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Review

Recent development of microwave applications for concrete treatment

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HIGHLIGHTS

- Summarized energy conversion mechanism and theoretical basis of microwave heating.
- Demonstrated applications and research progress of microwave treatment on concrete.
- Discussed challenges and future works to promote its engineering applications.

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ABSTRACT

Microwave heating is an attractive new technique for concrete treatment due to its high efficiency and low energy consumption. This paper provides a comprehensive review of the scientific and technical achievements of microwave-assisted concrete treatment. The research progress is classified into microwave heating mechanism, experimental studies and numerical studies. The theoretical fundamentals for the microwave-assisted concrete heating process are investigated in detail, covering areas such as the microwave heating characteristics, governing equations, dielectric properties and multi-field coupling effects. Several attractive microwave applications for concrete treatment are summarized, including microwave-assisted concrete recycling, microwave-accelerated concrete curing, microwave-assisted concrete drilling, and microwave-assisted nondestructive monitoring. Future efforts, as well as theoretical and technical challenges for industrial applications of microwave for concrete treatment, are discussed, which providing guidance for the development of microwave applications for concrete treatment.

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1. Introduction

The construction industry satisfies the basic requirements of human survival. Concrete is one of the most important construction materials, and is widely used in buildings, roads, tunnels, bridges and other infrastructure constructions. The continuous development of the construction industry results in the production of large amounts of concrete and cement around the world. This increased production of cement and concrete leads to increased energy consumption. Eco-friendly and sustainable new technologies are needed to resolve the energy and environmental issues throughout the concrete lifecycle. Microwave heating has attracted the attention of engineers particularly concrete specialists since the 1980s [1–8]. Since then, this technology has been applied to many aspects of the concrete life cycle, including production, demolition, and recycling.

Microwaves are electromagnetic waves in the frequency range of 300 MHz to 300 GHz [9]. Microwave heating is a process where materials interact and couple with microwaves. The electromagnetic energy is absorbed by the microwave-absorbed materials and then transformed into heat energy [10–15]. Thus, the heat generation is based on the interactions of molecules with the electromagnetic field. Compared with the conventional heating methods, microwave heating is not limited by heat conduction, radiation or convection from external heat sources to the heated materials. In the conventional heating process, the surface of material is first heated by the heating source, and then thermal energy is transferred into the internal materials [16,17]. However, microwaves volumetrically heat materials from the indies, representing a reversal in the heating direction compared with conventional heating [18,19]. The microwave heating efficiency depends on the material properties, that is, the microwave selective heating characteristic. When a microwave acts on a composite material with different dielectric properties, it selects the higher-loss material to react with first. Microwave heating is generally an efficient process, with rapid heating rates, short treatment times, and low energy consumption. Owing to these advantages for heating and years of research efforts throughout the world, microwave applications have become feasible candidates for concrete treatment [20–26].

Microwave curing has great potential to revolutionise the curing process of concrete. Compared with conventional steam-heating curing, microwave heating can improve the concrete early strength within a shorter curing time [27]. Another area of application may involve the need to accurately remove a specific component or portion from concrete, that is concrete aggregate recycling [28–30]. Concrete recycling is effective for the disposal of demolition debris. The selective heating property of microwaves provides a source of recycled aggregate for reuse in further concrete production processes [31–35]. Microwave-assisted concrete drilling has proven to be an eco-friendly and sustainable method, with low pollution levels and high controllability. A certain size hole in concrete can be efficiently obtained using this method. Additionally, microwave-nondestructive testing (MNDT) has attracted considerable attentions owing to its industrial potential. This application is based on the microwave absorption ability of concrete. The microwave diagnostic property can reveal the cracks and flaws and be used to evaluate the moisture content and early strength of concrete.

In this paper, we summarise the developments of microwave heating for concrete treatment. The related achievements are summarised with regard to the following three aspects: (a) research progress for concrete heating process via microwave irradiation, including theoretical, numerical and experimental results; (b) the development of microwave applications for concrete treatment, including microwave-assisted concrete recycling, acceleration of curing, concrete drilling, and nondestructive monitoring; (c) theoretical and technical challenges for future development, including the physical mechanism of the concrete heating process under microwave irradiation, microwave heating characteristics, and new heating systems with a higher efficiency and lower energy consumption.

2. Microwave heating fundamentals

Microwaves constitute electromagnetic radiation. The spectrum lies between the infrared and radio frequency bands, as shown in Fig. 1. Industrial applications employ five electromagnetic frequencies, i.e., 0.433, 0.915, 2.45, 4.0 and 5.8 GHz to avoid other application and overlaps. The fundamentals of microwave heating

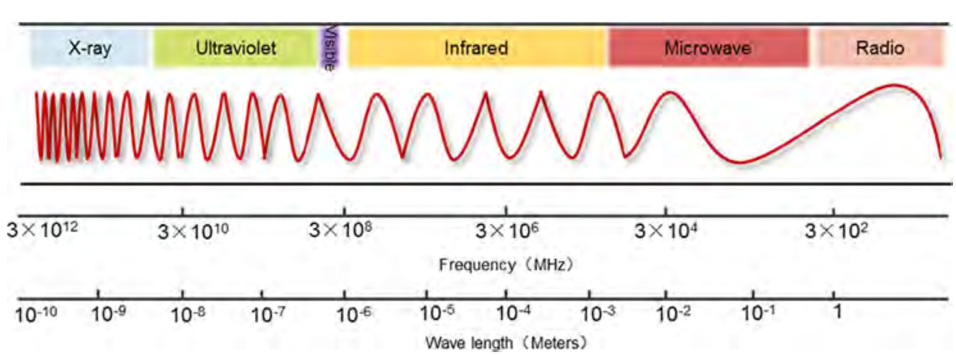

Fig. 1. Electromagnetic spectrum.

materials are the key to promoting the development of their applications in concrete treatments.

2.1. Microwave heating characteristics

Microwave heating is a volumetric heating process. Heated materials with microwave absorption ability can be easily heated with almost no cavity warm-up time. In the conventional heating process, the materials are forced to be heated through thermal conduction from the outside environment [36–37]. For microwave-absorbing materials, the volumetric and selective heating characteristics lead to a rapid heating reaction. In contrast, conventional heating, microwave heating occurs volumetrically, with almost all the microwave absorbing materials being heated simultaneously. Microwave are excellent heating sources with volumetric heating, selective heating, rapid warmup, easy control and a clean heating process [38,39]. These heating characteristics allow sustainable applications in concrete treatment [40].

When microwaves penetrate heating objects, materials exhibit different microwave-absorbing properties owning to the variations in the electric field **(E)** and magnetic field **(H)** strengths [41]. The amount of energy that can be converted into thermal energy depends on the dielectric properties of the target materials. Because of the variation of the dielectric properties, not all the materials present the same response under microwave irradiation. According to the microwave energy-absorption characteristics, materials can be classified into the following four types [42–45]:

(i) Transparent: Low-loss insulator materials without microwave absorption (Teflon, quartz);
(ii) Absorber: High-loss insulators with complete microwave absorption, dielectric materials in which microwaves are completely absorbed depending on their dielectric loss factor (water, SiC, Fe_3O_4, etc.);
(iii) Opaque: No loss insulators with low energy absorption, conductor materials in which microwaves are reflected without energy absorption (bulk metals);
(iv) Mixed absorbers: Composite materials comprising a high-loss insulator and low-loss insulator. As, concrete is a composite material that can be defined as a typical mixed absorber. The microwave-absorption abilities of mortars and aggregates differ significantly. Even among aggregate, different mineral components lead to different microwave responses (ceramic matrix composite, polymer matrix composite, metal matrix composite) [40].

2.2. Maxwell's equations

Maxwell's equations are the core of electromagnetic theory, which govern the behavior of electric and magnetic fields [46,47]. The equations describe how electric and magnetic fields propagate, interact, and how they are influenced by objects [48,49]. Maxwell's equations are a set of equations written in differential or integral form. Effects of many electromagnetic characteristics are considered in these equations, such as the electric field intensity **E**, the electric displacement or electric flux density **D**, the magnetic field intensity **H**, the magnetic flux density **B**, the current density **J**, and the electric charge density ρ_q. The vectors **E** and **B** are the basic field vectors defining the force on a charge moving in an electromagnetic field. Maxwell's equations describing electromagnetic space and time dependence are shown in Eqs. (1) and (2).

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla \times D = \rho_q \tag{3}$$

$$\nabla \times B = 0 \tag{4}$$

The constitutive relations between current density, electric flux density, magnetic flux density, electric field intensity, and magnetic field intensity are described as:

$$J = \sigma ED = \varepsilon EB = \mu H$$

in that way,

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu H) \tag{5}$$

$$\nabla \times H = \sigma E + \frac{\partial}{\partial t}(\varepsilon E) \tag{6}$$

where σ is the electrical conductivity, ε is the electrical permittivity, μ is the magnetic permeability. When combined with the Lorentz force equation and Newton's second law of motion, these equations provide a complete description for the classical dynamics of interacting between charged particles and electromagnetic field.

2.3. Energy absorption

Microwave heating involves the conversion of electromagnetic energy into heat. Energy is transported through any medium as electromagnetic waves. The energy carried by microwaves per unit time and per unit area is expressed by the Poynting vector, which is the cross product of the electric- and magnetic-field vectors. It could be expressed as follows:

$$S = E \times H \tag{7}$$

where S represents Poynting vector, which propagates perpendicularly to both the oscillating E and H fields. The direction of energy propagation can be determined by starting from the E and H vectors and using the right-hand rule. By applying the Poynting power theorem, the power per unit volume can be calculated as follows:

$$Q = -\mathrm{Re}(\nabla \cdot \mathbf{S}) = \frac{1}{2}\omega\varepsilon_0\varepsilon''|\mathbf{E}|^2 \tag{8}$$

where ω represents the angular frequency ($\omega = 2\pi f$), ε_0 represents the permittivity of free space and E represents the electromagnetic-field strength. ε' represents the electrical energy-storage capacity of the medium, and ε" represents the ability of the medium to convert E into heat. The amount of microwave energy absorbed by the materials can be calculated using the following Eq. (8). Using the heat conduction equation, the temperature distribution in the medium can be obtained.

2.4. Dielectric properties

The microwave heating effects of a material depend on the dissipation factor, which is the ratio of the dielectric loss or loss factor to the dielectric constant of the material. The dielectric constantε' and dielectric loss factors$\varepsilon''$are two key parameters reflecting the dielectric response of materials under microwave processing [50].

The two essential elements are related by Eq. (9):

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{9}$$

whereε^* represents the complex relative permittivity (complex dielectric constant), ε' represents the relative permittivity, is the real part (dielectric constant); ε'' represents the dielectric loss factor, is the imaginary part; and $i = \sqrt{-1}$.

The dielectric properties are significantly influenced by the material characteristics. For concrete, the extent of hydration, water-to-cement (w/c) ratio, aggregate type, gradation, and age of the demolished concrete can affect the dielectric properties, leading to different microwave heating responses.

Microwave heating is due to electric and magnetic fields. The microwave energy-conversion mechanism can generally be divided into dielectric and magnetic losses [40]. The dielectric loss refers to the conversion of microwave-induced electromagnetic energy into heat energy in an electric field. The dielectric loss energy pathway is the route whereby energy is converted from the electric field to the thermal output. When a non-conductive material is heated by microwaves, at the beginning, the electric field is oscillatory in its polarity in the electromagnetic radiation field. The electric field of the microwaves instantaneously rotates the electric dipoles of the material molecules, and the molecules then align with the electric field [51]. When the direction of the electric field changes, the molecules rotate in the direction of the electric field to maintain their alignment [52]. As the molecules rotate, heat is efficiently produced. Because of the inability of molecule clusters to move exactly with the electric field, dielectric heating involves unorganised movements at the micro scale [53]. The hysteresis phenomenon is generally recognized as the main reason for the transformation of electromagnetic radiation into heat [54,55]. The heating process is the conversion of energy into rotating molecules, resulting in a temperature variation. When a conductive material is irradiated with microwaves, the electric field under microwave radiation produces an electric current, leading to the generation of heat energy, which is defined as the resistance loss [56].

The component of magnetic field can also cause heating under microwave irradiation; the loss mode in this process is called magnetic loss. Magnetic loss refers to the magnetic material converted into heat when it is magnetised. Magnetic loss can be divided into three categories according to different heating mechanisms: eddy current loss, hysteresis loss, and magnetic resonance loss [57]. When a relative motion between the conductive materials and the external magnetic field exists, eddy current loss heating occurs [58]. Hysteresis loss heating arises from the irreversible magnetisation process under an alternating magnetic field [59]. For some metal oxides, e.g. ferrite, magnetic resonance loss occurs because if the domain wall and electron spin resonance [60].

2.5. Multi-field coupling

In most of the work, researchers have attempted to explain the microwave heating process on concrete considering the interaction phenomena as 'black box'. There are many attempts to understand the response of concrete under the influence of an electromagnetic field. The phenomena associated with the multi-field heating processing are less understood. Microwave heating is a multi-field coupling heating process, involving electric, magnetic, and mechanical fields, along with energy, heat, and mass transfer, as shown in Fig. 2. The analysis of microwave heating is an interdisciplinary research topic, involving energy, physics, chemistry, mechanics and electromagnetism.

When concrete is irradiated with microwaves, concrete would be heated rapidly in the heating cavity owing to the continuous conversion of electromagnetic to thermal energy. The microwave frequency, concrete size and morphology, and mortar and aggregate dielectric properties can affect the distribution and magnitude of the electric field during microwave heating. The heating efficiency is affected by the dielectric and thermal properties of the mortar, and aggregate, the water content, and the electric-and magnetic-field distributions in the heating cavity, which are related to the research fields of electromagnetism and thermodynamics. Energy conversion and the transfer of mortar, aggregate and surrounding materials occur throughout the heating process. Phase changes and chemical-composition variations occur when the temperature reaches a certain level. The mechanical behavior, such as the stress and strain of the concrete changes continuously during the heating period.

Moisture and its transformation play an important role in the heating process, as shown in Fig. 3. Moisture exists in different states in concrete: surface adsorbed water, which is located on the surfaces of the concrete particles; the interparticle water, which is in mortar-mortar, aggregate-aggregate, and mortar-aggregate crevices; interior adsorbed water, which exists in the micropores of concrete; and capillary water [61]. The conversion and transformation of moisture affect the heating result. During the microwave heating of concrete, only polar molecules with strong dielectric properties absorbed microwave energy, leading to a temperature increase. The polar molecules rotate owning to the microwave energy, clustering together as vapour bubbles when the temperature reaches the boiling point. They transition from the concrete phase to the surrounding-air phase. The formation of bubbles leads to the energy and mass transfer in the concrete. When the bubbles move from the concrete to the air phase, the process of heat and mass transfer occurs, leading to the generation of

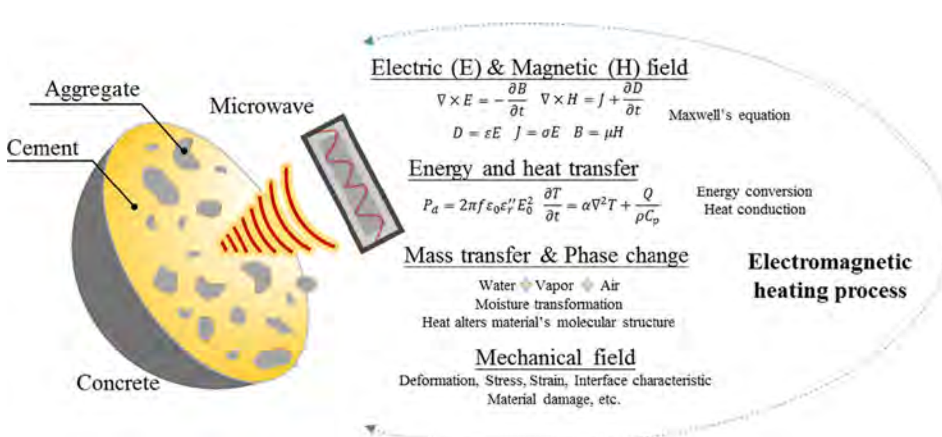

Fig. 2. Schematic of the multi-field heating process under microwave irradiation.

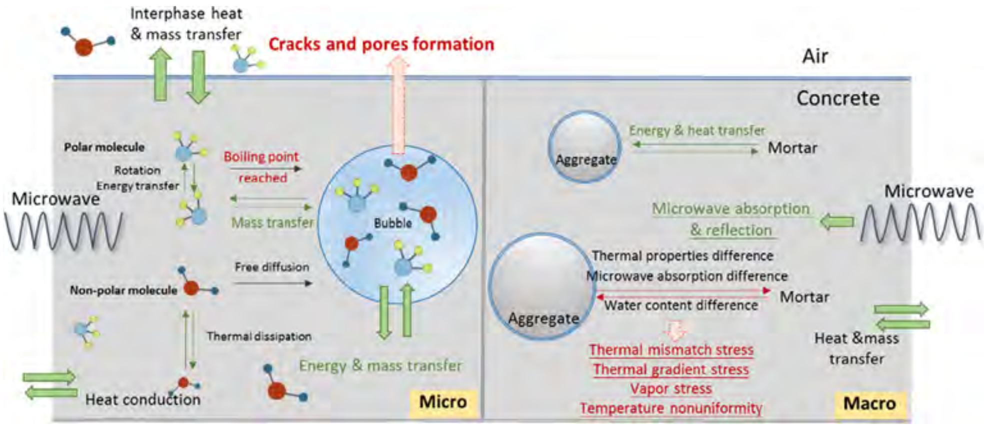

Fig. 3. Energy, heat and mass transfer of concrete under microwave irradiation.

cracks. Thermal dissipation also occurred within non-polar molecules owing to heat conduction and convection. At the macroscale, the energy, heat, and mass transfer occur among the air, coarse aggregate, fine aggregate, and mortar. Moisture existence plays an important role in the heating process, and quantitative microscopic examinations and analyses are still required for a deeper understanding of the heating process. The mass transfer process is affected by the heat-transfer conditions (and vice versa). Multi-field coupling software, such as COMSOL Multiphysics, may allow comprehensive analysis of the whole mass-transfer process.

Changes in the phase and chemical composition may occur when the temperature of the mortar and aggregate reaches a certain level. Such changes can alter the response variation of the entire concrete sample and then the stress field distribution, affecting the heating results [62]. The moisture transfer and phase change can also be investigated using the multi-field coupling software under microwave heating. Further studies are needed to obtain a deeper understanding at the microscale. Many techniques, such as X-ray diffraction analysis, X-ray fluorescence, energy-dispersive X-ray spectroscopy, scanning electron microscopy (SEM) and X-ray computed tomography, can be used to obtain microscale information regarding the morphological and mineralogical characteristics of treated samples before and after microwave irradiation [63–65].

3. Research progress

In recent years, research on microwave heating of composite materials such as concrete has seen considerable progress. These investigations are the precondition and top priority for further investigations and subsequent industrial applications. The recent research progress related to the microwave heating mechanism, along with experimental and numerical studies related to concrete, is presented in this section.

3.1. Microwave heating mechanism

The microwave heating mechanism, electromagnetic field, and mechanical field of concrete compositions under microwave irradiation are important research topics. Electromagnetic theories such as Maxwell's equation, electromagnetic power generation, and Poynting theory are the basis of theoretical investigations. The microwave heating process is a multi-filed coupling process, which requires amalgamate multifield subjects. The heating mechanism involves heat conduction, heat convection and electromagnetic heating. Few theoretical researches related to the concrete response under microwave irradiation, the heating mechanism, the mechanical-field variations induced by the temperature field, etc. have been performed [66,67]. The heating mechanism of different combinations determines the stress field of the concrete,

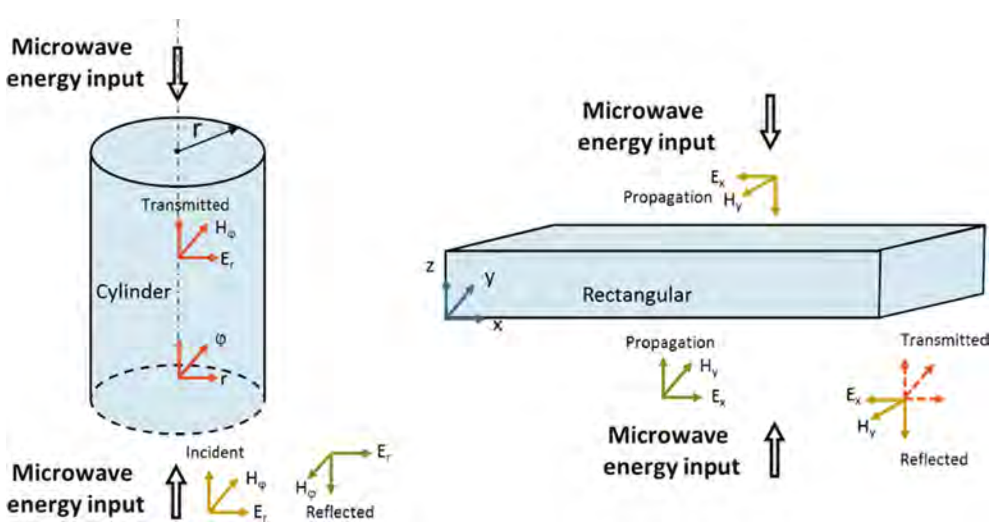

Fig. 4. Schematics of three-dimensional cylindrical and rectangular objects heated by electromagnetic microwaves.

which then influences the crack formation and propagation during the heating process [68]. The change in the phenomenon is due to internal variation, which is related to the heating mechanism under microwave treatment [69]. In electromagnetic heating, the concrete temperature distribution significantly depends on the dielectric properties, which are functions of the microwave frequency, temperature, and concrete composition. Many experimental and numerical investigations of microwave heating have been conducted owning to its widespread use of microwave in food, ceramics, and other applications. However, few researchers have theoretically analysed these problems. Hossan et al. developed an analytical expression for the temperature distribution in a typical three-dimensional rectangular and cylindrical object under electromagnetic heating, in which the electromagnetic power absorption is computed from the electric-field distribution [70,71]. Their research provided an analytical solution for the effects of the electromagnetic frequency, dielectric properties, and heat-transfer coefficient on the temperature distribution, as shown in Fig. 4.

Such multi-field analytical solutions can provide the basis explanations of the experimental and numerical results. As the composite material, the microwave energy absorptions and temperature distributions were varied in the concrete within the different composites. The heat conduction process within different composites during the heating process must be considered. The solution of heating conduction containing an internal heat source can give a further explanation and prediction of the temperature field in concrete, which will provide a reference for the control of the temperature within concrete under the application use of microwaves for the accelerated curing of concrete.

Research has already proven that microwave can induce intergranular fractures along the mineral' boundaries rather than trans-granular fractures. These studies provide a set of parameters to facilitate the formation of intergranular fractures for enhancing the effectiveness of concrete breaking and aggregate recycling processes. However, when the concrete was irradiated with microwaves, the mechanism underlying the behavior of the mortar-aggregate interface induced by electromagnetic heating was not specific or clear, which was directly related to the aggregate recycling process. Investigations of the interface thermal stress and crack propagation under microwave heating are needed. The crack propagation is highly dependent on the thermal stresses. The internal thermal stresses of cement-based materials are of two types: the thermal mismatch stress, which is caused by different coefficients of thermal expansion between the cement and the aggregate, and the thermal gradient stress, which is due to the temperature difference between different phases. How can boundary separation between the mortar and the aggregate accelerated during the recycling process? How can we select the proper microwave parameters for recycling to reduce the performance deterioration of recycled aggregate? Does the internal thermal stress negatively affect the concrete structure during the non-destructive monitoring process? The mechanism related to the mortar-aggregate interface properties under microwave irradiation required further study.

For the microwave-assisted concrete curing process, how can we control the uniformity of the heating effect within the concrete curing period? How can we determine whether the hybrid heating, i.e. conventional and microwave heating, is needed to provide a more uniform heating process? To solve these problems, the heating mechanism for concrete must be investigated under different heating parameters and different heating conditions, e.g. different water contents and sample sizes. Quantification equations are required, which is the universal law of the heating process. The definite heating effects of hybrid heating are needed, which are also based on an in-depth understanding of microwave heating. How can the proper penetration depth of microwave-assisted concrete drilling be determined for different concrete parameters? The mechanism research must connect the microwave absorption ability of different types of concrete with the microwave penetration depth $D_p \approx \lambda_0 \sqrt{\varepsilon'}/2\pi\varepsilon''$. The penetration depth varies with respect to the dielectric loss of the material, microwave frequency, operating temperature, concrete chemical composition and microstructure, which is an essential issue that must be understood for an effective drilling process. In the microwave-assisted concrete non-destructive monitoring process, the proper microwave frequencies for different properties of detected concrete are needed to obtain accurate monitoring results. Further investigation of the microwave heating mechanism is needed.

3.2. Experimental studies

Microwave applications for the treatment of concrete have been experimentally investigated over the past several years. Many laboratory tests have been conducted to investigate microwave-assisted concrete curing, recycling, drilling and non-destructive monitoring. Various industrial microwave heating system were designed for different microwave applications on concrete. These experiments have proven that microwave application on concrete is workable and is superior to those conventional dispose methods as clean and green energy. The results of microwave-assist concrete recycling, curing and drilling were obtained experimentally. Microwave non-destructive monitoring of concrete properties such as concrete defects, properties, water content and volume positions were also achieved through experiments. Owning to the limitations of achievements in industrial applications, the majority of the studies were conducted only in the laboratory. Recently, more research closely related to engineering projects has been conducted. From a macroscopic viewpoint, properties such as the concrete heating temperature, internal stresses, deformation, and damage under microwave treatment were investigated experimentally. Because of the development of electronic devices and experimental systems, studies have increasingly focused on the microscopic variation analysis of concrete under microwave heating. The effects of microwave processing on materials' chemical properties, phase transformations, morphologies, mineralogical textural features, chemical compositions, and magnetic properties, as well as the formation of new materials, have been studied [72–75].

As the basis of microwave heating technology, the microwave-absorption abilities of different compositions of concrete must be known. Many experiments were conducted to test the microwave-absorption abilities of different construction materials [76]. The conclusions were limited to materials with certain origins and ages in a certain heating cavity, and no universal rules were established [77]. The dielectric properties measured in the experiment can reveal the response of materials under microwave treatment. The dielectric characterisation of concrete at different temperatures is essential for practical use [78]. Compared with recycled or on-site concrete, the dielectric properties of concrete from the lab with clear properties can be obtained more easily [79]. Recently, the dielectric properties of recycled concrete from construction sites were investigated, and the results may provide a valuable reference for the microwave-assisted concrete recycling and curing industry [80]. Before the stabilisation of the concrete properties, the dielectric constant fluctuated drastically and continually during the early stage of the hydration reaction. A few studies clearly indicated that the variation of dielectric properties is related to the hydration process, e.g. the hydration time, external hydration conditions and concrete properties. Moreover, the selection and accuracy of dielectric-property tests affect the test results,

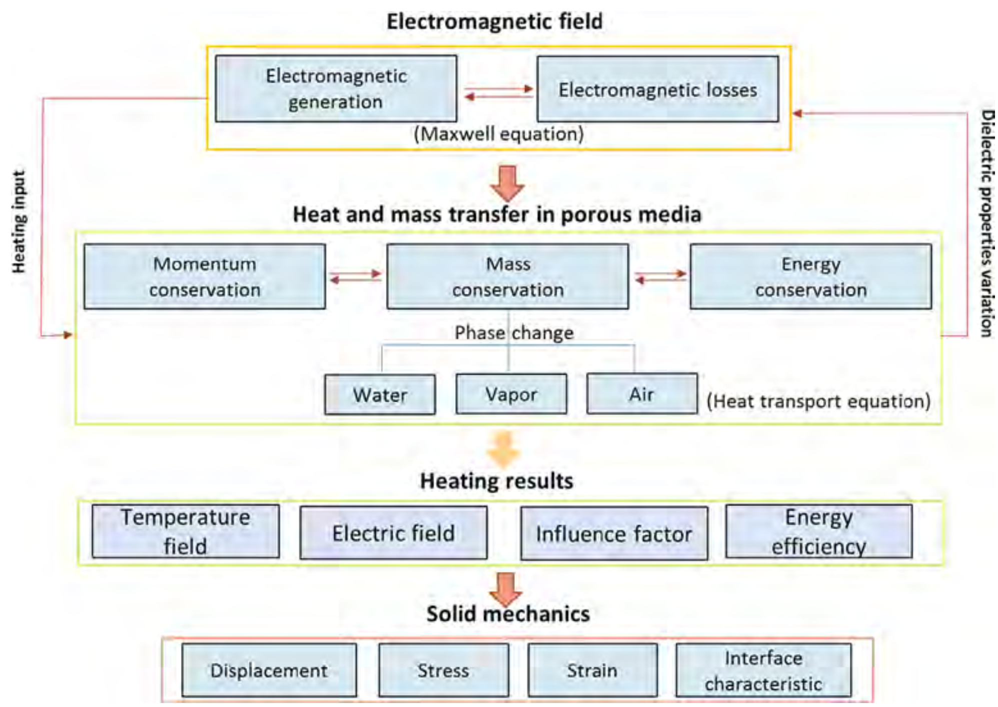

Fig. 5. Fully multi-field coupled microwave heating of concrete.

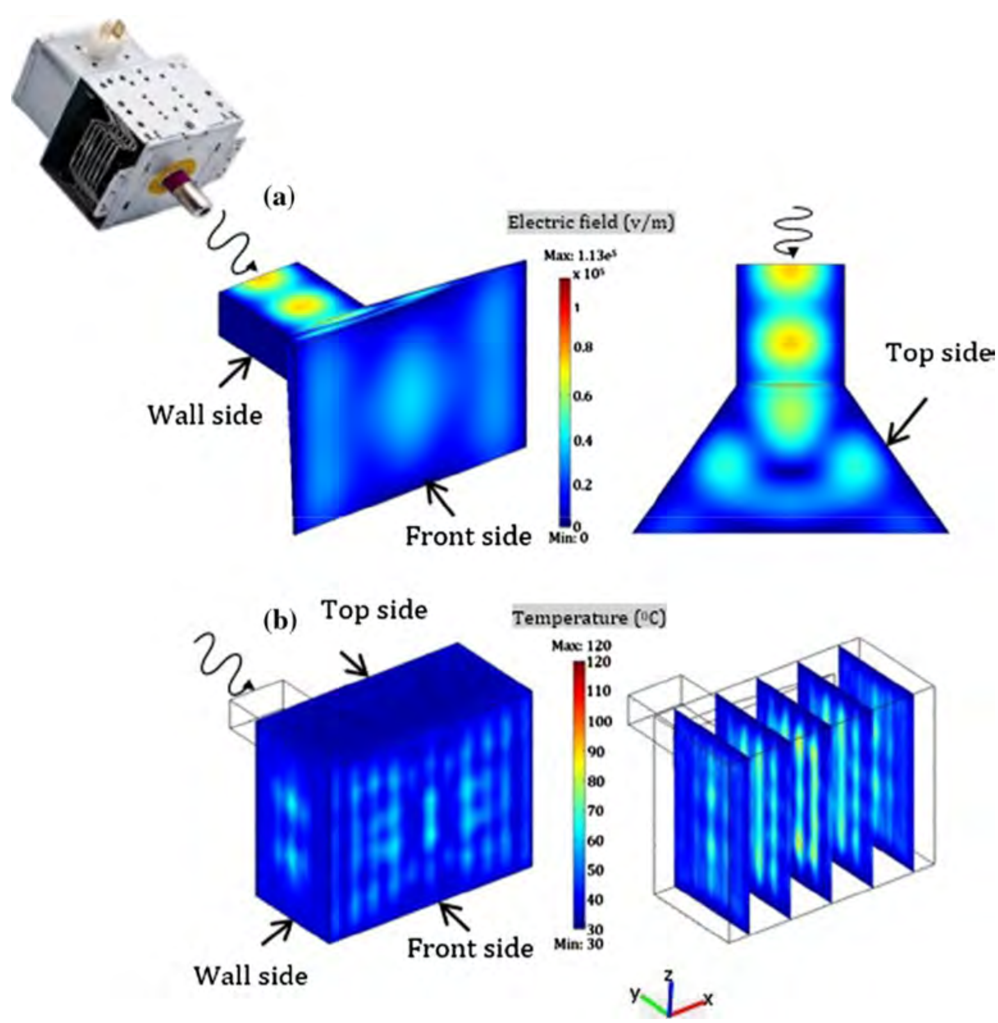

Fig. 6. Distribution of electromagnetic field and temperature field within concrete.

for example, transmission or reflection line, perturbation, free-space, and open-ended methods [81–82]. The dielectric properties of concrete under various conditions should be investigated in future research.

3.3. Numerical studies

Generally, software such as Analysis of Continua (FLAC), Particle Flow Code (PFC), Ansys and Abaqus, etc., was employed for the numerical simulation research. The majority of these studies focused on the thermo-mechanical properties of the model [83–88]. The temperature field, stress field, strain variation, boundary characteristics between two materials during microwave irradiation, and factors influencing the heating process were numerically analysed and discussed. Most of the simulations were the two-dimensional analysis, revealing the basic heating phenomenon, where it was assumed that the heated materials were homogeneous. The electromagnetic-field variations, moisture transfer, and phase changes were not considered, in contrast to an actual heating circumstance.

Recently, a simulation employing COMSOL Multiphysics and the finite-difference time-domain method was performed from a multi-field and microscopic perspective. Toifl et al. investigated the temperature and stress field of inhomogeneous rocks under different microwave treatment parameters and got an illustration of electric-thermo-mechanical coupling process [62,89]. The powerful COMSOL Multiphysics software simulates microwave heating by coupling electromagnetic, solid heating, solid mechanics and mass-transfer modules [90]. Hong et al. [91] simulated the heating behavior of coal under microwave irradiation using COMSOL Multiphysics. The simulation process was similar to that for concrete as the porous materials. The multi-field simulation process for concrete is shown in Fig. 5. Electromagnetic generation is the basis of microwave heating. Multiphase heat and mass transport in porous media involve momentum, mass and energy conservation. Microwave heating can lead to variations of the temperature and moisture, affecting the dielectric properties of concrete. The temperature field, electric field, heating influence factors, and energy efficiency of the heating process can be determined. Through coupling with the solid field, the mechanical properties of concrete can be analysed, such as the displacement, stress and strain of the mortar and aggregate.

Rattanadecho et al., analysed the concrete curing process under microwave heating through the coupling electromagnetic-thermal approach in COMSOL Multiphysics, as shown in Fig. 6. The size change of the input waveguide affected the uniformity of the temperature distribution in the concrete [92].

A few investigations have been conducted on the full multi-field coupling problem of concrete under microwave treatment. The temperature distribution within the mortar and aggregate compositions, electromagnetic-field distribution, heating conduction conditions, moisture evolution through the mortar and aggregate, mechanical field, concrete deformation, and features of the mortar-aggregate interface are the vital issues for obtaining a deeper understanding of the microwave heating of concrete [93].

4. Applications of microwave on concrete treatment

In recent years, the applications of microwave for concrete treatment have developed rapidly owning to the advancements in experimental approaches and computer science. This section presents various applications of microwave energy to concrete, including the use of microwaves for improving the quality of recycled concrete aggregates (RCAs), the accelerated curing of concrete, drilling in concrete, and the non-destructive monitoring of concrete.

4.1. Use of microwaves for improving quality of RCA

Construction and demolition (C&D) waste is produced during new construction projects, building renovation, and building demolition, which has become a serious worldwide problem [94]. Among the world's countries, China currently produces the largest amount of C&D waste owning to its rapid urbanisation and economic growth as a developing country. The construction industry employs more than 40 million people, accounting for more than 5% of the total labor force and 25% of the gross domestic product. Accordingly, C&D waste is becoming one of the largest waste streams. It was estimated to be approximately 8 times larger than municipal solid waste, accounting for 30% −40% of the total solid wastes in China [95,96]. However, the recycling rate for China's C&D waste is <10%. Demolished concrete constitutes a large part of the C&D waste. Concrete recycling is one of the most effective waste-management strategies for dealing with the large amount of demolished concrete. On one hand, concrete recycling can reduce the incurred cost and energy consumption caused by debris dumping in remote landfills and can reduce the amount of landfill space needed [97]. On the other hand, many countries are currently facing the problems of natural-aggregates shortages and continuously increasing aggregate prices. Concrete recycling can provide a sustainable source of concrete aggregates by turning concrete debris into recycled aggregates for reuse in the construction industry. The disposition of the aggregate in demolished concrete is the key issue for sustainable and reusable development with this non-renewable resource. The effective utilisation of RCAs is important for the sustainable and renewable development of the construction industry [98,99].

Recently, microwave heating has been considered as a potential candidate for the effective recycling of concrete aggregates [100,101]. Owning to the microwave heating characteristic, the gypsum plaster and tiles attached to concrete can be theoretically de-bonded. After the primary treatment of the demolished concrete, the separation of the cement and aggregate is the first consideration for the continuous reuse of aggregate [102]. Previous studies have revealed that the cementitious mortar adhering to the aggregate is the most important factor reducing the quality of RCAs compared with natural aggregates. The presence of cementitious mortar results in a lower density, higher water absorption, stability loss and performance deterioration of recycled concrete.

The conventional heating approach can separate the mortar and aggregate at a certain temperature. In conventional thermal separation, aggregates are heated to a temperature varying from 300° to 600 °C, depending on the properties of the mortar and aggregate [103,104]. Generally, several hours are needed to reach the required temperature in the conventional heating cavity. Mortar has a larger thermal expansion coefficient than the aggregate within concrete, thus, the temperature and thermal stresses are higher within mortar, causing the breakage of adhering mortar to occur firstly. The different heating properties of the two materials lead to different thermal stresses at the interface during the heating process. The mortar adherence can be weakened via conventional thermal separation. However, during the conventional heating process, a long heating period is needed to reach the required temperature, along with high energy consumption. Additionally, the high temperature and long heating duration may lead to the performance degradation of the recycled aggregate compared with a natural aggregate. Researchers found that numerous microcracks in the cement matrix were formed when the material was exposed to a higher temperature between 600 °C and 800 °C, leading to the degradation, breakdown, and density loss of the aggregate [105]. Considering the environmental and economic impacts, conventional thermal heating is not an effective recycling method.

Mechanical methods for mortar-aggregate separation employ rubbing and impact forces to separate the adhering mortar. These methods can remove the adhering mortar easily [77,106–108]. However, large amounts of dust and noise pollution are generated, and energy consumption is relatively high, and secondary pollution is produced. Moreover, with regard to the mechanical properties, the aggregate yields owing to the rubbing, impact, and breakage induced by the external force.

Microwave-assisted concrete aggregate recycling, which uses a clean form of energy, has been highlighted by many scholars. Studies have indicated that microwave heating significantly affects the interface between two materials with different dielectric properties, such as mortar and aggregate, [75,100,111]. The principle of microwave-assisted aggregate recycling is based on the selective heating property of microwaves. The responses of the mortar and aggregate under microwave irradiation differ significantly, along with their heating rates and thermal expansions. A large temperature gradient results in relatively high thermal stresses near the mortar-aggregate interface. This leads to the development of stresses that are favorable for phase boundary weakening during rapid heating [112]. Moreover, the interfical transition zone (ITZ) around aggregate particles significantly affects the embrittlement behavior of concrete during microwave heating because of its high porosity and high w/c ratio. The amount of energy absorbed by a material increases significantly with an increase in the water content, and the heating of the ITZ is expected to be accelerated under microwave irradiation owning to its effects on the micro-structure and moisture. Thus, higher differential thermal stresses may develop in the ITZ, leading to more efficient removal of the adhering mortar.

Akbarnezhad et al. compared microwave heating with other beneficiation methods, and the results indicated that microwave heating results in a higher-quality RCA. Compared with the 12% mortar reduction of conventional heating, microwave heating resulted in reductions of approximately 48% and 32% in the mortar content in saturated concrete and dried concrete, respectively, within a single run under a heating condition of 10 kW for 1 min [113]. Bru et al., reported that microwave heating improved the liberation degree of aggregates after impact crushing. The degree of liberation reached >90% within 5 min [28]. The recycling temperature of the microwave treatment was about 140 °C, which is significantly lower than that of conventional heating methods [29]. Choi et al., found that an RCA contained less than <5% of paste and fine aggregate after 180 s of 1800 W microwave treatment. The recovered recycled aggregate was very similar to the original coarse aggregate [114]. It appears that the aggregate properties were not degraded under the microwave treatment. Experiments proved that the microwave-recycled aggregate led to a significantly smaller reduction in the compressive strength of the concrete compared with other methods.

Research has demonstrated that microwave pre-treatment combined with standard mechanical treatment can positively affect the aggregate liberation and cement matrix removal, as shown in Fig. 7 [115]. In the experiments, microwave heating enhanced the aggregate liberation and cement matrix removal when used in combination with mechanical crushing under a heating time of 60 s. The aggregate recovery obtained for microwave-electrodynamic fragmentation was 35% and 14% for the mechanical crushing technique. Almost all the microwave heating power inputs in the experimental tests were <10 kW, and only several minutes were needed for the liberation of both the aggregate and cement phases. The energy consumption was significantly lower than that of the traditional methods, i.e. <50 kW h t^{-1} [30]. Orman

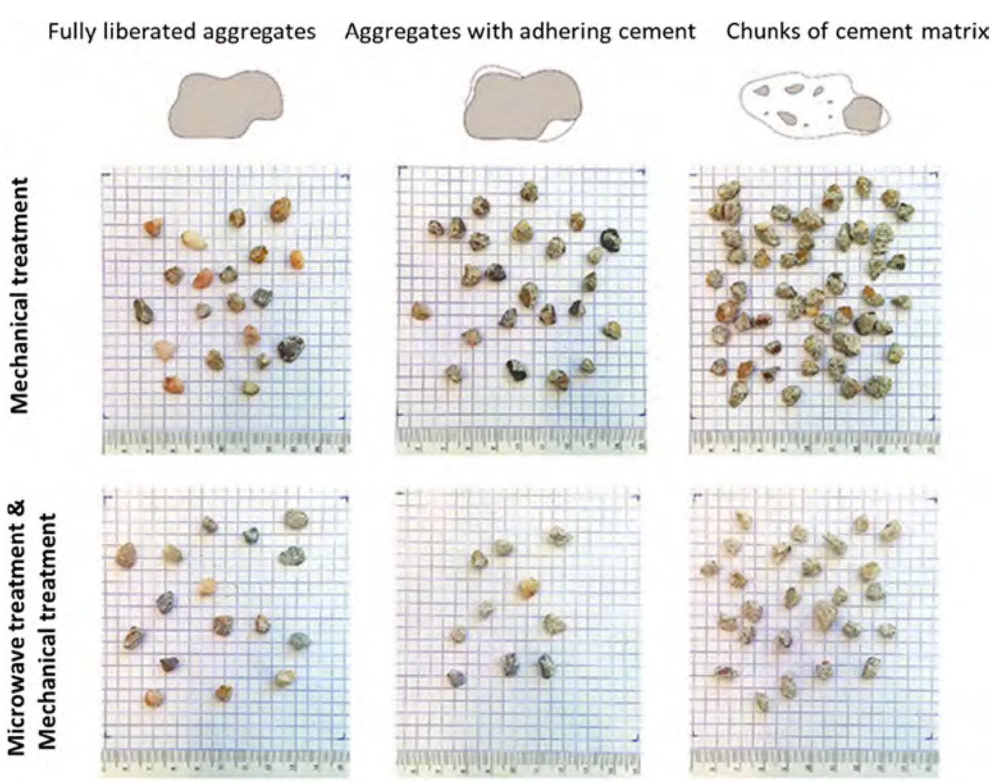

Fig. 7. Recycled aggregate under mechanical treatment and microwave treatment combined with mechanical treatment.

et al., compared the energy consumption of microwave heating (900 W, 60 s) and conventional heating (furnace, 600 °C, 1 h), and the results indicated that the furnace (5.33 kWh) consumed approximately 225 times more energy than the microwave heating (0.0237 kWh), while the damage was more extensive under microwave irradiation [112]. It can be concluded that a shorter heating time and volumetric heating properties lead to a high energy efficiency of the microwave heating-assisted aggregate recycling process [116].

Moisture plays an important role in the heating process as a good-microwave absorbing material. Numerous studies have indicated that increasing the water content of concrete enhances the microwave weakening process [117–120]. The presence of RCA in water may result in better adhering mortar separation effects. Mortar is a porous material that has a higher water-absorption capacity than aggregates. Therefore, saturating the adhering mortar by soaking the RCA particles in water can increase the differences in water content between two materials. Leading to the differences in the microwave heating rate and temperature distribution. Additionally, microwave heating can generate high pore pressures because of the rapid formation of steam from water within the material when the heating temperature reaches the boiling point (100 °C). When the heating temperature reaches the boiling point, phase change and mass transfer occur. The superheated steam pressure in the sample promotes the propagation of cracks and eventually the fracture of the sample.

Applying different cooling methods after the heating process may influence the separation by changing of thermal stress gradients. A higher thermal stress gradient results in more serious interface damage between two brittle materials. Theoretically, applying the spraying water-cooling method after irradiation may enhance the separation effect of the adhering mortar compared with cooling in air [121,122]. A microwave-assisted aggregate recycling schematic based on the foregoing discussions can be proposed (Fig. 8). The aggregates are expected to be pre-soaked in water and then heated in the microwave cavity. Mechanical treatment may be needed to further separate the adhering mortar. The cooling-method selection is based on the separation results, as shown in Fig. 8. An increase in the water content, mechanically assisted separation and water-cooling methods all promote the separation of the aggregate and mortar. Methods for improving the microwave absorption of materials have recently been proposed in addition to water pre-soaking methods [123,124]. For example, TiO_2-clay has large relative dielectric constant, and the addition of TiO_2 powder can significantly improve the microwave absorptive ability. Such methods can be employed in the microwave-assisted aggregate recycling process. By coating the mortar by TiO_2 powder, SiC, Fe_3O_4, etc. before the heating process, the heating rate and temperature gradient from the mortar to the aggregate can be increased, which may enhance the separation results [125].

In the microwave heating process, the selection of the heating parameters according to the properties of the mortar and aggregate is the key issue for achieving a high energy efficiency. Properties such as the demolished concrete age, w/c ratio, aggregate type, and sample size must be considered for the selection of proper heating parameters. Further research on the combination of the mechanical separation process and the subsequent cooling period is needed. The appropriate combination of different approaches with microwave heating may provide an effective and eco-friendly recycling process. A suitable microwave system and rational procedures must be developed. Although the initial cost of microwave equipment may be expensive, microwave-assisted aggregate recycling can provide an eco-friendly heating process and high-quality aggregates. Considering the aggregate utilisation and energy consumption, microwave heating-assisted aggregate recycling can be regarded as a potential and prospective technique for future applications.

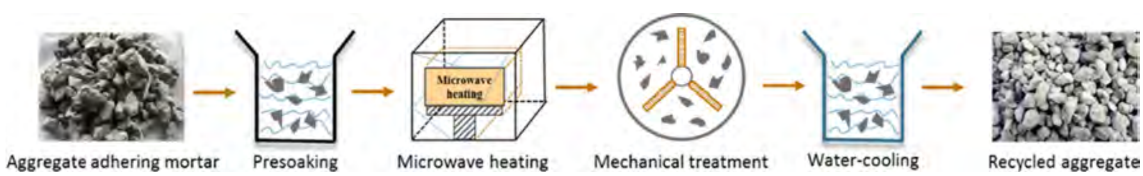

Fig. 8. Schematic of microwave heating assisted aggregate recycling.

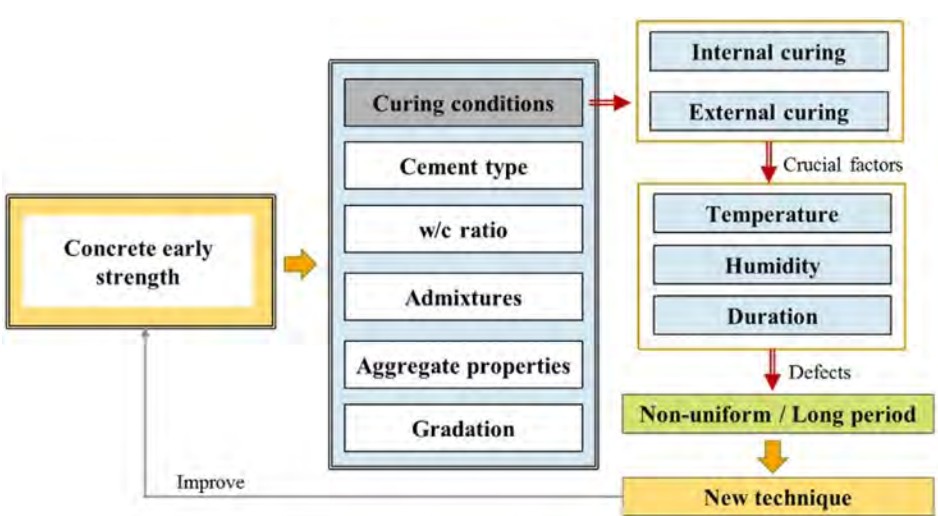

Fig. 9. Factors affecting the strength of concrete and the improvement of the concrete strength via new curing methods.

4.2. Use of microwaves for accelerated curing of concrete

Microwaves have been investigated for acceleration form of curing for both newly cast concrete and repair mortars. According to the microwave-specific heating characteristics, the microwave curing of freshly poured concrete was introduced for improving concrete early strength. Regarding the repairing of mortar, studies indicated that microwave repair of concrete can accelerate the hydration of old concrete within a short heating time, which can improve its mechanical performance and ensure its future usability.

New concrete curing can be realised under certain temperature, humidity, and time condition via the common method, which may spend far more time to reach a certain strength for its industrial uses. Various curing approaches have been proposed for accelerating the strength development of concrete materials in the early age phase.

Strength is a crucial factor in both the prophase structural design period and the construction period. Increasing the early strength can benefit the concrete production by reducing the construction duration, labor force, and energy consumption, facilitating resource conservation and ensuring eco-friendliness. The early strength development of concrete is influenced by several factors, such as the curing conditions, cement type, w/c ratio, mineral and chemical admixtures, aggregate size and quality and gradation, as shown in Fig. 9. Several methods can be employed to increase the early strength of concrete. Favorable moisture and temperature conditions are needed to ensure the degree of hydration and the strength development of concrete during the curing process.

The curing condition and methods affect the rate of strength development of concrete. Conventional curing techniques, such as steam-heating curing, rely on heat and moisture conduction from the sample exterior to the interior. Some curing methods may lead to non-uniform heating. Additionally, a long period may be needed to reach the required temperature and humidity for ensuring the strength development.

Owing to its heating characteristics of microwave, microwave curing of concrete was introduced as a new effective and economical method to replace conventional curing techniques. It is well known that the thermal-curing concrete approach has a positive effect on the concrete strength development. A crucial question

Table 1
Summary of recent research on microwave-assisted concrete curing.

Microwave heating condition	Main findings	Reference
P = 60, 120, 132, 180 or 264 W t = 45 min	MW curing is suitable for normal, non-rapid setting repair materials. The presence of steel reinforcement in repair mortar does not cause arcing during MW curing.	[6,126]
P = 400, 800 W t = 10, 15 min	Compressive strength development of a concrete workpiece subjected to MW curing is greater than that achieved by air curing or water wet curing at early age. Highest strength achieved by MW curing is 239 kg/cm^2, which is equal to 85% of the strength achieved by water curing within only 120 min.	[92]
P = 900 W t = 5 min	MW curing processes can accelerate cement hydration and enhance the strength compared with water curing.	[127]
P = 240, 360, 600 W t = 0–120 min	MW curing for 120 min resulted in compressive strengths similar to or higher than those of mortars heat-cured at 75 °C for 48 h. MW curing yields microstructure densification and a uniform microstructure.	[128]
P = 300, 350, 400 W t = 45 min	The overall performance of MW cured concrete (short-and-long term) is comparable to that of concrete containing accelerators as well as commercial rapid-hardening concrete.	[130]
P = 150–1250 W t = 15–120 min	Compressive and flexural strength of mortar treated by microwave increase significantly. The increment of the early strength is larger than that at a later age.	[132]
P = 780, 800, 1600 W t = 15–100 min	The use of microwave-assisted low-pressure processing improved the cement mechanical properties. The energy consumption was minimised: 0.35 and 0.45 w/c cement paste were controlled at a pressure of 30 kPa for 50 min, and 12 specimens were controlled at 0.45 for 120 min. MW-cured cement developed a higher compressive strength over 28 d than water-cured cement. MW energy can accelerate the compressive-strength development 15 min after the completion of curing. With a delay time of 60 min, MW can process the paste almost a day faster than water curing.	[27,131,133,134,139,142]
P = 140,260, 440 W t = 30, 60, 120 min	MW curing improves the compressive strength of mortar before the age of 28 d, slightly increasing the porosity of the mortar, while it significantly reduces the volume of pores with sizes of >100 nm.	[135]
P = 260 W t = 35, 45, 55 min	Microwave curing accelerated the hydration of cement particles. Although microwave curing slightly increased the porosity at the early age, the volume of pores larger than 50 nm did not increase, which had a small effect on reducing the compressive strength.	[136]
f = 10 GHz t = 0–60 min	The w/c ratio and the type of cement are the major parameters that affect the conductivity and relative permittivity of cement, which result in changes in the hydration process under microwave heating.	[140]
P = 20, 31.5 kW t = 0–180 min	The ply orientation did not affect the temperature distribution of composite materials, and the thickness was an important influencing factor. A multi-pattern real-time compensation method was proposed to achieve better temperature uniformity on the surface of composite laminates during MW curing, which can significantly improve the homogeneity of the temperature field. A convolutional neural network-based microwave control strategy estimator was designed, and a process control system was developed, which achieved a temperature-difference reduction of 42.3%.	[129,141,143,144]
P = 1200 W t = 120 s	MW heating is an effective method that can be used to heat asphalt concrete for accelerating its healing. The addition of conductive materials (steel fibers and graphite powder) can increase the thermal conductivity and microwave heating rate of asphalt concrete.	[145]
P = 900 W t = 3, 6, 9, 12 min	Temperature treatment of cement resulted in a higher strength than water-curing methods. MW curing was effective at the ages of 3 and 7 d and resulted in a more open microstructure (higher porosity).	[146]

can be raised: can microwave heating be employed in the concrete curing industry? Theoretically, this is possible, because the main components of concrete are dielectric. Microwave volumetric heating provides a heating mode volumetrically and rapidly, with continuous interaction between the microwave field and the heated material. Microwave heating can result in a violent cement-water-aggregate interaction, accelerating the curing of the concrete.

Many studies have proven that microwave heating can improve the early strength of concrete, with little degradation of its long-term performance [127–147]. Table 1 summarized some of recent research undertaken recently. Leung and Pheeraphan [130] proved that the 7-d strength of concrete under microwave curing was superior to that of conventionally cured concrete. With regard to both the short- and long-term aspects, even for concrete containing accelerators and commercial rapid-hardening concrete, the performance of microwave-cured concrete was comparable to that of concrete cured using conventional methods. Other studies also indicated that microwave energy can accelerate the early compressive strength without affecting the 28-d strength. M Natt et al., indicated that microwave curing reduces not only the energy consumption but also the curing time (Fig. 10) [131]. The compressive strength after 30 min microwave treatment was lower than that after 15 min, which may have been related to the microstructural variations of the concrete under different microwave curing times.

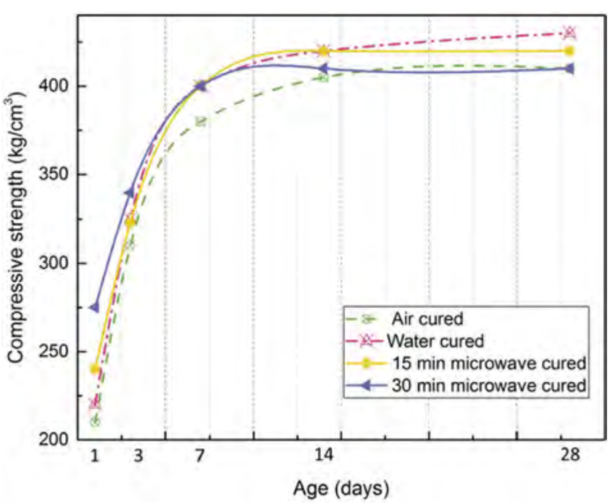

Fig. 10. Comparison of compressive strength development for different curing methods.

Concrete is generally composed of cement, aggregate and water, which are all dielectric materials and can absorb microwave. Thus, the temperature of concrete increases under microwave irradiation, which can provide conditions for more thorough cement-water interactions and hydration [132]. The mechanical performance of concrete is related to its hydration level. The water content and form must be considered, particularly owning to the principle heating response under microwave treatment. Generally, in the initial state of microwave curing, the temperature of the concrete and cement paste increases rapidly, because of the high moisture content. With continuous microwave treatment, the temperature increases of the concrete decreases slightly, which is consistent with the remaining water-cement ratio [133,134,139].

The cement–water system is a complex multicomponent system with temperature-sensitive composites. The transformation of material properties' or new matter formation may occur during the curing period. To gain a better understanding of the heating response, concrete materials subjected to microwave irradiation must be characterised from a microstructural perspective. Experiments proved that microwave curing can reduce the w/c ratio compared with normal steam curing. The ITZ between the cement and the aggregate can be improved, enhancing the strength and durability. SEM and EDS analyses of the concrete microstructure revealed that the connection between the aggregate and cement was increased by the reticular calcium silicate hydrate (C-S-H), resulting in a denser microstructure of the ITZ (Fig. 11). In the early stage, the strength of the concrete can be enhanced, and the heat-release rate of hydration can be increased owing to the existence of C-S-H [135–139]. Compared with conventional curing, looser and more porous structure can be observed after the microwave curing process. However, the microstructural analysis revealed that a denser microstructure was formed owing to the formation of new matter, and a lower w/c ratio was observed, leading to higher strengths of the concrete and mortar.

The following reactions occur after the cement comes into contact with water [140]:

$$C_3S \rightarrow C_2S + Ca^{2+} + OH$$

$$C_3A + 6H + 3CSH_2 \rightarrow 6Ca^{2+} + 2Al(OH)_4 + 3SO_4^{2} + (OH)$$

$$C_3S + H \rightarrow C\text{-}S\text{-}H + CH$$

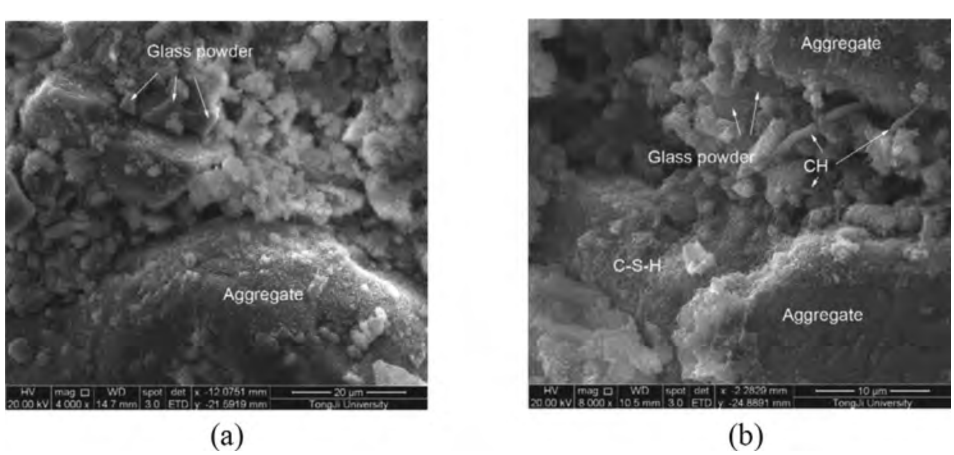

Fig. 11. (a) 80 °C steam curing at 1 d (b) Microwave curing at 1 d.

Additionally, proper w/c ratio is needed to achieve full hydration process. For concrete or cement with a low w/c ratio, all the water molecules reacted for hydration, and almost no capillary pores existed after the hydration. The capillary pores formed a path between the water molecules and cement throughout the hydration process. The absence of capillary pores can result in incomplete hydration, undermining the strength development. However, increasing the w/c ratio affects the porosity of the internal structure, which may reduce the early strength [141].

Concrete is a heterogeneous material, and different types of raw materials used in its manufacture can significantly affect the microwave absorption and temperature increase rate. When microwaves are used for accelerated curing of concrete, similar to all other forms of accelerated curing, the late-age strength is reduced. However, Mangat et al. established relationships between the main parameters of microwave curing i.e. the power, curing time, temperature rise and volume for different commercial repair mortars (fast setting cement-based materials were excluded) [6]. Their research indicated that when the temperature of fresh concrete or repair mortar does not exceed 40–45 °C during the period of microwave curing (approximately 45 min) the reduction in the late-age strength is significantly smaller than that for other methods of accelerated curing such as steam curing and electric heating blankets.

When the cavity is subjected to microwave irradiation, the uneven electromagnetic field generally results in an uneven temperature distribution both within both cavity and the whole sample. This is a significant obstacle in industrial applications. Vacuum-assisted microwave processing technologies and a modified sensing system can improve the uniformity of temperature distribution [142]. Zhou et al. proposed a multi-pattern compensation method for achieving a uniform temperature distribution on the surfaces of composite materials. They first constructed a heating-pattern database. Continuous monitoring revealed that the uneven temperature in the heating process was compensated according to the database [143]. An intelligent temperature control method was proposed to obtain a more homogeneous microwave curing process for composite materials such as concrete [144]. A convolutional neural network was used to learn the dynamic relationship between the heating pattern and the microwave control strategy in real time, which provided an accurate solution for the uneven temperature distribution. Regarding industrial applications of microwaves are concerned, there have been some recent developments. One example is the development of a pre-industrial prototype remote robotic system for performing in-situ microwave curing of patch repairs [126]. The surface temperature and moisture content of the installed fresh repair mortar, as well as the magnetron power of the microwave system, are constantly monitored in real time basis. Field trials of the foregoing system provided satisfactory results. These techniques may lead to the industrial application of microwave-assisted concrete curing.

4.3. Use of microwaves for drilling in concrete

Drilling holes in ceramics, concrete, rock, etc. is a basic operation in almost all industrial or construction operations. Advanced drilling technologies are being developed for drilling hard materials. Traditional drilling and cutting methods can satisfy the basic requirements of most construction projects [148]. The noise generation, dust accumulation, and strong vibration of the traditional drilling approach negatively affect the drilling process. Other drilling methods, e.g. water-flow, laser, and ultrasonic drilling, are generally expensive and not conducive for on-site operation.

The key principle of microwave-assisted drilling is the transformation of microwave energy into a high temperature at a hot-spot. When the temperature reaches a certain value under microwave irradiation, the mechanical properties of the materials deteriorate, and the materials finally become softer under sufficient energy input. The bit is then inserted into the workpiece to shape the boundary. As a new energy resource, microwave-assisted drilling can provide an eco-friendly drilling process, with little pollution and a high degree of controllability [149]. Microwave-assisted drilling can be evaluated as an ideal candidate a for more effective drilling process. Fig. 12 shows the microwave-assisted drilling principle with the combination of reamer mechanical crushing and microwave heating. The drilling debris can be mechanically removed through the liftable and adjustable reamer to ensure the insertion of the entire drill bit.

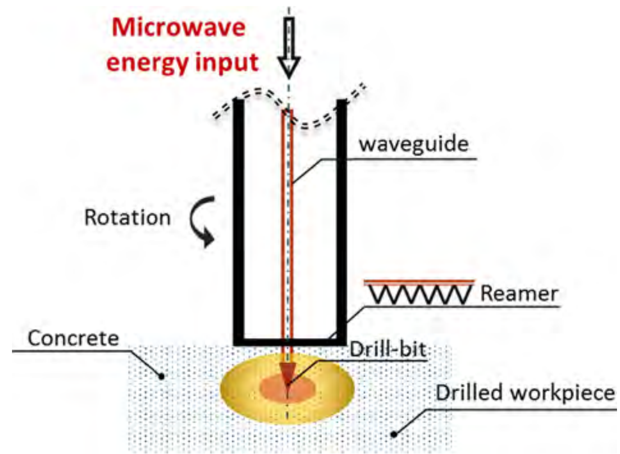

Fig. 12. Principle of microwave-assisted concrete drilling.

In concrete, a 2-cm-deep hole with a 2 mm diameter can be achieved within tens of seconds, and the melting temperatures can reach approximately 1500 °C [150].

Jerby et al. proposed a silent, remotely controlled microwave-assisted drilling system. Their drill bit formed a 26-cm-deep holed with a diameter of 12 mm in concrete [151]. According to greater than 100 field tests, the measured average drilling speed was 0.6 cm/min. The detected acoustic noise level was < 70dBC. Their achievement confirmed the applicability of microwave-assisted drilling technology to concrete, basalt, glass, and ceramics, as well as the considerable potential of this technology for construction applications [152,153].

For concrete with various cement types, ages, w/c ratio, aggregate types, and gradation, proper microwave heating parameters must be determined to achieve the appropriate drilling penetration depth and the required maximum temperature for avoiding an excessive energy input.

4.4. Use of microwaves for non-destructive monitoring of concrete

Over the past decades, concrete property assessment and structure monitoring, which are required for concrete structure maintenance, have led to the development and progress of non-destructive testing (NDT) techniques [154–156]. NDT methods are used in the construction industry for to the following four reasons: quality control in construction, troubleshooting, condition assessment of structures, and quality assurance of repair works [157]. NDT can test the material defects, materials properties and chemical processes.

Advanced composite materials are widely in the industrial projects throughout the world. Ultrasonic wave and X-ray monitoring cannot detect such material properties because of the low acoustic transmission performance. However, microwaves can be used to monitor these material properties owning to their special characteristics, with the advantages of rapid heating and noncontact, non-destructive operation. Microwave-nondestructive monitoring testing (MNDT) has attracted considerable attention for the assessment of materials or structures where visual inspection is not possible. The application of microwave heating in the concrete life cycle is promising owning to the remarkable dielectric properties and microwave-absorption ability of concrete [158]. Microwave can sense and penetrate light-opaque materials within a fair trade-off between penetration and resolution [159]. The principle of MNDT is based on the diagnostic properties of microwaves, which can reveal the structure of matter. The fundamental parameters of microwaves are closely associated with the micro-factors of the detected materials. The interactions between microwaves and materials are expressed through waves. The microwave parameters can reveal the internal structures of the materials. Therefore, MNDT can be categorized as a nondistinctive technique with instantaneous measurement, concise and quick results, low energy consumption, and a good penetration ability.

MNDT of concrete has become an important method for revealing cracks and flaws, and evaluating the moisture content, inhomogeneities and early strength. Previous research proved that the microwave energy could be used to predict the acceleration strength of concrete, the error was within 15% agreement with actual test results [160]. Additionally, the moisture contents, workability of concrete, and cracks in concrete can be examined through microwave irradiation [161,162]. The propagation of microwaves is controlled by the electromagnetic properties of concrete. Moisture plays an important role in the heating process as a good microwave absorbed material. The relationship between water content and microwave propagation properties in concrete can be observed to determine its moisture volume. The water penetration depth can be evaluated using the near-field microwave methods [163]. Keo at al., indicated that microwave infrared thermography can used to detect vertical steels, deducing positions, spacing and numbers of bars in concrete structure. Meanwhile, microwave caused a moderate temperature-increase and does not lead to alteration of inspected concrete [164]. This method can be used on large areas that can be observed using a camera simultaneously [165].

There are two general microwave methods for NDT, near and far-field microwave methods [166], as shown in Fig. 13.

Both methods are based on microwave signals, but near and far-field microwaves have distinct characteristics [167]. The near-field microwave imaging method is a non-destructive technique that can provide a quantitative measure of the surface and subsurface profiles of detected materials [168]. The near-field microwaves are close to the source. Near-field microwaves are evanescent waves rather than propagating waves, which are exponentially attenuating in free space and not constrained by diffraction limits [169]. Owning to their close proximity to the source, near-field microwaves can realise super-resolution imaging through a use of a scanning near-field microwave microscope [170]. Additionally, because of the low penetration of evanescent waves, only the properties of the surface and subsurface can be detected. A far-field microwave is a propagating wave [171,172]. Radiation of far-field microwave dominates at larger distances, and can penetrate multilayer, thick and complex structures [163].

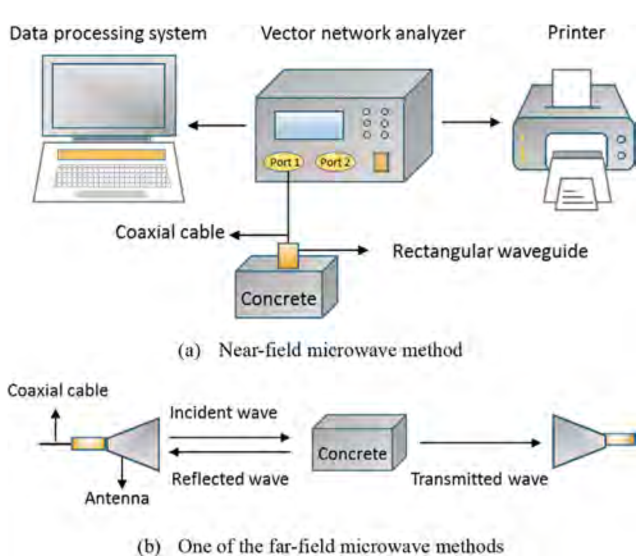

Fig. 13. (a) Near-field microwave method and (b) one of the far-field microwave methods.

5. Challenges for microwave industrial applications

Although applications of microwaves to cement and concrete have seen progress in recent decades, there are many challenges to be overcome for understanding the mechanism and realising additional large-scale industrial applications. The analysis will be used for the development of concluding remarks for proposing the industrial microwave applications for concrete processing. The main challenges can be summarised as the following three aspects: microwave heating response of concrete, microwave heating characteristics and microwave heating systems.

5.1. Heating response of concrete under microwave irradiation

Concrete is a typical composite material. Many factors can affect the concrete performance under microwave irradiation, such as the mortar type, aggregate type, aggregate distribution, and w/c ratio. Although many studies have revealed the microwave responses of different minerals through the experimental test, the properties of minerals within aggregate may be influenced by other complex constituents. Furthermore, minerals from various origins may lead to differences in the microwave absorption. In addition to the impact of the mineral composition of concrete, the heating responses of the aggregate and mortar interact with each other. The clear law and principle of the heating response of concrete were difficult to obtain. The modelling and simulation of the material behavior during the microwave process were more flexible owning to unavailability of experimental data. The poor repeatability of the results and the unavailability of experimental data limit the use of microwave treatment on industrial applications [173]. Obscure heating characteristics of different concretes may lead to the inappropriate selection of heating parameters, which can result in an incomplete heating process or energy waste.

5.2. Microwave heating characteristics

In addition to the heating interaction between the materials and microwaves, the nonuniformity of microwave heating may be induced by the shape and size of the heating cavity, position of the heating sample, port setting of waveguides, etc. The nonuniform heating of microwaves is the main cause of heat damage for processed materials, which can lead to the uneven heating of samples and even hotspot generation within materials. For example, materials within concrete have anisotropic properties which is the primary negative effect in the microwave-assist concrete curing process. Proper design of heating equipment, real-time monitoring of heating results, and the material microwave-absorption change can be used to control the uniformity of the heating process.

In many recent studies, the real-time neural networks have been employed to learn the dynamic relationship between the heating pattern and the microwave control system. Real-time monitoring of the heating process is difficult because of the rapid and continuous temperature variation within the sample. The interior temperature distributions in the sample cannot be obtained in real time. Additionally, the hysteresis effect between the real heating process and intelligent monitoring can lead to a control delay during the heating period. Clarifying of material heating response is a priority for achieving an effective heating process.

Research also indicated that microwaves of multiple frequencies can produce a more uniform power distribution within the cavity. It appears that more areas may be continuously heated by alternately using more than one microwave frequency [174]. When heated by microwaves, owning to the volumetric and efficient heating characteristics, the edge of the specimen loses heat rapidly because of the large temperature difference compared with the surrounding environment. Furthermore, the centre of the sample can be heated easily through the volumetric heating process. Therefore, coupling methods of microwave heating and conventional heating have been used to solve such nonuniformity heating problems, this approach is called microwave hybrid heating (MHH) [175,176]. The MHH has been successfully applied to the processing of the bulk metal materials [177].

The microwave-absorption ability can be improved by employing some catalysts and chemicals, such as Fe_3O_4, Fe_2O_3, MnO_2, Al_2O_3, MgO and TiO_2. Packaging materials with these chemical powders can significantly improve the microwave-absorption ability, which can be beneficial for the microwave treatment of concrete for industrial applications [177–179].

5.3. Microwave heating system

The design of a single-mode microwave heating oven is theoretically based on the electromagnetic-field equations for a cavity of a given size. However, the design of a multi-mode heating cavity is more complex. The following problems must be solved: complex design and high initial cost of the microwave heating system, the control of the microwave penetration depth, and the combination of the heating equipment, and the temperature-control system. Thus, a balance must be achieved among the heating efficiency, energy consumption, and operational safety. Considering that the heating target is the main composite, the volume and dimensions of the microwave heating cavity must be designed via an efficient curing process. The design of the heating-cavity size, the height of the sample settlement, and the waveguide position directly affect the heating efficiency. The designed heating cavity may only be suitable for typical-size samples according to the previous studies. Improving the applicability of the heating cavity to make it suitable for a certain size range of samples is a suggested topic for future research. Additionally, the design of large-scale microwave heating oven is needed to obtain the mass production in concrete curing, recycling and MNDT process. A rotary radiation structure was proposed to improve the heating uniformity within the heating cavity, which is based on a rotary disk for dispersing the heat energy [180]. Additionally, a pre-industrial prototype remote robotic system was developed, and the heating results can be constantly monitored in real-time [126].

As discussed previously, the pre-soaking of concrete can enhance the separation effect of the mortar and aggregate. A high moisture content in concrete would leads to abundant steam production when the temperature reaches the boiling point of water. The leakage of microwaves is harmful to human and the environment. How to release of steam with no microwave leakage is a vital issue that needs to be considered.

Further research is needed for the efficient utilisation of microwave heating systems as eco-friendly and sustainable energy sources.

6. Conclusion

Microwave heating is a high-performance volumetric heating approach that is appropriate for dielectric materials. Compared with conventional heating techniques, microwave are excellent candidates for concrete treatment. With the increasing emphasis on sustainable development and eco-friendly processes, microwave-assisted concrete treatment is gradually gaining popularity and recognition.

A review of the experimental, theoretical, and numerical results for microwave heating technology obtained over the past decades was presented. (a) The mechanism, characteristic, and theoretical fundamentals of microwave heating were discussed. (b) The progress of microwave applications for concrete treatment was examined, including microwave-assisted concrete recycling, microwave-assisted concrete curing, microwave-assisted concrete drilling, and microwave non-destructive monitoring. (c) Challenges for engineering applications involving microwave-assisted concrete treatment were finally identified, including heating response, heating characteristics, and heating system.

It can be concluded that engineering applications of microwave-assisted concrete treatment are theoretically possible and involve almost the entire concrete lifecycle. Such applications are gradually being put to practical and commercial use. Additional efforts are needed to ensure the safety, quality, and economy of this eco-friendly technology. Thus, considerable work is needed for the large-scale application of microwaves in engineering.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Declaration of Competing Interest

We declare that we do have no financial and personal relationships with other people or organizations that can inappropriately influence our work titled "*Recent development of microwave applications on concrete treatment*".

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