# Experimental Study on the Electromagnetic Response and Strength Deterioration of Mortar under Microwave Irradiation

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## Abstract

The crushing efficiency of concrete under microwave irradiation mainly depends on the crushing of mortar, and it is of great significance to study the strength deterioration law of mortar under microwave irradiation. To reveal the strength deterioration law of mortar under microwave irradiation, the dielectric properties of mortar blocks and their raw materials were first tested, as dielectric properties are the main influencing parameters for the conversion of electromagnetic energy into thermal energy. A vector network analyzer was used to obtain the complex permittivity of cement, sand, water, and mortar blocks, and the effects of factors such as frequency and temperature on the permittivity and heating rate were investigated. The influence of microwave heating duration on the compressive strength of mortars with different strength grades was further analyzed. The results show that temperature has a significant effect on permittivity, and the dielectric properties of water decrease markedly with increasing temperature. The higher the strength of the mortar, the stronger its dielectric properties and the faster its heating rate. A comprehensive analysis of the heating behavior, mass loss, and changes in compressive strength indicates that after microwave heating at 5kW for 60s, internal cracks in M20, M25, and M30 mortars all enter a rapid propagation stage, and their strength decreases significantly. After heating for 100s, the strengths of the three mortars decrease by 25%, 18%, and 16%, respectively. This study can provide a reference for microwave crushing and strength weakening of mortar, and further provide technical guidance for the popularization and application of microwave-based concrete crushing technology.

## Full Text

# Experimental Study on the Electromagnetic Response and Strength Deterioration of Mortar under Microwave Irradiation

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**Abstract:** The crushing efficiency of concrete under microwave action mainly depends on the crushing of mortar. Therefore, studying the deterioration law of mortar strength under microwave action is of great significance. To reveal the deterioration law of mortar strength under microwave action, the dielectric properties of mortar blocks and their raw materials were first tested; dielectric properties are the main parameters affecting the conversion of electromagnetic energy into thermal energy. The complex dielectric constants of cement, sand, water, and mortar blocks were obtained using a vector network analyzer. The effects of factors such as frequency and temperature on the dielectric constant and heating rate were investigated, and the influence of microwave heating duration on the compressive strength of mortars of different strength grades was further analyzed. The results show that temperature has a relatively significant effect on the dielectric constant; as temperature increases, the dielectric properties of water decrease markedly. The higher the strength of mortar, the stronger its dielectric properties and the faster its heating rate. A comprehensive analysis of heating law, mass loss, and variation in compressive strength indicates that after 60 s of 5 kW microwave heating, internal cracks in mortars of the three strength grades M20, M25, and M30 all enter a rapid propagation stage, and strength decreases markedly. After 100 s of heating, the strengths of the three mortars decrease by 25%, 18%, and 16%, respectively. This study can provide a reference for microwave crushing of mortar and strength weakening, and further provide technical guidance for the promotion and application of microwave concrete crushing technology.

**Keywords:** microwave; mortar; dielectric properties; temperature; compressive strength

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# Experimental Study on Electromagnetic Response and Strength Deterioration of Mortar under Microwave Heating

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**Abstract:** The crushing efficiency of concrete under microwave action mainly depends on the crushing of mortar, so it is of great significance to study the deterioration law of mortar strength under microwave action. In order to reveal the deterioration law of mortar strength under microwave action, firstly, the dielectric properties of mortar block and its raw materials are tested, which is the main parameter affecting the conversion of electromagnetic energy into heat energy. The complex dielectric constants of cement, sand, water and mortar blocks were obtained by vector grid analyzer. The effects of frequency, temperature, and other

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factors on the dielectric constants and heating rates were analyzed. The influences of microwave heating time on the compressive strength of mortars with different strength grades were further analyzed. The results show that the effect of temperature on the dielectric constant is significant, and the dielectric properties of water decrease markedly with increasing temperature. The higher the strength of the mortar, the stronger its dielectric properties and the faster its heating rate. Based on a comprehensive analysis of the heating behavior, mass loss, and variation trend of compressive strength, after 60 s of 5 kW microwave heating, the internal cracks in M20, M25, and M30 mortars entered a stage of rapid expansion, and their strengths decreased significantly. After heating for 100 s, the strengths of the three mortars were reduced by 25%, 18%, and 16%, respectively. This study can provide a reference for microwave-assisted mortar crushing and strength weakening, and further offer technical guidance for the popularization and application of microwave concrete crushing technology.

**Key words:** microwave; mortar; dielectric properties; temperature; compressive strength

Recycling waste concrete can effectively alleviate the environmental pressure caused by resource extraction and the accumulation of construction waste, achieve coordinated unification of economic development, resource conservation, and environmental protection, and conform to the major national strategic decision of the "dual carbon" goals[^1-3]. Concrete is an artificially synthesized multiphase material. The dielectric properties and thermodynamic parameters of its components differ greatly, which is the basis for separating aggregate from mortar. Microwave heating of concrete readily generates thermal stress at the aggregate-mortar interface, inducing interfacial fracture and thereby promoting the separation of aggregate and mortar[^4-5]. Using microwave heating technology to realize efficient crushing of concrete and aggregate recovery has the advantages of high efficiency, environmental friendliness, and energy saving. The extracted aggregate has low mortar adhesion and little damage, and can replace natural aggregate; it is currently a research hotspot among scholars in China and abroad[^6-7]. However, the efficiency of microwave crushing of concrete is an issue that cannot be ignored.

Fig. 1 Microwave heating effect of concrete with different moisture content

Figure 1: Fig. 1 Microwave heating effect of concrete with different moisture content

Concrete can be regarded as a particle-reinforced composite material composed of stone (coarse aggregate) and a mortar matrix (cement and sand). When microwave heating technology is used to crush concrete and extract aggregate from it, the inhibiting effect of mortar must, to a greater extent, be overcome. In essence, the crushing efficiency of concrete depends on the crushing efficiency of mortar under microwave action. Therefore, studying the strength-degradation law of mortar under microwave action is of great significance. Experiments have found that when concrete is crushed by the microwave method, the initial moisture content of the concrete is one of the key factors affecting microwave crushing efficiency, and concretes with different moisture contents exhibit different microwave heating effects (Fig. 1). In the saturated state, when high-power microwave heating is applied to concrete, overall crushing occurs within a short time, aggregate and mortar separate well, and after crushing a large amount of intact aggregate with low mortar adhesion is obtained[^8]. In the dry state, however, even high-power microwave heating makes it difficult to achieve overall crushing of the mortar. Microwave heating can only effectively promote crack propagation along the aggregate interface; as time increases, cracks gradually expand, penetrate through the specimen surface, and thus reduce the strength of the concrete[^9]. It can therefore be seen that increasing the moisture content of mortar is one of the important measures for improving the efficiency of microwave concrete crushing[^10].

*Labels in Fig. 1:*
- Concrete not crushed; aggregate-mortar interface separated
- Concrete crushed as a whole; aggregate separated well
- Crack
- Interfacial separation
- Internal crack propagation
- Dry concrete
- Saturated concrete
- Overall crushing

**Fig. 1** Microwave heating effect of concrete with different moisture content

The essence of microwave heating of solids is the conversion of electromagnetic energy into thermal energy, and its heating efficiency is closely related to the dielectric properties of the mineral components of the material[^11]. Dielectric properties refer to the ability of a substance, under the action of an electric field, to exhibit storage and dissipation of electrostatic energy, and are usually expressed by the complex permittivity.

Because water has an extremely strong capacity for microwave absorption, during the microwave treatment of concrete, the temperature of liquid water in the initial pores continuously rises and phase change vaporization occurs, filling the enclosed cavity space. With the continuous input of microwave energy, the phase change of pore water induces high vapor pressure within the microstructure, thereby causing explosive damage to the concrete in the high-temperature region; during the failure process, the deformation of the mortar is relatively large

12 − 15

. This also explains why increasing the water content can effectively improve the crushing efficiency of mortar. In addition to the influence of water content, the content of other minerals also affects the dielectric properties of mortar. Wang et al.

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studied the dielectric properties of mortar mixed with copper slag and found that both the real and imaginary parts of the dielectric constant increased with increasing copper-slag content; when the copper-slag content exceeded 30%, the dielectric constant of the mortar increased significantly. Guo et al.

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used copper slag to replace natural sand and prepared mortar whose microwave absorption performance varied with copper-slag content; mortar with a copper-slag content of 50% achieved the minimum reflectivity and the maximum effective bandwidth. Therefore, a full understanding of the dielectric properties of mortar can enable more efficient use of microwave energy and has important guiding significance for the crushing of concrete and the recovery of aggregate.

In concrete, sand and gravel aggregate forms the overall skeleton of the concrete, while strength depends on the hardened cement mortar

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. When concrete is irradiated by microwaves, the microwave energy consumed by the mortar adhering to the surface of coarse aggregate has a significant influence on the quality of recovered coarse aggregate

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. Studies have shown that microwave heating causes swelling in concrete specimens, thereby reducing their fracture energy and increasing the crushing rate and aggregate release rate of concrete specimens

20

. Lippiatt et al.

21

found that microwave heating induces pore cracks in concrete, establishing an important link between the local deterioration of concrete after microwave heating and macroscopic changes in mechanical properties. Zheng et al.

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, through real-time temperature and mass monitoring, investigated the effects of mortar mix ratio, water content, and microwave heating power on heating performance, and also analyzed the influence of microwave power on the explosive cracking effect of mortar specimens. In addition, some scholars have carried out extensive research on microwave-heated rocks, and the results show that microwave heating causes a large number of cracks in rocks and reduces their mechanical properties

$$23 - 24$$

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Existing studies have mainly focused on changes in the overall performance of concrete before and after microwave irradiation, including concrete crushing efficiency, interfacial transition zones, and mechanical properties. Mortar plays a decisive role in crushing efficiency, but related studies are relatively few.

To solve the above problems and explore the electromagnetic properties of mortar, the thermal response after microwave heating, and the variation law of compressive strength after heating, this work investigated the dielectric properties of mortars of different strength grades, as well as the thermal response and compressive-strength variation law under microwave irradiation, by means of dielectric-property testing, microwave heating, and uniaxial compression tests. The strength deterioration mechanism of mortar under microwave irradiation was revealed, with the aim of providing a reference for microwave crushing of concrete.

# 1 Dielectric-Property Testing

The dielectric constant is a physical quantity that describes the ability of a medium to respond to an electric field. To study the electromagnetic response and temperature-rise law of mortar under microwave irradiation, it is first necessary to determine its dielectric-property parameters and their influencing factors.

## 1.1 Test Principle of the Coaxial Single-Ended Open-Circuit Method

In this study, the coaxial single-ended open-circuit method was used to conduct dielectric-property measurements. The measurement principle is as follows: for an electromagnetic wave propagating on a uniform coaxial line, owing to the impedance mismatch between the open terminal and the specimen under test, the electromagnetic wave is reflected at the terminal surface. The dielectric properties of the specimen can be calculated by measuring the reflection coefficient.

Before conducting dielectric-property measurements, the single-port probe of the vector network analyzer was calibrated to eliminate errors. Air, deionized water, and a short circuit—three standard test specimens with known reflection coefficients—were selected as standards. The relationship between the measured reflection coefficient and the theoretical reflection coefficient satisfies Eq. (1):

$$\Gamma_{\mathrm{m}} = e_{\mathrm{d}} + \frac{e_{\mathrm{r}}\Gamma_{\mathrm{a}}}{1 - e_{\mathrm{s}}\Gamma_{\mathrm{a}}} \qquad (1)$$

where: $e_{\mathrm{d}}$ is the directivity error; $e_{\mathrm{r}}$ is the frequency-tracking error; $e_{\mathrm{s}}$ is the equivalent source match error; $\Gamma_{\mathrm{m}}$ is the measured reflection coefficient; and $\Gamma_{\mathrm{a}}$ is the theoretical reflection coefficient.

Substituting the measured reflection coefficient of air $\Gamma_{\mathrm{m1}}$, the reflection coefficient of water $\Gamma_{\mathrm{m2}}$, and the short-circuit reflection coefficient $\Gamma_{\mathrm{m3}}$, as well as the known theoretical reflection coefficients of air, water, and short circuit, $\Gamma_{\mathrm{a1}}$, $\Gamma_{\mathrm{a2}}$, and $\Gamma_{\mathrm{a3}}$, into Eq. (1), a system of three simultaneous equations can be obtained and solved for $e_{\mathrm{d}}$, $e_{\mathrm{r}}$, and $e_{\mathrm{s}}$. Substituting the obtained $e_{\mathrm{d}}$, $e_{\mathrm{r}}$, and $e_{\mathrm{s}}$ back into Eq. (1) gives the current probe-measured reflection coefficient $\Gamma_{\mathrm{m}}$. According to Eq. (2), the actual reflection coefficient $\Gamma_{\mathrm{a}}$ at the probe terminal is calculated, completing the single-port probe calibration:

$$\Gamma_{\mathrm{a}} = \frac{\Gamma_{\mathrm{m}} - e_{\mathrm{d}}}{e_{\mathrm{s}}\Gamma_{\mathrm{m}} - e_{\mathrm{d}}e_{\mathrm{s}} + e_{\mathrm{r}}} \qquad (2)$$

$$\eta_{\mathrm{r}} = \sqrt{(\mu_0\mu_1)/(\varepsilon_0\varepsilon_1)} \qquad (3)$$

Through iterative solution using Eqs. (3) and (4), the electromagnetic-property parameters of the material are obtained. Equation (4) is a nonlinear equation for the independent variable $\varepsilon_{\mathrm{r}}$ and the variable $\Gamma$.

## 1.2 Dielectric-Property Testing System

To obtain the dielectric-property parameters of the material, the dielectric-property testing system consisted of an R&S ZNL vector network analyzer and a dielectric-property automatic testing program (coaxial single-ended open-circuit method program). The testing system and material specimen are shown in Fig. 2. After calibration of the dielectric testing system was completed, the mortar test block was placed on the workbench, and the flange probe was closely attached to the ···

Fig. 2 Diagram of material dielectric properties measurement system and test samples

Figure 2: Fig. 2 Diagram of material dielectric properties measurement system and test samples

slurry smooth surface. For mortar, the factors affecting its dielectric properties mainly include mortar composition, moisture content, dielectric constant testing frequency, etc.

$$\frac{1-\Gamma}{1+\Gamma} = \frac{\eta_r}{\ln(b/a)} \int_0^{\infty} \frac{\left[J_0(k_c a) - J_0(k_c b)\right]^2 \left[1 + 2\exp\left(-\sqrt{k_c^2 - \omega^2 \varepsilon_0 \varepsilon_r \mu_0}\, d\right)\right] \varepsilon_r j\omega\varepsilon_0}{\left[1 - 2\exp\left(-\sqrt{k_c^2 - \omega^2 \varepsilon_0 \varepsilon_r \mu_0}\, d\right)\right] k_c \sqrt{k_c^2 - \omega^2 \varepsilon_0 \varepsilon_r \mu_0}}\, dk_c \tag{4}$$

In the formula: $a$ is one half of the outer radius of the inner conductor of the coaxial probe, m; $b$ is one half of the inner radius of the outer conductor of the coaxial probe, m; $d$ is the thickness of the tested specimen, m; $\omega$ is the angular frequency, rad/s; $J_0(x)$ is the zeroth-order Bessel function of the first kind; $k_c$ is the continuous eigenvalue; $\Gamma$ is the reflection coefficient; $\varepsilon_0$ is the vacuum permittivity; $\mu_0$ is the vacuum permeability; $\varepsilon_1$ is the relative dielectric constant of the coaxial probe material; $\mu_1$ is the relative permeability of the filler material in the coaxial probe; and $\varepsilon_r$ is the relative dielectric constant of the material being measured.

1 Vector network analyzer; 2 Testing software; 3 Coaxial probe; 4 Short-circuit probe; 5 Deionized water; 6 Mortar test block; 7 Sand; 8 Cement

Figure 2 Diagram of material dielectric properties measurement system and test samples

Fig. 2 Diagram of material dielectric properties measurement system and test samples

## 2 Microwave Heating Test and Methods

### 2.1 Specimen preparation

A 100 mm(×)100 mm(×)100 mm cubic mortar specimen was prepared using P. O. 425 ordinary Portland cement; all performance indicators met the national standards. The fine aggregate was natural medium sand from Weihe River, Shaanxi, with a fineness modulus of 2.6 and a moisture content of 5%. The main components of the sand were quartz and calcite, and all performance indicators complied with *Sand for Construction* (GB/T 14684–2022). Municipal tap water was used as the mixing water, and a polycarboxylate high-efficiency water-reducing agent was added during mixing. Mortars of common strength grades M20, M25, and M30 were selected for comparative analysis, and the mix proportions are shown in Table 1. Standard mortar slurry was prepared according to the specification; after being cast in molds, the specimens were cured at room temperature for 24 h and then demolded. After demolding, they were cured in a YH-60B constant-temperature and constant-humidity curing chamber at 95% relative humidity for 28 d. After curing was completed, the moisture on the surface of the mortar test blocks was wiped off, and the tests were carried out directly.

### 2.2 Microwave heating system

The microwave heating test used an industrial multimode microwave heating system independently designed by the research group (CY-MU1000C-L). The microwave heating power was linearly adjustable within 0–6 kW. The microwave generator consisted of four 1.5 kW water-cooled magnetrons, operating in the $TE_{10}$ mode at a frequency of 2.45 GHz, with an operating voltage of $380 \pm 10$ V/50 Hz. The four magnetrons were connected through four WR-340 (BJ26) waveguides, and the generated microwaves were transmitted through the waveguides to the microwave ports. The heating chamber was a closed stainless-steel chamber of 410 mm(×)320 mm(×)414 mm. Reserved holes were arranged in the chamber, allowing an infrared thermometer to be used during heating for real-time monitoring of the specimen surface temperature. The microwave heating parameters were controlled by a programmable logic controller (PLC) together with a touch screen. To obtain the distribution of the surface temperature field of mortar after microwave irradiation, a Fotric348x thermal imager was used to monitor the surface temperature of the mortar after microwave heating. The thermal imager had a resolution of 640 × 480, a range of 20–1 550 ℃, an accuracy of (±)2 ℃, and the mortar emissivity was 0.95. To ensure the temperature-measurement effect, when using the thermal imager to measure the mortar surface temperature, the measurement was completed within 15 s after the chamber door was opened.

The compressive strength after microwave irradiation was tested using an AW-200 electro-hydraulic servo pressure testing machine, with a maximum load of 2 000 kN. According to the *Standard for Test Methods of Basic Properties of Building Mortar* (JGJ/T

70—2009) [25], the compression test should be loaded continuously and uniformly; the pre-tightening speed was 10 mm/min, the force loading rate was 3 kN/s, and the stress rate was 0.3 MPa/s, with loading continued until the specimen was completely crushed.

**Table 1 Mortar mix ratio**
**Tab. 1 Mortar mix ratio** Unit: kg/m$^3$

| Strength grade | Cement | Water | Sand | Water-reducing agent | Water-cement ratio |
|---|---|---|---|---|---|
| M20 | 350 | 280 | 1 550 | 1 | 0.80 |
| M25 | 380 | 280 | 1 550 | 1 | 0.73 |
| M30 | 430 | 270 | 1 550 | 1 | 0.63 |

### 2.3 Test scheme

Before the microwave-heating test, the dielectric-performance test system was used to measure the dielectric-performance parameters of the materials. The raw materials used to prepare the mortar—water, cement, and sand—and mortar specimens of three strength grades were tested for dielectric constants. The measurement system was used to obtain the real part, imaginary part, and loss-angle tangent of the dielectric constant of the materials, with a measurement frequency range of 2 200–2 600 MHz.

Microwave treatment at 5 kW with different heating times was carried out on M20, M25, and M30 mortar specimens; the heating durations were 20, 40, 60, 80, and 100 s, respectively, to investigate the influence of different heating times on the microwave-heating effect. To eliminate electromagnetic-field differences caused by different positions during microwave heating, each mortar specimen was placed at a fixed position each time.

An AW-200 electro-hydraulic servo pressure testing machine was used to conduct uniaxial compression tests on the mortar specimens before and after heating, in order to analyze the influence of microwave heating on the compressive strength of mortar. It should be noted that each group of test conditions was repeated three times, and the average value of the heated data was taken. The main test equipment and procedure are shown in Fig. 3.

**Fig. 3 Test main equipment diagram**

## 3 Test results and analysis

### 3.1 Analysis of the dielectric properties of mortar

To investigate the wave-absorbing effect of dielectric materials in a microwave field, the dielectric constant $\varepsilon$ is usually used to characterize the response of a dielectric to microwaves, as described by Eq. (5), namely

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0(\varepsilon' - \mathrm{j}\varepsilon'') \qquad (5)$$

$$W = \frac{1}{2}\varepsilon_0 \varepsilon' E^* \cdot E \qquad (6)$$

$$W' = \frac{1}{2}\varepsilon_0\varepsilon'' E^* \cdot E \qquad (7)$$

where $\varepsilon_0$ is the dielectric constant of vacuum, $8.854\times10^{-12}$ F/m; $E$ is the vector-varying electric field; j is the imaginary unit; and $E^*$ is the conjugate form of $E$. Since the dielectric constants of most dielectric materials are generally very small, the complex dielectric constant $\varepsilon_r$ is usually used to express the dielectric response of the material during microwave absorption.

From Eqs. (5)-(7), it can be seen that the complex dielectric constant $\varepsilon_r$ has two components: the real part $\varepsilon'$ and the imaginary part $\varepsilon''$. The real part $\varepsilon'$ represents the ability of the material to store electric charge in an electric field and is related to the electromagnetic energy $W$ stored per unit volume of dielectric molecules. The imaginary part $\varepsilon''$ is called the dielectric loss factor, representing the absorption and dissipation of electric-field energy by the material, and is related to the electromagnetic energy $W'$ dissipated per unit volume of dielectric molecules. Dielectric loss includes the effective loss used to heat the material and the ineffective loss reflected when electromagnetic waves enter the material; it is expressed by the ratio of $\varepsilon''$ to $\varepsilon'$, namely the dielectric loss-angle tangent ($\tan\delta$).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (8)$$

It can be seen from Eq. (8) that the dielectric loss-angle tangent ($\tan\delta$) characterizes the ratio of the energy dissipated by the dielectric in each cycle to the energy stored by the dielectric in each cycle, reflecting the efficiency with which the dielectric transmits electromagnetic-field energy and absorbs microwave energy to generate heat.

Using the automatic dielectric-property measurement system described above, the real part $\varepsilon'$, loss factor $\varepsilon''$, and loss-angle tangent $\tan\delta$ of the dielectric constants of M20, M25, and M30 mortar specimens were measured, as shown in Fig. 4. The differences in the real parts of the dielectric constants of the three mortar strengths were relatively evident. The real part of the dielectric constant of M30 mortar was the largest, while that of M20 mortar was the smallest.

small. The higher the strength of the mortar, the larger the real part of the dielectric constant. It can be seen from the figure that the imaginary part of the dielectric constant and the loss factor of the mortar both increase slowly with increasing microwave frequency, and the dielectric constant varies with frequency in a wavelike trend. This is mainly related to the orientational polarization of dipoles in the material. As the frequency changes, because a certain resistance exists between molecules inside the material, the orientational polarization of dipoles gradually lags behind the change in the external electric field, forming a relaxation. Since the water in mortar is sensitive to microwaves, the relaxation causes fluctuations in the dielectric constant of the material.

Fig. 4 Dielectric property test results of mortar

Figure 3: Fig. 4 Dielectric property test results of mortar

Figure 4 Dielectric property test results of mortar

Fig. 4 Dielectric property test results of mortar

## 3.2 Effects of Frequency and Temperature on Dielectric Properties

The commonly used industrial microwave-heating frequencies are currently 2.45 GHz and 915 MHz. Studying the dielectric properties of materials at these frequencies is of great significance for experimental research. The raw materials used to prepare mortar—cement, sand (dry), and water—were tested for dielectric properties; for each material, the average value of three measurements was taken. For the three mortar specimens, the average value of the measurement data was likewise taken. According to the magnitude of the relative dielectric constant (real part), dielectric materials can be classified as polar substances (greater than 3.6), weakly polar substances (2.8-3.6), and nonpolar substances (less than 2.8). From Table 2, it can be seen that at 2.45 GHz the dielectric constant of water is 78.87, indicating a strongly polar substance; the dielectric constants of cement and sand are 3.50 and 3.04, respectively, indicating weakly polar substances; the real parts of the dielectric constants of M20, M25, and M30 mortar are 3.45, 3.84, and 4.76, respectively. Thus, as the strength of the mortar increases, its dielectric properties continuously increase, gradually changing from a weakly polar substance to a polar substance. Cement and sand are both weakly polar substances, while water is a strongly polar substance. For the three strength grades of mortar—M20, M25, and M30—the water-cement ratio of M30 is the smallest, but M30 has the strongest polarity, indicating that hydration has a very large influence on the dielectric properties of mortar.

Table 2 Dielectric properties of the material at 2.45 GHz

Tab. 2 Dielectric properties of the material at 2.45 GHz

| Material to be tested | Complex dielectric constant | Loss tangent |
|---|---|---|
| Cement | 3.50−0.45j | 0.130 |
| Sand | 3.04−0.35j | 0.110 |
| Water | 78.87−10.58j | 0.130 |
| M20 mortar | 3.45−0.54j | 0.156 |
| M25 mortar | 3.84−0.62j | 0.162 |
| M30 mortar | 4.76−0.71j | 0.149 |

In general, dielectric materials are composed of several materials with different dielectric properties, and their dielectric properties ultimately depend on the

Fig. 5 The dielectric constant of water varies with microwave frequency

Figure 4: Fig. 5 The dielectric constant of water varies with microwave frequency

material with high dielectric performance. As a polar molecule with high dielectric loss, water interacts with microwaves more strongly than other minerals or cement hydration products. Although water accounts for only a small volume fraction in cement mortar, it strongly determines the dielectric properties of the material. Under microwave action, water can heat up rapidly; therefore, in industrial applications, most microwave heating of materials is achieved by heating water to accomplish microwave heating of solids. This is also the cornerstone of the feasibility of microwave-heating applications[^26]. Changes in the dielectric properties of water directly affect the dielectric properties of the heated dielectric material.

Generally, the dielectric properties of a material vary with the test frequency. Figure 5 shows the real part, imaginary part, and loss tangent of the dielectric constant of water measured at 25 °C by the coaxial method. The real part of the dielectric constant of water decreases with increasing frequency, while the loss factor and loss

the tangent loss value increases; this indicates that when the microwave frequency increases from 2 200 MHz to 2 600 MHz, the ability of water to store electric charge decreases, whereas its ability to convert microwave energy into heat increases. The dielectric properties of the material are affected not only by the microwave-heating frequency but also by temperature, and the influence of temperature on the dielectric properties of the material is relatively pronounced. Fig. 6 shows the variation curve of the complex dielectric constant of water with temperature at a frequency of 2.45 GHz. It can be seen that, as temperature rises, both the real and imaginary parts of the dielectric constant of water show a rapid downward trend. The real part decreases approximately linearly with increasing temperature, while the loss factor decreases rapidly at first as temperature increases; after the temperature exceeds 50 ℃, the rate of decrease gradually becomes smaller. In short, as temperature increases, the microwave absorption capacity of water continuously decreases; this is the main reason for the decrease in the dielectric properties of saturated mortar after it is heated and its temperature rises.

图 5 水的介电常数随微波频率的变化曲线

Fig. 5 The dielectric constant of water varies with microwave frequency

图 6 2.45 GHz 下水的介电常数随温度的变化曲线

Fig. 6 The change curve of dielectric constant of 2.45 GHz water with temperature

Fig. 6 The change curve of dielectric constant of 2.45 GHz water with temperature

Figure 5: Fig. 6 The change curve of dielectric constant of 2.45 GHz water with temperature

Fig. 7 Temperature field on each surface of M20 mortar heated by 5 kW microwave for 100 s

Figure 6: Fig. 7 Temperature field on each surface of M20 mortar heated by 5 kW microwave for 100 s

### 3.3 Analysis of Temperature Distribution and Mass Loss

Fig. 7 gives the temperature distribution on the surface of M20 mortar after 100 s of heating by 5 kW microwave. Because the microwave forms high-energy and low-energy regions in the mortar, the heating rates at different positions of the mortar are inconsistent. From the surface temperature distribution, microwave heating is nonuniform, and obvious high-temperature and low-temperature regions appear, forming corresponding cold spots and hot spots. The high-temperature regions on the various surfaces of the specimen are mainly concentrated at the edges of the specimen. The main reason is that the microwave-heating chamber causes excessive reflection of microwaves, and in addition, the edges of the specimen are relatively sharp, so the microwaves form a standing-wave effect[^27]. The high-temperature and low-temperature regions form an obvious temperature gradient, producing relatively high thermal stress, which leads to expansion of cracks inside the mortar and a reduction in mortar strength. Fig. 8 shows the change with time in the nonuniform temperature distribution on the same surface (bottom surface) of M20 mortar under the action of 5 kW microwave. The temperature distributions on different surfaces of the mortar specimen are generally consistent, but the sizes of the high-temperature regions differ. Under microwave action, a "U-shaped" high-temperature region appears on the specimen surface, while the temperature at the middle position is relatively low. With the continuous input of microwave energy, under the combined action of electromagnetic-energy conversion and heat conduction, the high-temperature region gradually expands. At heating times of 20 s and 100 s, the maximum surface temperature differences are 28.3 ℃ and 81.5 ℃, respectively. This is mainly due to the rapidity of microwave heating and the lag of heat conduction: the time required for temperature rise by microwave heating is much shorter than the time at which heat conduction occurs. Therefore, as the heating time is gradually prolonged, the temperature gradient gradually increases.

图 7 5 kW 微波加热 M20 砂浆 100 s 各面的温度分布

Fig. 7 Temperature field on each surface of M20 mortar heated by 5 kW microwave for 100 s

Fig. 8 Temperature distribution of M20 mortar heated by 5 kW microwave at different heating times

Figure 7: Fig. 8 Temperature distribution of M20 mortar heated by 5 kW microwave at different heating times

Fig. 9 Maximum surface temperature and mass loss of mortar samples heated by 5 kW microwave

Figure 8: Fig. 9 Maximum surface temperature and mass loss of mortar samples heated by 5 kW microwave

图 8 5 kW 微波加热 M20 砂浆不同加热时间的温度分布

Fig. 8 Temperature distribution of M20 mortar heated by 5 kW microwave at different heating times

Figure 9 shows the maximum temperature and mass loss on the mortar surface under 5 kW microwave heating. According to the heating rate, the heating process can be divided into two stages. The first stage is the first 60 s, during which the heating rate is roughly proportional to the heating time; the second stage is 60–100 s, during which the heating rate decreases; overall, the trend is fast at first and then slow. The M30 mortar specimen underwent local crushing after 100 s of heating, and its temperature dropped abruptly. At 20 s of heating, the overall temperature of the mortar had not reached 100 ℃; the specimen had no mass loss, and the water in the mortar had not reached the threshold temperature for evaporation. At 40, 60, and 80 s of heating, M25 had the greatest mass loss, followed by M30, while M20 had the smallest mass loss. This is because the temperature rise of M25 mortar was relatively fast and its permeability was relatively high, resulting in a larger mass loss. When the heating time increased from 80 s to 100 s, the mass loss rate of M20 mortar was the fastest. As the mortar strength increased, its density also increased, while permeability decreased; therefore, escape of internal moisture from low-strength mortar led to more obvious mass loss.

Fig. 9 Maximum surface temperature and mass loss of mortar samples heated by 5 kW microwave

In the first stage of temperature rise, the heating rates of M20, M25, and M30 were 2.31, 2.58, and 2.95 ℃/s, respectively. From the dielectric-property test results in Section 3.2, it can be seen that the higher the strength of the mortar, the larger its dielectric loss factor $\varepsilon''$. The microwave absorption power $P_d$ of a dielectric material is given by Eq. (9). Under the same heating power, the electric-field intensity is the same; the greater the microwave absorption power, the faster the mortar temperature rises. In the second stage, because physical and chemical reactions of compounds in the mortar absorb heat during heating—such as the decomposition heat absorption of hydration products and the latent heat of vaporization during water evaporation—as the temperature rises, the dielectric loss factor of water decreases and the heating rate slows. The study by Zheng et al. [22] also confirmed that changes in dielectric properties caused by moisture evaporation and decomposition of hydration products are the main reason for changes in the heating rate of mortar under microwave heating. On the other hand, under microwave action, water-phase transformation causes an increase in pore vapor pressure, crack propagation, and steam diffusion, carrying away a large amount of heat, so the temperature of the specimen also decreases accordingly.

$$P_d = 2\pi f \varepsilon'' E^2 \qquad (9)$$

In the equation, $P_d$ denotes the absorbed power per unit volume of the dielectric material, $W/m^3$; $f$ denotes the frequency of the electromagnetic wave, Hz; $\varepsilon''$ denotes the dielectric loss factor; and $E$ denotes the electric-field intensity, V/m.

The tests found that after 100 s of microwave heating at 5 kW, the M20 and M25 mortars did not undergo explosive fragmentation, whereas the M30 mortar underwent local explosive fragmentation after 93 s of 5 kW heating. The edge of the high-temperature region at the bottom of the specimen was crushed into small fragments, and a large amount of white vapor was present in the cavity. This is because the higher the strength of the mortar, the lower its porosity, the denser its structure, and the lower its permeability. Under microwave action, the pore water in high-strength mortar rapidly undergoes phase change and vaporization but cannot readily escape, thereby forming a relatively high pore vapor pressure. Within a relatively short time, the volume of water vapor expands rapidly, producing a crushing effect similar to "steam explosion." With the aid of a thermal imager, it can be measured that the maximum internal temperature of the mortar specimen after crushing is about 200 ℃, significantly higher than the surface temperature of the mortar block. The reasons are as follows. First, because of the existence of heat flux, during heating the heat on the mortar surface diffuses toward the air in the cavity; in addition, microwaves penetrate into the mortar from all sides, producing a superposition effect inside the mortar. In short, under high-power microwave input, mortar with relatively high moisture content is more likely to undergo low-temperature bursting within a short irradiation time (about 200 ℃, whereas the bursting temperature of concrete under conventional heating is about 600 ℃ [28]). This is also one of the advantages of the efficient crushing of concrete by microwave heating.

### 3.4 Analysis of Uniaxial Compression Test Results

Figure 10 shows the stress-strain curves of cubic mortar specimens under 5 kW microwave heating for different durations. As heating time increased, the compressive strength of the mortar gradually decreased. After microwave heating, the reductions in compressive strength of M20 and M25 mortars were more significant. This is because, under high-temperature conditions, moisture vaporization and microcrack propagation damaged the microstructure of the mortar.

Fig. 10(a) M20 mortar stress-strain curve

Figure 9: Fig. 10(a) M20 mortar stress-strain curve

Fig. 10(b) M25 mortar stress-strain curve

Figure 10: Fig. 10(b) M25 mortar stress-strain curve

The compressive strength of M30 decreased less, indicating stronger resistance to deterioration, because high-strength mortar has higher cement content and a dense microstructure. After short-time heating, the elastic modulus of the mortar did not decrease significantly; however, when the heating time exceeded 60 s, the elastic modulus of the mortar decreased markedly, the stiffness of the mortar decreased, and it became more prone to deformation under external force. According to the stress-strain curves, the failure of mortar can be divided into a compaction stage, an elastic stage, and a failure stage. In the compaction stage, when loading begins, the stress increases slowly with increasing strain and the curve shows a concave segment; pores and initial microcracks in the mortar close under pressure. As loading increases, microcracks slip and merge, strain increases, and stress increases slowly, producing an obvious plateau. In the elastic stage, as loading continues to increase, the stress-strain curve is a straight line; as mortar strain increases, the stress increases linearly, and the slope in this stage is the elastic modulus of the mortar, eventually reaching the peak ultimate stress. In the failure stage, the stress-strain curve enters the descending stage, and the stress follows the strain ⋯

increasing deformation, and propagated rapidly, until the mortar specimen was completely crushed and thoroughly lost its load-bearing capacity.

(a) M20 mortar

(b) M25 mortar

(c) M30 mortar

Fig. 10 Stress-strain curves of mortar under 5 kW microwave heating

Figure 11(a) shows the surface morphology before and after 5 kW microwave heating and the failure mode under uniaxial compression. After microwave heating, obvious cracks appeared on the mortar surface, and longitudinal spalling occurred during compression in the universal testing machine. Figure 11(b) shows the variation of compressive strength with heating time. As the heating time increased, the compressive strength decreased significantly after 40 s, and the strength decreased first rapidly and then slowly, which was consistent with the

Fig. 10(c) M30 mortar stress-strain curve

Figure 11: Fig. 10(c) M30 mortar stress-strain curve

Fig. 11(a) Surface morphology before and after microwave heating and compression failure

Figure 12: Fig. 11(a) Surface morphology before and after microwave heating and compression failure

Fig. 11(b) Compressive strength variation with heating time

Figure 13: Fig. 11(b) Compressive strength variation with heating time

heating-rate variation of the mortar. A comprehensive analysis of the variations in heating law, mass loss, and compressive strength indicates that, after 60 s of 5 kW microwave heating, the internal cracks in M20, M25, and M30 mortars all entered a stage of rapid expansion, and the strength decreased markedly. After 100 s of microwave heating, the compressive strengths of M20, M25, and M30 decreased by 5.53, 5.07, and 4.99 MPa, respectively, with reductions of 25%, 18%, and 16%. The compressive strength of mortar is closely related to its pore structure. After microwave heating, hydration products decompose, increasing the number and volume of pores and reducing mortar strength [29]. In addition, during microwave heating, the pores inside the mortar and the initial defects generate pore vapor pressure, while the temperature gradient induces thermal stress. Under the action of these two driving forces, the pore structure of the mortar penetrates through and the initial defects gradually develop, leading to a decrease in mortar strength.

Before heating

Heating for 100 s

Surface cracks after heating

Cracks

Specimen crushing

(a) Surface morphology before and after 5 kW microwave heating and uniaxial compression failure mode

(b) Variation of compressive strength with heating time

Fig. 11 Changes in properties of mortar under 5 kW microwave heating

### 3.5 Discussion of the deterioration mechanism of mortar

The strength deterioration of mortar under microwave irradiation can be divided into two stages: the first stage is the rapid heating stage, and the second stage is the strength deterioration stage. In the first stage, when the mortar is irradiated by microwaves, polar substances (water molecules) are selectively heated; heat is generated by mutual friction between water molecules and is transferred to the mortar matrix through conduction and convection, causing the mortar to heat up rapidly.

temperature rises, but the overall temperature is relatively low; therefore, the strength does not show an obvious weakening effect.

In the second stage, microwave irradiation causes the mortar to form a nonuniform temperature field. Owing to the mutual constraint between the high-temperature region and the low-temperature region, compressive stress forms in the high-temperature region, while tensile stress forms in the low-temperature region. The mortar in the low-temperature region undergoes relatively large deformation under the action of local tensile stress, and microcracks form when the tensile stress exceeds the tensile strength of the mortar. As the temperature continues to rise, when the phase-transition critical temperature of water is reached, liquid water changes into water vapor. Vapor pressure forms inside the pores of the mortar; the vapor pressure acts perpendicularly on the inner walls of pores and microcracks. The combined action of pore vapor pressure and thermal stress produces strain, microcracks gradually evolve, and as the stress continuously increases, macroscopic cracks form. The strength deterioration mechanism of mortar is shown in Fig. 12. Xiao et al.[30] also verified that when the tensile stress exceeds the critical strength of mortar, microcracks appear on the surface. In the high-temperature region, the mortar is subjected to compressive stress; the evolution of microcracks is limited. In the high-temperature region, the hydration products of mortar decompose more rapidly, the number of pore structures increases, and the resulting increase in the volume of pores and cracks in the mortar significantly reduces its mechanical properties[31]. In addition, after microwave heating, the sandstone produces dehydration shrinkage cracks, cracks along particle boundaries, and cracks inside particles[32]. As the temperature of the mortar rises, the pore vapor pressure increases sharply. Because no pores favorable for the escape of water vapor are formed, the vapor pressure rapidly reaches saturation and is difficult to release effectively. The vapor pressure exceeds the ultimate strength value of the mortar, causing local crushing of the mortar[33].

*Visible labels in Fig. 12 include: microcrack evolution; tensile region; compressive region; cracks; nonuniform temperature field; 500×; 20×; 1×; local crushing; pore vapor pressure; high-temperature-region local crushing; temperature field after crushing; mortar; crack; thermal stress; q vapor pressure.*

**Fig. 12** Schematic diagram of mortar deterioration mechanism under microwave irradiation

## 4 Conclusions

To investigate the effects of microwave irradiation on the thermal response and mechanical properties of mortar, dielectric-property tests, microwave-heating tests, and compressive-strength tests were carried out. Short-duration, high-power microwave irradiation can substantially reduce the mechanical properties of mortar, which is of great significance for concrete-related research. The main conclusions are as follows.

1) As the mortar strength increases, the dielectric properties become stronger, and the dielectric properties vary with temperature and frequency. Because the mix proportions of the mortars differ, the more cement hydration products there are in the mortar, the stronger the dielectric properties. The dielectric loss factor of water increases with increasing frequency and decreases with increasing temperature.

2) Microwave heating causes the mortar to form a nonuniform temperature field, and the higher its strength, the faster the heating rate. Owing to the reflection of microwaves by the cavity, high-temperature hot spots appear at the edges of the specimen; meanwhile, the temperature inside the mortar is higher than the surface temperature. As the temperature rises, the loss factor of water inside the mortar decreases, and the heating rate of the mortar slows down.

3) Microwave heating can effectively reduce the compressive strength of mortar. Because microwave heating causes decomposition of the hydration products in the mortar and development of initial cracks, the compressive strength of the mortar decreases. After 100 s of 5 kW microwave heating, the strengths of M20, M25, and M30 mortars decrease by 25%, 18%, and 16%, respectively.

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