating time 20 s.

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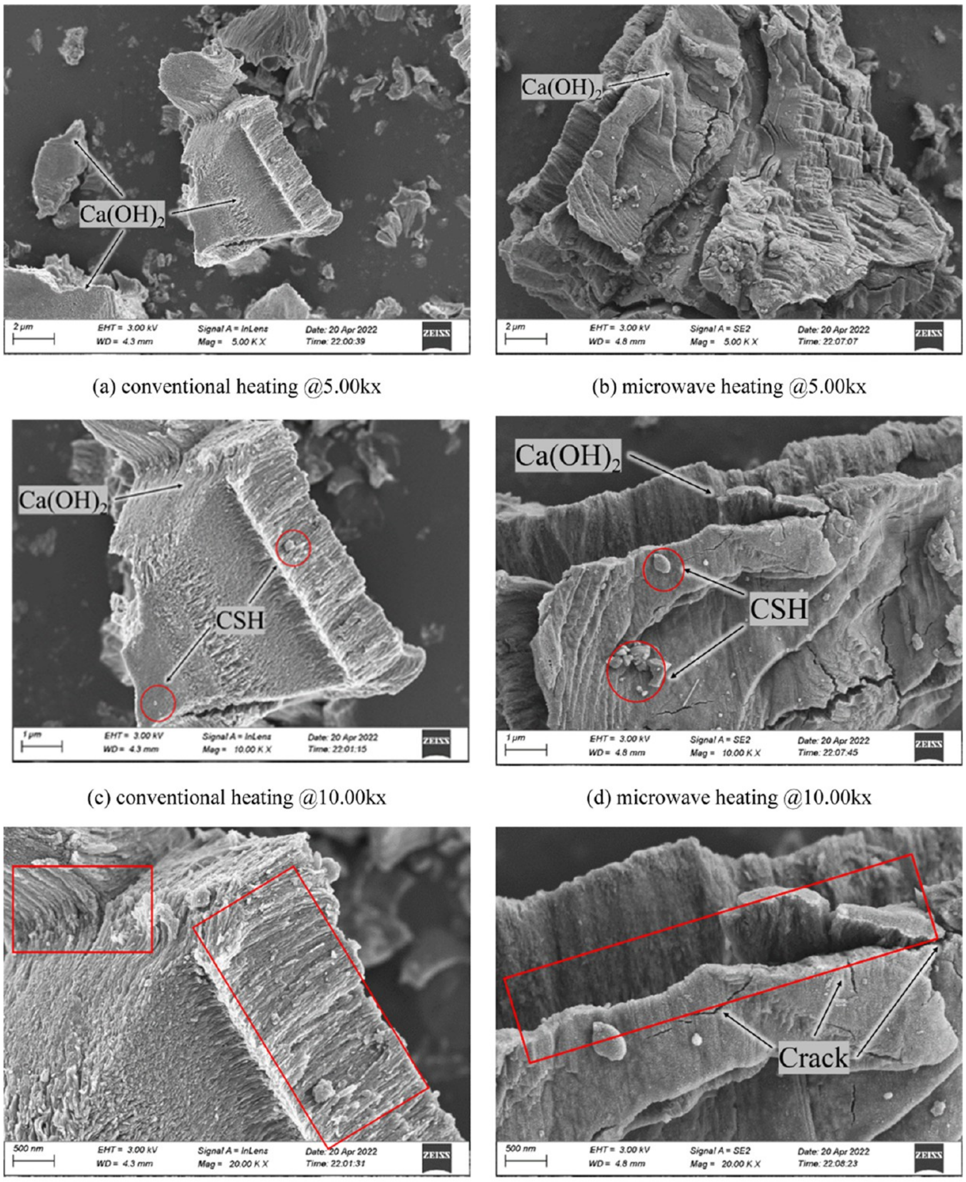

(a) conventional heating @5.00kx (b) microwave heating @5.00kx

(c) conventional heating @10.00kx (d) microwave heating @10.00kx

(e) conventional heating @20.00kx (f) microwave heating @20.00kx

Figure 11. Scanning electron microscope image of the hydration product of the static crushing agent.

As shown in Figure 15, concrete specimen cracking tests show that the degree of crack expansion in concrete specimens increases with time but microwave-heated concrete specimens crack more quickly than unheated concrete specimens. The initial cracking of the microwave-heated concrete specimens appeared earlier, and the final cracking effect was more pronounced.

To analyze and grasp the condition of the test fracture process and to present the cracking process with time more clearly and distinctly, the main crack width−time curves for each test specimen were plotted according to the recorded test results as shown in Figure 16. It can be seen from the curves that in concrete specimens, the time of main crack unfolding width and the time of expansion pressure change are basically the same, and microwave heating can accelerate the hydration heating rate of the static crushing agent, thus significantly enhancing the cracking effect of the static crushing agent. From the perspective of the whole crushing process, the static crushing agent studied in this paper can achieve the purpose of high-efficiency rock breaking through microwave irradiation, which is feasible in actual production.

6. CONCLUSIONS

In this paper, by comparing the experimental temperature and pressure changes under different heating conditions, the microscopic analysis of the hydration reaction products under various conditions is carried out, and the influence mechanism of microwave is clarified by numerical simulation, and the following conclusions are obtained:

(1) There are four stages in the temperature variation of microwave irradiated static crushing agent with time: heating up, rapidly falling, rapidly rising, and falling stage. The volume expansion of the static crushing agent is mainly concentrated in the stage of rapidly falling and rapidly rising.

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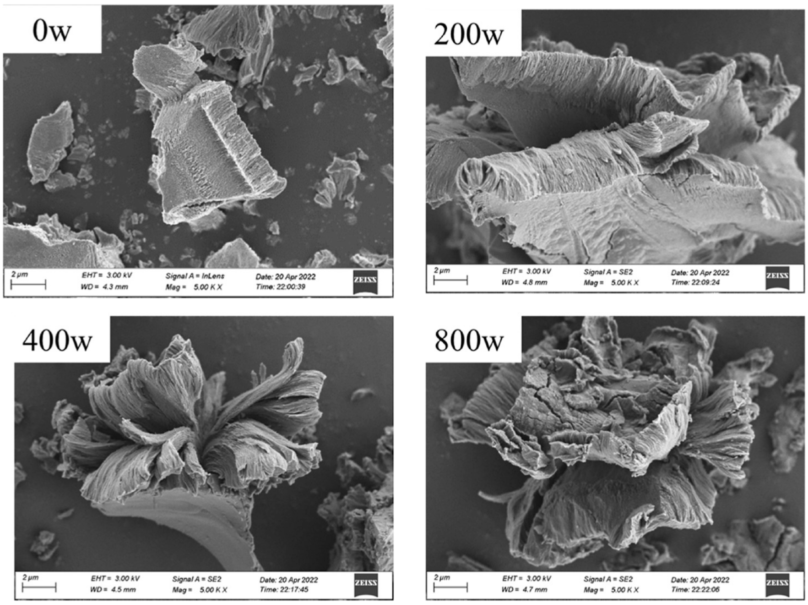

Figure 12. Morphology of the hydration products of $Ca(OH)_2$ under different conditions.

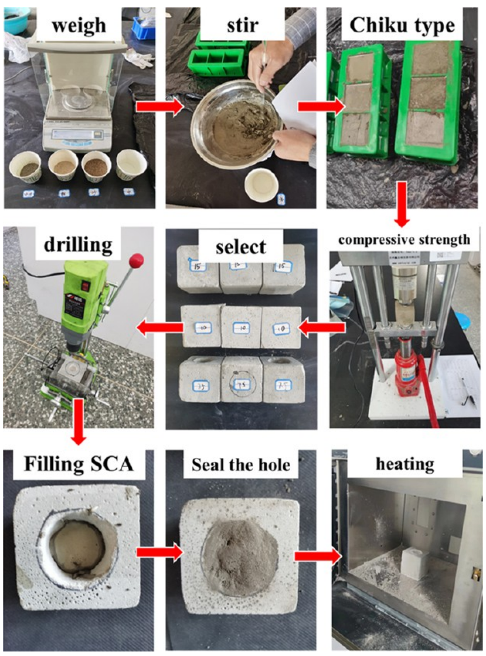

Figure 13. Experimental flow in this experiment.

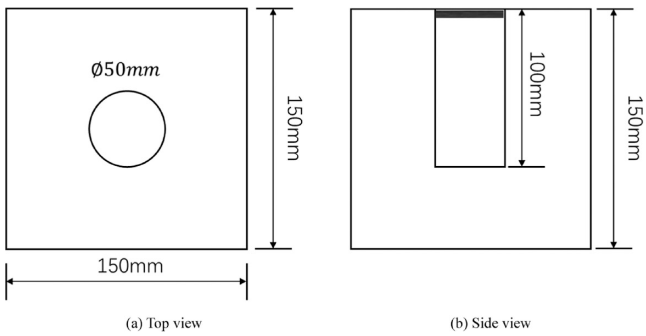

Figure 14. Schematic diagram of concrete test block dimensions.

Table 5. Concrete Load Pressure

load pressure (MPa)	average load pressure (MPa)
10.2	10.2
10.5	
10.3	
10.1	
10.1	
10.2	
10.1	
10.1	
10.6	

(2) Compared with no heating and conventional heating methods, microwave heating can greatly accelerate the rate of heating, increasing the peak temperature and peak pressure. The microwave heating method of expansion and pressure of the preadaptation phase is significantly better than the other two ways and faster pressurization.

(3) According to different microwave irradiation conditions, it can be concluded that the rate of temperature rise and expansion pressure is proportional to the microwave heating input energy, but a too high input energy will reduce the peak temperature and there is no significant change in the increase in expansion pressure. Therefore, when choosing microwave power and heating duration, it should be ensured that the initial temperature is not higher than the local water boiling point.

(4) Microwave heating can reduce the energy loss generated by heat conduction, and synchronous heating with the material, simultaneous heating, high heating efficiency, and microwave heating significantly improve the uniformity of heating, and its thermal effect can be deep heating of the system, faster heating rate, and better way of heating.

(5) Microwave selective heating can enhance the main hydration reaction of CaO and inhibit the production of secondary product, CSH gel; under the condition of microwave, the surface gullies of particles increase obviously, the surface morphology is rough, there are obvious cracks, and the increase of contact area is more

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ACS Omega 2022, 7, 29344−29355

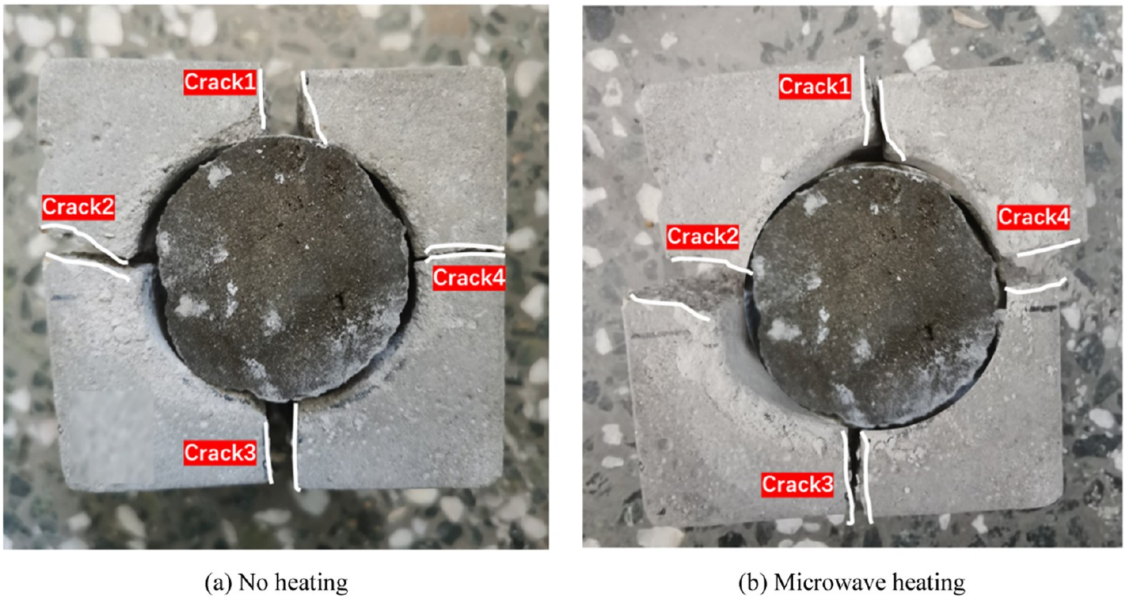

Figure 15. Physical view of cracks.

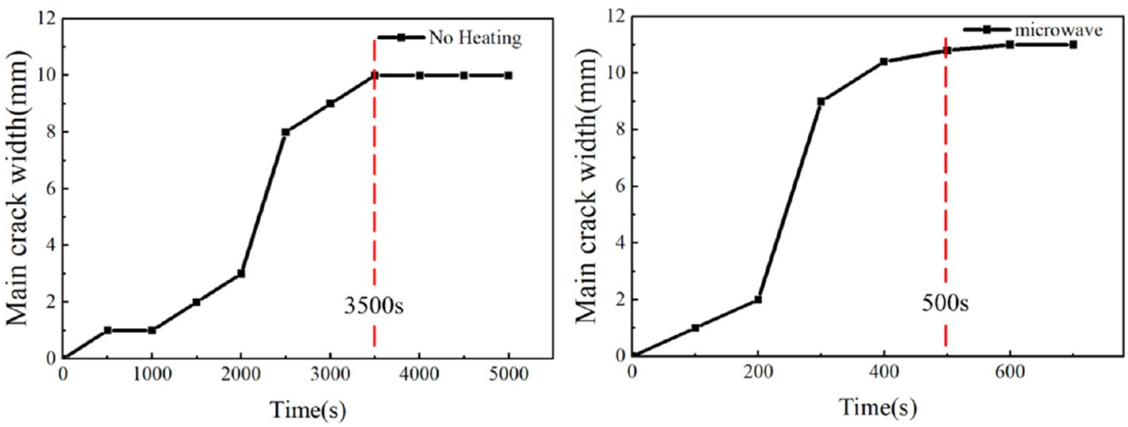

Figure 16. Width−time curve of main crack expansion in concrete specimens.

conducive to the hydration reaction. From the microscopic point of view, it is verified that microwave heating can make the reaction hydration more complete, which is conducive to the generation of higher expansion pressure.

(6) Through the concrete cracking experiments to verify the results can be obtained, microwave irradiation of the static crushing agent can accelerate the concrete cracking time and effect, to achieve the purpose of efficient rock breaking and to verify that its practical production application is feasible.

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https://doi.org/10.1021/acsomega.2c03598
ACS Omega 2022, 7, 29344−29355

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https://pubs.acs.org/10.1021/acsomega.2c03598

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by National Innovation Training Program for College Students (grant no. 202110755003), National Natural Science Foundation of China (grant no. 52164011), and National Natural Science Foundation of China (grant no. 51764050).

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