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Appendix

A study of the interaction between steel-reinforced concrete and microwave energy using a single-mode rectangular waveguide: Theory and experiment

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Abstract

Microwave heating is a highly efficient technique for various thermal processes. Advantages of microwave heating compared to conventional processing methods include energy-saving rapid heating rates, deep penetration of the microwave energy, instantaneous and precise electronic control, and clean heating processes. This research provides a comprehensive study on the interaction between steel-reinforced concrete and microwave energy using a single-mode rectangular waveguide. We begin by investigating the mechanisms of changes in the adaptive dielectric properties of concretes and reinforced concretes to predict how these properties are altered when microwave energy is applied. Finally, we will formulate mathematical models to describe the relationship between microwave curing and mass transfer for steel-reinforced concrete. The obtained results show that dielectric properties are relatively high and remain constant during the dormant period. After this period, the hydration reaction resumes and dielectric properties decrease rapidly. With the use of microwave heating, early-age strength increases during the first 7 days; however, during the next 7 days, early-age strength decreases slightly, until it reaches its lowest at the 28-day mark. The temperature rise as actually recorded at the center of the sample during microwave heating in our experiment consistently agreed with figures calculated by a mathematical model.

Keywords: Interaction; Heat and mass transfer; Microwave energy; Rectangular waveguide; Steel-reinforced concretes

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Applications of microwave energy in cement and concrete – A review

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ABSTRACT

Microwave heating is a highly efficient technique for various thermal processes. Advantages of microwave heating compared to conventional processing methods include energy-saving rapid heating rates and short processing times, deep penetration of the microwave energy (which allows heat to be generated efficiently without directly contacting the work-piece), instantaneous and precise electronic control, clean heating processes, and no generation of secondary waste. Microwave energy processes for heating, drying, and curing have been developed for numerous laboratory-scale investigations and, in some cases, have been commercialized. Microwave energy use should theoretically be advantageous in the processing of cement and concrete materials (*e.g.*, hydraulic Portland cement, aggregate, and water). These materials exhibit excellent dielectric properties and, therefore, should be able to absorb microwave energy very efficiently and instantaneously convert it into heat.

This paper provides a comprehensive review of the use of microwave energy to process cement and concrete materials, as well as a critical evaluation of currently utilized microwave heating mechanisms and high-performance microwave systems. The current status of microwave applications and future research and development trends are also discussed, including such thermal processing methods as the high-temperature sintering of cement materials, the accelerated curing of precast concrete products, as well as the drilling and cleaning of decontaminated concrete surfaces by the built-up internal pressure. The results of this review indicate that microwave heating is directly associated with dielectric loss by the cement and concrete. Microwave processing can be used to improve clinkering and to reduce the clinkering temperature by about 100 °C. Considerations when constructing mathematical models of microwave heating for cement and concrete should include the influences of heat and mass transfer during microwave curing on the temperature difference in the concrete, the degree of uniformity of the internal structure, and the ultimate performance of the product. Future studies of microwave energy in cement and concrete applications might include investigations of adaptive (time-dependent) dielectric properties, coupling chemical reactions in the presence of microwave energy, the design and construction of suitable microwave systems, and the prediction of related phenomena (*e.g.*, thermal runaway, as a highly regulated safety issue).

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1. Introduction

Cement and concrete products are well accepted as man-made construction materials. Owing to their numerous advantages (e.g., easy handling of compression forces, brittle nature that enables a rigid structure to be obtained, transportability, and durability/ability to withstand severe environments), these materials are used widely in civilian buildings and universally in infrastructures. A report on global cement use published by Morgan Stanley research [1] (Table 1) found that worldwide cement consumption decreased in the 2006–2013 period due to the economic downturn. The years 2012 and 2014 showed the slowest growth for every country in the world, except China and India, since the crisis years of 2007–2009. However, cement consumption is expected to increase gradually from 2014 forwards.

The increased production of cement and concrete leads to the increased consumption of energy. Conventionally, the cement production procedure includes a clinkering process, consisting of precalcination and pyro-processing steps, as shown in Fig. 1 [2,3]. This process requires energy consumption, especially in the cyclone preheater, precalciner (cyclone preheater plus calciner), and rotary kiln steps (burning consumes 60–70% of the fuel input). The average specific thermal energy consumption in a conventional cement clinker manufacturing process is about 31.5 GJ per ton of clinker [3].

High-level energy consumption, which refers to both a high level of consumption and a long time for the burning process, is affected by the heat transfer mechanism and the thermal conductivity of the cement-making materials (i.e., calcium oxide, CaO; silicon dioxide, SiO_2; alumina oxide, Al_2O_3; and ferric oxide, Fe_2O_3). When cement is made with conventional burning using fuel (e.g., oil and gas), the cement components are heated by an external heat source, and heat is transferred via conduction from the outside inward. Thermal properties, such as the specific heat, latent heat, and so on, regulate the kinetics of the heating process. However, cement-making materials have intrinsically low thermal conductivities and low heat transfer rates. Thus, they must be heated for long times until the inner portion of cement melts and sinters at a high temperature, to become a cement clinker nodule (at $\sim$1450 °C). To overcome this problem, microwave heating may be applied in the burning process of cement.

Unlike conventional heating, microwave heating principally occurs when the electric field of the microwave interacts with a material. Energy from the field is transferred to the molecular bonds of the materials. This energy transfer causes the bonds to vibrate and leads to heat dissipation within the material. Microwave heating is particularly efficient for heating dielectric materials (e.g., microwave heating was at least twice as effective as conventional methods for heating dielectric materials [4,5]). Therefore, microwave heating should be useful in the cement and concrete industry, as cement-making materials exhibit excellent dielectric properties and should be able to absorb microwave energy very efficiently.

Furthermore, internal (volumetric) heating by microwave energy offers many benefits for the cement and concrete industries, including [6,7]:

- Rapid heating rates and short processing times, which save energy and time.
- Deep penetration of the microwave energy (in cement and concrete materials, a microwave system operating at 2.45 GHz can typically penetrate several centimeters), which allows heat to be generated efficiently without directly contacting the cement constituents.
- Instantaneous and precise electronic control, which is convenient for designing and constructing heating systems.
- Unique and fine microstructural development, which permits better properties of produced cement.
- Clean heating processes that do not generate secondary waste.

Based on International Telecommunication Union (ITU) regulations, the electromagnetic frequency band for non-telecommunication (e.g. industrial, scientific, and medical) purposes ranges from 6.765 MHz to 246 GHz. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz (wavelengths from 0.001 to 1.0 m). Microwave systems operate at average frequencies of 896 $\pm$ 10 MHz (in the UK), 915 $\pm$ 13 MHz (in North and South America), and 2450 $\pm$ 5 MHz (worldwide, except where 2375 $\pm$ 50 MHz is used), as assigned by the International Microwave Power Institute (IMPI). When used for Industrial, Scientific, and Medical (ISM) purposes, microwave systems are most often operated in the range from 433.92 MHz to 40.00 GHz [4].

Many investigations and practices have recently reported using microwave heating for concrete applications, such as for accelerated curing [8,9], decommissioning and decontaminated surfaces [10,11], and drilling/melting [12,13]. Moreover, microwave systems have been applied as high-performance nondestructive monitoring and surveying methods for cement and concrete structures [14,15].

This paper offers a comprehensive and systematic review of the use of microwave energy in cement and concrete materials. This review systematically summarizes important results from previous experimental and numerical studies, covering such areas as the

Nomenclature

$\vec{B}$	magnetic flux density (Wb/m^2)
$\vec{D}$	electric flux density (C/m)
D_p	penetration depth (m)
$\vec{E}$	electric field intensity (V/m)
$\vec{H}$	magnetic field intensity (A/m)
L	material length
$\vec{P}$	energy flux density (W/m^2)
Q	local electromagnetic heat-generation (J)
T	temperature (°C)
S_{11}	reflected scattering coeffient from Port 1
S_{22}	reflected scattering coeffient from Port 2
S_{21}	transmitted scattering coeffient from Port 1
S_{22}	transmitted scattering coeffient from Port 2
V	volume (m^3)
a	thermal diffusivity (m^2/s)
c_p	heat capacity at constant pressure (J/(kg·K))
f	frequency (Hz)
q	electric charge density (C/m^3)
t	time (s)
e	Euler's number (=2.7182818...)

Greek letters

Γ	reflection coefficient
σ	effective conductivity (S/m)
ε_0	permittivity of free space (=8.8514 × 10^{-12}) (F/m)
ε_∞	permittivity at the high frequency limit
ε_s	static, low-frequency permittivity
ε^*	complex (electric) permittivity, $\varepsilon' - j\varepsilon''$
ε_r	relative permittivity
ε_r'	relative dielectric constant
ε_r''	relative dielectric loss factor
μ^*	complex magnetic permeability, $\mu' - j\mu''$
μ_o	permeability of free space (=4π × 10^{-7})(m kg/s^2 A^2) or (h/m)
μ_r	relative permeability
v	microwave speed in the dielectric material (m/s)
ω	angular frequency, field's frequency (s^{-1})
tan δ	loss tangent coefficient ($\varepsilon''/\varepsilon'$)
σ	electric conductivity (1/Ohm)
τ	characteristic relaxation time (s)
ρ	density (kg/m^3)
λ_g	wavelength in sample.
$\lambda_{\text{free space}}$	wavelength of free space
λ_{cutoff}	wavelength of cutoff frequency

dielectric properties of cement and concrete, the mechanisms of microwave processing, the applications of microwave systems for cementitious materials, the health and safety of microwave processing, and future Research and Development (R&D) trends. Laboratory-based R&D and a practice-based scale innovation approach are discussed.

On the basis of findings in this review, some topics are recommended for further study and development, including the analysis of adaptive (time-dependent) dielectric properties, the coupling of heating mechanisms with the chemical reactions in cement and concrete, the design and construction of suitable microwave systems for use with cement and concrete, and the prediction of related phenomena (e.g., thermal runaway, as a highly regulated safety issue). Findings from this review can be used to guide future R&D for developing microwave energy applications in the cement and concrete field, in order to decrease energy consumption compared to other energy sources in heating/burning and to reduce the high temperatures needed for producing cement and curing concrete. These findings can also aid in the development of innovative and nondestructive microwave-based methods for monitoring the properties of cement and concrete products, for surveying deteriorated concrete structures, and for selecting suitable methods for concrete repair.

2. Dielectric properties

Microwave heating involves the interactions between electromagnetic energy and the properties of dielectric material, especially

Table 1
Cement consumption growth by region (year over year) (%) [1].

Region	Year									
	2006	2007	2008	2009	2010	2011	2012	2013E(*)	2014E	2015E
Western Europe	5.0	0.0	−9.8	−19.5	−6.3	−0.5	−14.2	−6.8	−1.1	1.7
Eastern Europe	15.7	7.6	0.2	−12.6	3.0	8.6	−4.4	2.9	1.5	3.5
Former Soviet Union	13.8	16.8	0.2	23.4	9.5	13.9	9.2	4.3	3.8	4.1
North America	−0.3	−7.9	−15.8	−26.3	0.9	2.5	8.8	3.8	6.4	6.2
Latin America	11.8	8.5	6.4	−2.0	5.9	7.0	3.9	2.1	3.7	3.5
Middle East and North Africa (MENA)	7.6	11.8	10.2	7.8	6.6	1.6	4.1	1.4	3.9	5.1
Sub-Saharan Africa	11.8	15.7	1.9	5.3	3.3	11.4	9.6	7.0	6.8	7.1
China	14.9	13.1	3.3	18.3	14.4	10.8	6.6	7.1	3.5	2.1
India	12.2	8.9	5.0	10.6	7.2	6.2	6.7	3.6	5.2	6.8
North Asia	2.5	−0.8	−4.3	−8.9	2.5	2.0	1.8	3.3	0.0	0.6
South Asia	4.3	5.7	7.5	6.0	8.3	6.3	7.1	2.4	3.7	5.1
Australia/Pacific	−0.5	6.5	3.8	−8.5	1.0	4.9	−2.1	−0.8	3.0	−4.1
World (excl-China)	7.3	5.5	0.4	−4.7	4.0	5.1	3.1	2.1	3.5	4.6
Emerging Markets (excl-China)	9.8	9.3	5.1	0.7	6.2	6.1	4.9	2.8	3.9	4.9

Remark: Source from industry and national sources, Global Cement Report, Morgan Stanley Research estimates (E(*)).

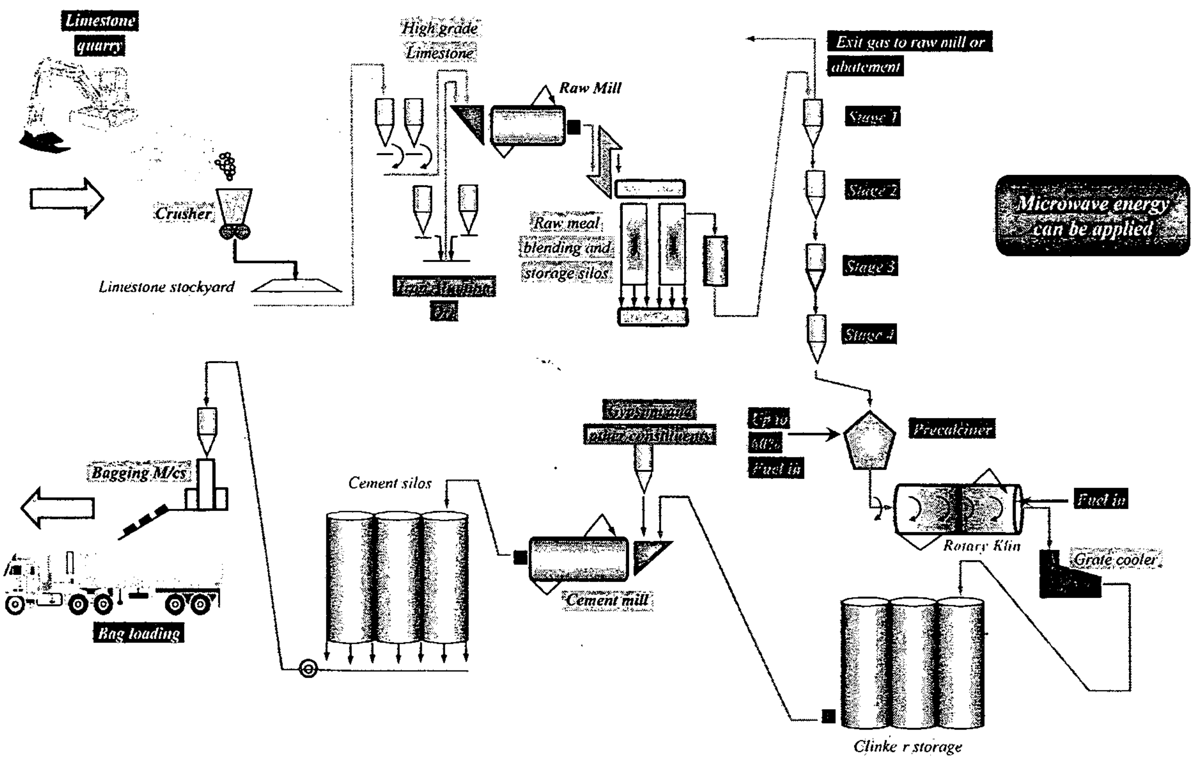


Fig. 1. Overview of a conventional cement manufacturing process [2,3].

dielectric propery. This property plays an important role to describe the behavior of concrete materials when subjected to microwave energy. This section describes theories of dielectric, measurement techniques of cement and concrete, and blended cement and concrete. Modeling work of calculation of cement is also explained.

2.1. Dielectric theories

Cement and concrete are dielectric materials. Their intrinsic properties affect the way they interact with the electric and magnetic fields of the microwaves. Dielectric property can be characterized by two independent electromagnetic properties: the complex (electric) permittivity ε^* and the complex (magnetic) permeability μ^*. However, most common concrete materials are non-magnetic and yield permeability μ^* that is very close to the permeability of free space ($=4\pi \times 10^{-7}$)(m kg/s^2 A^2) [16]. Thus, the complex (electric) permittivity ε^*, which comprises real and imaginary parts that can be defined as the relationship expressed in Eq. (1):

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \quad (1)$$

where ε_r' and ε_r'' are the real part and imaginary parts respectively, of the complex permittivity, and $j=\sqrt{-1}$.

The real part of the relative complex permittivity, referred to as the dielectric constant, ε_r', measures how much energy transferred from an external electric field is stored in a material. The imaginary one, ε_r'', measures how lossy a material is to an external electric field and is referred to as the relative loss factor. Besides an essential ratio that shows the energy lost (relative loss factor) to the energy stored (relative dielectric constant) in a material is given as loss tangent tan δ, as shown in Eq. (2):

$$\tan\delta = \varepsilon_r''/\varepsilon_r' \quad (2)$$

The dielectric properties of the concrete including dielectric constant and loss factor are important parameters in microwave-dielectric material interactions. They are strongly dependent on moisture content, temperature, extent of hydration. Reports of prior investigations [17–19] studies did not attempt to correlate experimental results with dielectric properties in order to develop a fundamental link to the field equations listed in Eq. (3), a task that must be accomplished in order to predict real-time changes during microwave curing. The internal distribution of free water in the sample is also an important consideration until the structure has been formed since this will decrease the efficiency of microwave heating.

$$\left.\begin{aligned} \varepsilon(\omega) &= \varepsilon_\infty + \frac{\varepsilon_s-\varepsilon_\infty}{1+(i\omega\tau)^{1-\alpha}} - j\frac{\sigma(0)}{\omega\varepsilon_0} && (\textit{Maxwell-Wagner effect}) \\ \varepsilon(\omega) &= \varepsilon_\infty + \frac{\varepsilon_s-\varepsilon_\infty}{1+(2i\omega\tau)^{\beta}+i\omega\tau} - j\frac{\sigma(0)}{\omega\varepsilon_0} && (\textit{Double layer polarization}) \\ \varepsilon(\omega) &= \varepsilon_\infty + \frac{\varepsilon_s-\varepsilon_\infty}{1+(i\omega\tau)} - j\frac{\sigma(0)}{\omega\varepsilon_0} && (\textit{Debye effect}) \end{aligned}\right\} \quad (3)$$

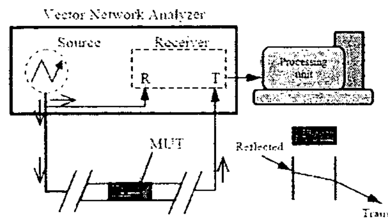
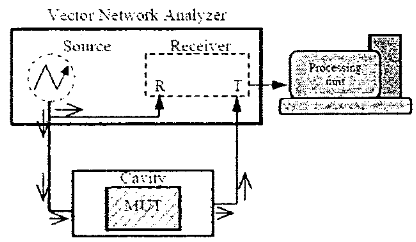
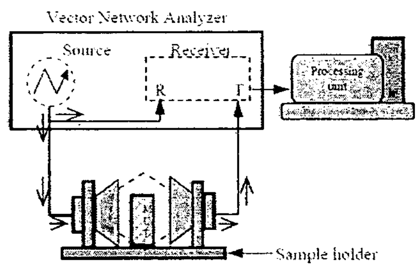
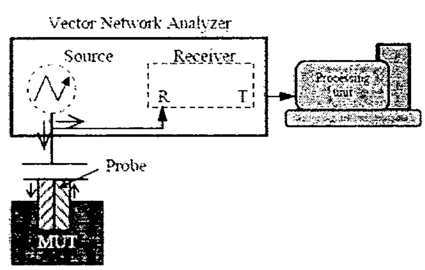
2.2. Measurement techniques and calculation

2.2.1. Measurement techniques

Many techniques have been developed to understand the dielectric property (Table 2), including the transmission/reflection line, perturbation, free-space, and open-ended methods [20,21]. Selection of the appropriate method depends, in part, on the operating frequency of the microwave system (Fig. 2) [21]. For example, at the commonly utilized frequency of 2.45 ± 0.05 GHz, the dielectric property should be measured by transmission line. This method allows the measurement of specimens with a slab-shaped geometry placed across the cavity. However, this method is limited by the air-gap effect. The open-ended probe method could also be used, which involves measuring the phase and amplitude of the reflected signal at the end of an open-ended coaxial line inserted in a specimen. This method, too, has limitations, due to the reflection effect from the specimen.

Choices of the measurement equipment and sample holder design depend on several factors, including the dielectric materials to be

Table 2
A summary of the technique for measuring dielectric properties [20,21].

Technique	*Characteristics*	*Feature*	*Dielectric properties*
Transmission/ reflection line	The Material Under Test (MUT) must be made into slab geometry. *Advantages:* • Common coaxial lines and waveguide • Used to determine both ε_r, μ_r of the MUT *Disadvantages:* • Limit by the air-gap effect • Limit to low accuracy		ε_r, μ_r
Perturbation (Cavity) (Resonant)	The measurement is made by placing a sample completely through the center of a waveguide that has been made into a cavity. *Advantages:* • Simple and easy data reduction • Accuracy *and* high temperature capability • Suite to low dielectric loss materials *Disadvantages:* • Need high frequency resolution Vector Network Analysis (VNA) • Limit to narrow band of frequency band only		ε_r, μ_r
Free-space	The sample is placed between a transmitting antenna and a receiving antenna, and the attenuation and phase shift of the signal are measured. *Advantages:* • Used for high frequency and allow nondestructive measurement • Measure MUT in hostile environment *Disadvantages:* • Need large and flat MUT and diffraction effects at the edge of sample • Limit to low accuracy		ε_r, μ_r
Open ended probe	The technique calculates the dielectric properties from the phase and amplitude of the reflected signal at the end of an open-ended coaxial line inserted into a sample to be measured. *Advantages:* •After calibration, can be routinely measured in a short time *Disadvantages:* •Available for reflection measurement		ε_r

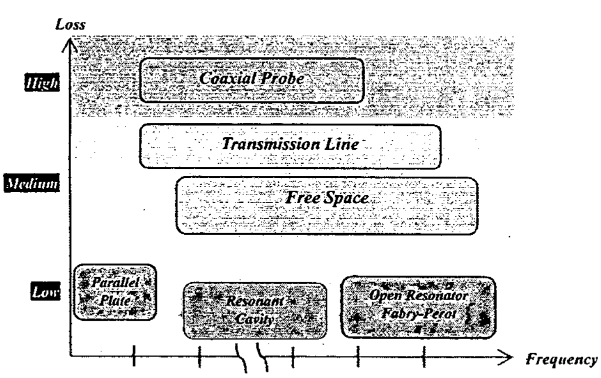


Fig. 2. Summary of dielectric measuring techniques [21].

characterized, extent of the research, as well as the equipment and resources that are available. Two types of dielectric analyzers have recently been used: the scalar network analyzer and the Vector Network Analyzer (VNA). The VNA is quite popular, very versatile, and useful for extensive studies; however, it is also very expensive. Although less expensive, scalar network analyzers and impedance analyzers are generally still too costly for many applications.

The HP 8510 [22] is a VNA that has been used to measure the dielectric properties of cementitious materials, including cement paste, mortar, and concrete. It can measure the magnitude and phase characteristics of linear networks, such as filters, amplifiers, attenuators, and antennae. As with all network analyzers, and as shown in Fig. 3(a), the HP 8510 apparatus measures both reflection and transmission of electromagnetic waves at an interface. An incident signal generated by an RF source is compared with the signal transmission through the analyzer or reflected from the wave input

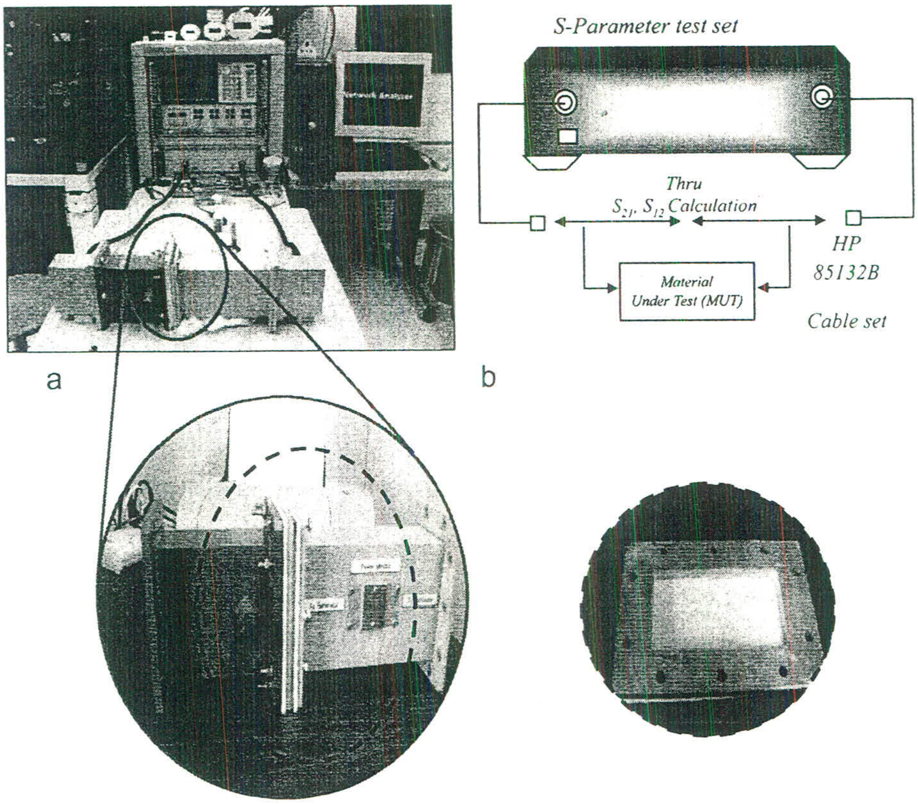


Fig. 3. (a) Network analyzera and (b) schematic of S-parameter test [22].

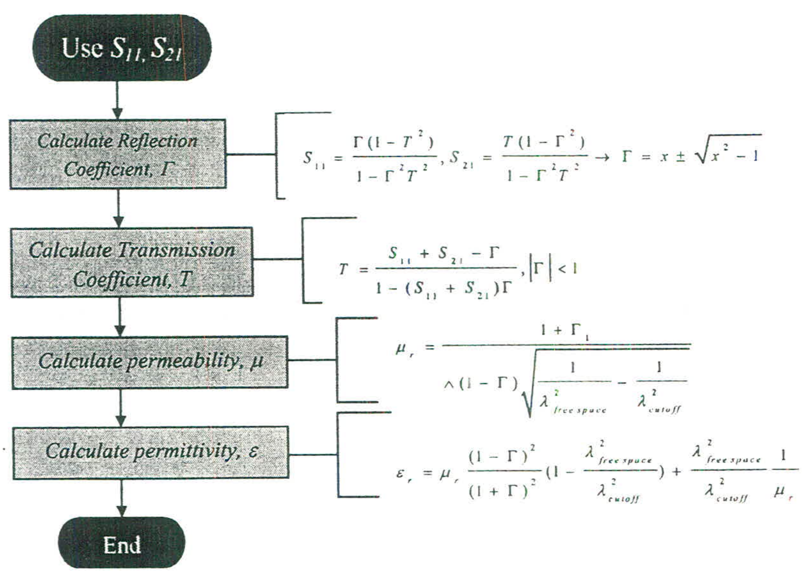


Fig. 4. Nicholson–Ross–Weir conversion process for calculating dielectric permittivity [23].

when passing through the waveguide (Fig. 3(b)). However, this method is strongly affected by the air-gap content, with high air content tending to decrease the dielectric property of the material. It is also influenced by the consistency of the cement and concrete materials. In particular, when materials behave like liquids, the settling of the material under its own weight can result in the non-uniform behavior of the whole specimen. Consequently, the measurement results are not representative of the whole body of the specimen.

A measurement using the transmission/reflection-line technique involves placing a sample in a section of the waveguide or coaxial line and measuring the two ports' complex scattering parameters with a VNA. Calibration must be carried out before carrying out the measurement, though. The technique involves measuring the reflected (S_{11}) and the transmitted signal (S_{21}). The relevant scattering parameters relate closely to the complex permittivity and permeability of the material by equations. The conversion of S-parameters to complex dielectric parameters is computed by solving the equations using a Nicholson–Ross–Weir (NRW) technique as shown in Fig. 4 [23].

2.2.2. Measurement of cement and concrete

There have been several investigations [17–19,24] of the dielectric properties of cement and concrete materials, covering their measurement methods, their behaviors, and the factors influencing their variations. Initially, microwave radiation was used to determine the evaporable moisture (free-water) content in building materials and structural elements by monitoring the absorption level of microwave [17]. Later, Hasted and Shah [18] used the Robert and Von-Hippel method [24], a time-domain reflectometry-based measurement method, to study standing-wave behavior within a waveguide at 10, 3.3, and 1.25 cm. Wittmann and Schlude [19] studied microwave absorption at 9–11 GHz by hardened cement paste, using a free-wave method with a specimen of specified diameter and height. They consistently agreed that the real and imaginary parts of the complex permittivity of cement could be determined as a function of the moisture content, temperature, and hydration duration of the cement, when using the transmission/reflection line method [25] or a cavity-resonant method [26].

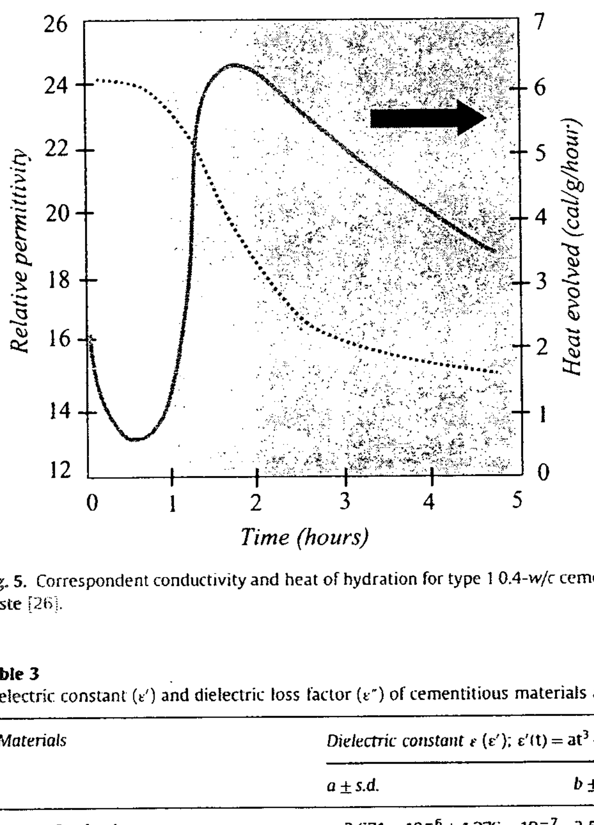


Fig. 5. Correspondent conductivity and heat of hydration for type 1 0.4-w/c cement paste [26].

The permittivity of a concrete mixture is influenced by the w/c ratio under various free-water volume absorption conditions. Variations in permittivity, due to the effects of the w/c ratio, cement type, and superplasticizer use, are closely related to changes during the four stages of cement hydration. The ion concentration is correlated with the mixing of the cement and water particles. When the cement first contacts with water, the ion concentration increases to a relatively high level. It remains constant during the dormant period, decreases rapidly during the hydration reaction, and continues to decrease during the acceleratory period, as shown in Fig. 5 [26]. Some typical dielectric constant (ε') and dielectric loss factor (ε'') values of cementitious materials as a function of temperature are shown in Table 3 [27]. Many microwave-based methods are available for monitoring variations in the dielectric properties during the hydration process. Microwave heating units are commonly operated at 2.45 GHz, which is a suitable frequency for monitoring concrete mixtures using a custom-designed parallel-plate setup with a network analyzer [28,29].

The dielectric properties of cement and concrete materials change drastically and continually in the early stages of concrete formation (i.e., from the time when cement particles first contact with water molecules until the final setting occurs). Parameters that affect the dielectric property during this process should be considered. For example, the measurement method should be able to represent the whole specimen. The method should not be

Table 3
Dielectric constant (ε') and dielectric loss factor (ε'') of cementitious materials as function of temperature [27].

Materials	Dielectric constant ε (ε'); $\varepsilon'(t) = at^3 + bt^2 + ct + d$			
	$a \pm$ s.d.	$b \pm$ s.d.	$c \pm$ s.d.	$d \pm$ s.d.
Type 1 Portland cement	$-3.671 \times 10^{-6} \pm 1.276 \times 10^{-7}$	$3.529 \times 10^{-4} \pm 1.869 \times 10^{-5}$	$-2.014 \times 10^{-5} \pm 8.294 \times 10^{-3}$	$3.712 \pm 4.803 \times 10^{-1}$
Type 3 Portland cement	$-1.122 \times 10^{-6} \pm 1.599 \times 10^{-7}$	$4.021 \times 10^{-4} \pm 1.007 \times 10^{-5}$	$-1.476 \times 10^{-3} \pm 5.356 \times 10^{-4}$	$6.023 \pm 3.911 \times 10^{-1}$
Pulverized fuel ash	$3.333 \times 10^{-6} \pm 3.215 \times 10^{-7}$	$-6.667 \times 10^{-4} \pm 5.508 \times 10^{-5}$	$4.200 \times 10^{-2} \pm 2.859 \times 10^{-3}$	$4.138 \pm 3.109 \times 10^{-1}$
Silica fume	$-3.500 \times 10^{-7} \pm 7.071 \times 10^{-8}$	$5.500 \times 10^{-5} \pm 2.121 \times 10^{-5}$	$-3.350 \times 10^{-2} \pm 1.344 \times 10^{-3}$	$2.217 \pm 1.790 \times 10^{-1}$
Superplasticizer (polycarboxylic water-based) (42.5% solid content by weight)	$-2.333 \times 10^{-5} \pm 8.083 \times 10^{-5}$	$4.767 \times 10^{-2} \pm 9.935 \times 10^{-3}$	$-3.260 \times 10^{-1} \pm 2.989 \times 10^{-2}$	$2.865 \pm 1.933 \times 10^{-1}$
Fine aggregate (River sand)	$-1.000 \times 10^{-7} \pm 7.000 \times 10^{-8}$	$-2.333 \times 10^{-5} \pm 1.079 \times 10^{-6}$	$2.333 \times 10^{-4} \pm 6.429 \times 10^{-5}$	$2.600 \pm 1.565 \times 10^{-1}$
Coarse aggregate (Crushed limestone rock)	$-8.500 \times 10^{-7} \pm 1.626 \times 10^{-7}$	$2.600 \times 10^{-5} \pm 4.808 \times 10^{-6}$	$-1.950 \times 10^{-3} \pm 3.606 \times 10^{-4}$	$1.224 \pm 1.409 \times 10^{-1}$
Materials	Dielectric loss factor (ε''); $\varepsilon''(t) = et^3 + ft^2 + gt + h$			
	$e \pm$ s.d.	$f \pm$ s.d.	$g \pm$ s.d.	$h \pm$ s.d.
Type 1 Portland cement	$3.333 \times 10^{-7} \pm 4.989 \times 10^{-8}$	$-7.667 \times 10^{-5} \pm 1.115 \times 10^{-6}$	$5.000 \times 10^{-3} \pm 7.874 \times 10^{-4}$	$1.565 \times 10^{-1} \pm 1.844 \times 10^{-2}$
Type 3 Portland cement	$7.987 \times 10^{-7} \pm 3.043 \times 10^{-8}$	$-3.008 \times 10^{-5} \pm 9.453 \times 10^{-6}$	$6.225 \times 10^{-3} \pm 2.114 \times 10^{-4}$	$3.922 \times 10^{-1} \pm 1.042 \times 10^{-2}$
Pulverized fuel ash	$-1.800 \times 10^{-7} \pm 3.111 \times 10^{-8}$	$2.650 \times 10^{-5} \pm 4.738 \times 10^{-6}$	$-1.500 \times 10^{-3} \pm 2.687 \times 10^{-4}$	$2.763 \times 10^{-1} \pm 7.092 \times 10^{-2}$
Silica fume	$-3.667 \times 10^{-7} \pm 2.082 \times 10^{-8}$	$6.333 \times 10^{-5} \pm 3.512 \times 10^{-6}$	$-3.733 \times 10^{-3} \pm 1.850 \times 10^{-4}$	$2.223 \times 10^{-1} \pm 2.045 \times 10^{-2}$
Superplasticizer (polycarboxylic water-based) (42.5% solid content by weight)	$-2.000 \times 10^{-5} \pm 1.414 \times 10^{-6}$	$3.400 \times 10^{-3} \pm 1.273 \times 10^{-3}$	$-1.664 \times 10^{-1} \pm 5.155 \times 10^{-2}$	9.635 ± 1.025
Fine aggregate (river sand)	$7.000 \times 10^{-8} \pm 1.224 \times 10^{-9}$	$-2.000 \times 10^{-5} \pm 2.633 \times 10^{-6}$	$1.000 \times 10^{-3} \pm 1.467 \times 10^{-4}$	$2.645 \times 10^{-1} \pm 6.029 \times 10^{-2}$
Coarse aggregate (crushed limestone rock)	$7.000 \times 10^{-8} \pm 1.453 \times 10^{-9}$	$-2.000 \times 10^{-5} \pm 8.201 \times 10^{-7}$	$1.000 \times 10^{-4} \pm 4.798 \times 10^{-5}$	$5.680 \times 10^{-2} \pm 4.334 \times 10^{-3}$

Remark: s.d. = Standard Deviation.

affected by external moisture or temperature, nor should it be set in the system to be measured, as it is in an adiabatic system. In addition, the strong sensitivity of cement and concrete materials to each microwave range needs to be considered.

2.2.3. *Measurement of blended cement and concrete*

In addition to conventional cement, researchers have investigated the dielectric properties of cement–pozzolan mixtures, as well as blended cement and concrete. For example, using a perturbation method with microwave systems operated at 8.2–12.4 GHz during the early hydration reaction, researchers found that the dielectric constant increased and the induction period decreased with an increasing percentage of slag in cement paste [30]. A breakthrough in the dielectric measurement of materials containing high-performance cement–pozzolanic materials indicated that the relative dielectric constant at a microwave frequency of 10 kHz ± 1 MHz decreased from 29 to 21 with the addition of increasing silica fume content [31].

Later, Levita et al. [32] studied the electrical properties of liquefied type 1 52.5 R Portland cement (European standard ENV-197/1) containing microsilica fume during the early stage of hydration. These authors made measurements at ambient temperature for up to 40 h, in the frequency interval from 30 Hz to 200 kHz. The electrical properties of the paste mixtures had major variations in the first 40 h of hydration. They reported the values of ε' and ε'' as a function of frequency. At low frequencies, the dielectric constant was very large ($\sim 10^8$) because of an induced dielectric amplification effect, which was previously described by Coverdale et al. [33] and Ding et al. [34]. This effect involved a decrease of the dielectric permittivity with the progression of hydration, due to an increasing amount of calcium–silicate hydrate (C–S–H) or the conversion of free water to combined water in the C–S–H molecule. The permittivity varied depending on the chemical composition of the constituents, the amounts of hydration product phases, and local topological variations. At high frequencies, the dielectric amplification effect was significantly reduced.

Dielectric properties of fresh concrete compositions during the early stage of hydration were also investigated [35]. The dielectric constant varied with time between 30 and 60 min after cement was mixed with water. These results were consistent with the findings of Paul and Stephen, who used frequencies from 100 Hz to 7 MHz [36], Ping and Beudoin, who used frequencies from 1 to 1000 MHz [37], and Youssef et al., who used frequencies from 10 Hz to 1 GHz [38].

The electromagnetic characteristics and absorbing properties of fly ash were studied for cement composite in which fly ash was used as a cement replacement. The ε' was almost constant ($\sim$3.15) in the whole frequency range from 2 to 8 GHz, whereas ε'' showed obvious changes in the range from 0.03 to 0.1 GHz. Several peaks in ε'' were obtained at fixed positions [39]. The work of Makul et al. [27] comprehensively investigated the behaviors of various blended cement and concrete mixtures during a 24-h first-hydration period at 2.45 ± 0.05 GHz. The dielectric permittivity was relatively high and remained constant during the dormant period. Thereafter, it decreased rapidly when the hydration reaction resumed, and continued to decrease during the acceleratory period, consistent with the works of Moukwa et al. [26] and Zhang et al. [30].

Apart from experimental investigations, Hager and Domszy [40] tried to fit the experimental results of hydrating cement paste to a model over the frequency range of 10 kHz–8 GHz, from initial mixing through several weeks of cure. The model included the following terms: (1) Cole–Davidson relaxation near 1 MHz, (2) Debye relaxation near 100 MHz, (3) free-water relaxation near 10 GHz, and (4) ion conductivity and electrode polarization. The first two terms initially increased, and all four terms decreased with advancing cure. This work was the first to present long-term changes in the dielectric properties of cement, and it is applicable for pozzolanic cements with long-term reactions. The classical effective permittivity theory described by Prasad and Prasad [41] indicates that low-permittivity inclusions can decrease the effective permittivity of composites. In that study, the Cuming equation had the highest degree of acceptability (errors < ±15%) in all cases.

Some limitations of the aforementioned investigations should be noted. First, the dielectric constant fluctuates during the early stage of the hydration reaction. Second, other equations may be more optimal than the Cuming equation, such as the Maxwell–Wagner, Webmann, Skipetrov, and modified Cule–Torquato equations, depending on the sensitivity of the moisture (water) content of the cementitious materials.

2.2.4. *Modeling work*

In addition to the experimental studies described above, theoretical-based analyses of the dielectric properties of cementitious materials have been performed. For example, Finite Difference-Time Domain (FD-TD) modeling has been used to visualize the propagation of electromagnetic fields in concrete (as a dielectric medium) and to predict electromagnetic phenomena associated with concrete targets

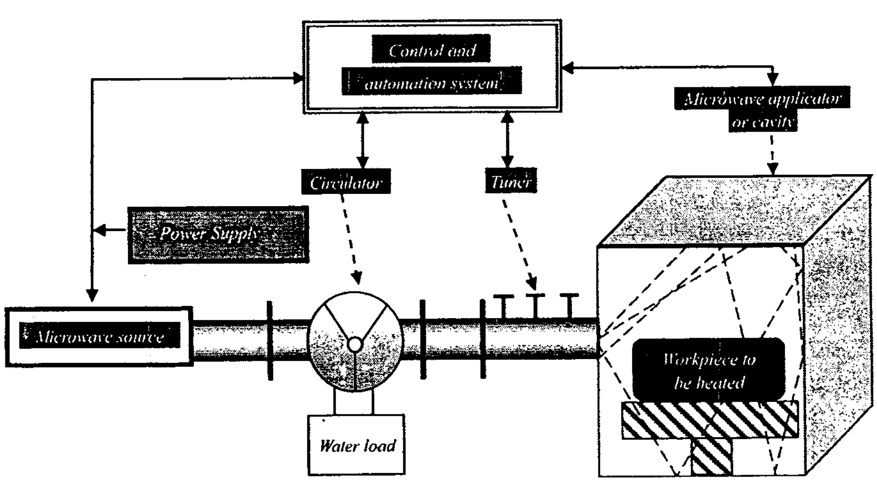


Fig. 6. Microwave system diagram.

for nondestructive testing purposes [16,42]. Klysz et al. [43] proposed a numerical FD-TD model of a ground-penetrating radar-coupled antenna to evaluate the dielectric properties of concrete. Using their method, the permittivity and conductivity of different concretes at different degrees of saturation were in agreement with those provided by Soutsos et al. [44], who used a coaxial transmission line system. These results were later validated in model experiments by an open-ended coaxial probe method over a microwave frequency range from 0.1 to 20 GHz. The results suggested that the outer geometry of the specimens (*i.e.*, shape and size) affected the ability to detect the targets and inclusions [16].

A survey of proposed mathematical models and validations indicated that the model needs to be validated with various concrete mixtures with different internal moisture contents because the latter factor strongly affects the dielectric constant and loss factor of concrete. The dielectric parameters (ε' and ε'') are not linked to the porosity; rather, all of the concrete pores must be filled with moisture in both the saturated and partially saturated states, especially in the early stage of hydration. Therefore, additional *w/c* ratios of concrete will need to be investigated in detail.

3. Microwave systems

This section presents the components and function of existing microwave systems, as well as their practical use for different applications. Conventionally a suitable microwave system is required to generate and introduce microwave energy to material (dielectric) to be heated. A typical microwave system is shown in Fig. 6. Most microwave-heating systems consist of three basic components: microwave power generator (usually magnetron), wave guide, and microwave chamber or cavity where the specimen is to be processed and supplementary components *e.g.* control system, tuner, circulator and so on. In detail, most importantly, microwave power generator connecting to power supply unit: its purpose is to convert the alternating current (a.c.) of 50 or 60 Hz to a desired high frequency microwave radiation. This is achieved by a device called magnetron. Magnetron must also be shielded to prevent the leakage radiation of harmonics, as well as for safety. Waveguide is an important component and it transmits microwave energy through free space and delivers to the specimen. The waveguide is any structure that directs the propagation of energy in the form of an electromagnetic wave along a predetermined path [45]. Waveguides may assume many different physical forms depending up on a large extent on the frequency band. Last is microwave chamber/cavity that obeys with the laws of electromagnetic – transmit, absorb, reflect microwave energy.

Practically, microwave system can be categorized into three subsystems depending on type of applicator associated with supplementary equipment or system as follows:

- Traveling-wave applicators in which a traveling wave is produced by matching the microwave source to a heated load using rectangular and cylindrical waveguide.
- Near-field applicators – this is a resonant open-ended waveguide or cavity attached directly at the end of the waveguide, at which the energy is fed through slots into a cavity.
- Resonant applicators – this is these types can be classified into single and multimode resonators as shown in Fig. 7 (single mode) [46,47] and Fig. 8 (multimode) [48], respectively.
  - For single mode resonant cavity, the standing wave applicator is attached to the end of the waveguide microwave power-feed line. Microwave energy was generated by a magnetron and transmitted directly along the propagation direction ($+z$) of a rectangular wave guide toward a water load situated at the end of the waveguide to ensure that a minimal amount of microwave energy would be reflected back to the sample. A warming water load was circulated through the cooling tower in order to reduce the temperature in the water load system.
  - For multimode applicators, Fig. 8(a), the microwave cavity was rectangular shape with exterior dimensions of 900 mm × 450 mm × 2700 mm. The drier operates at a frequency of 2.45 GHz with maximum working temperature of 180 °C. The microwave power was generated by means of

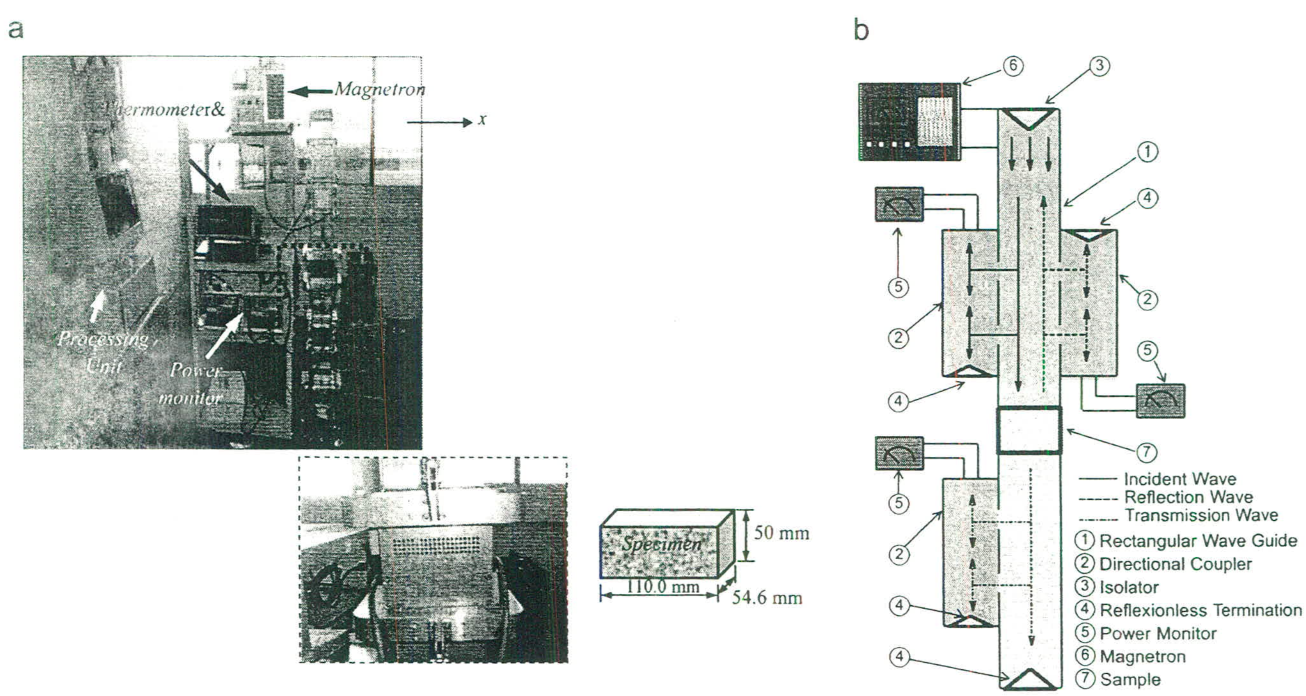
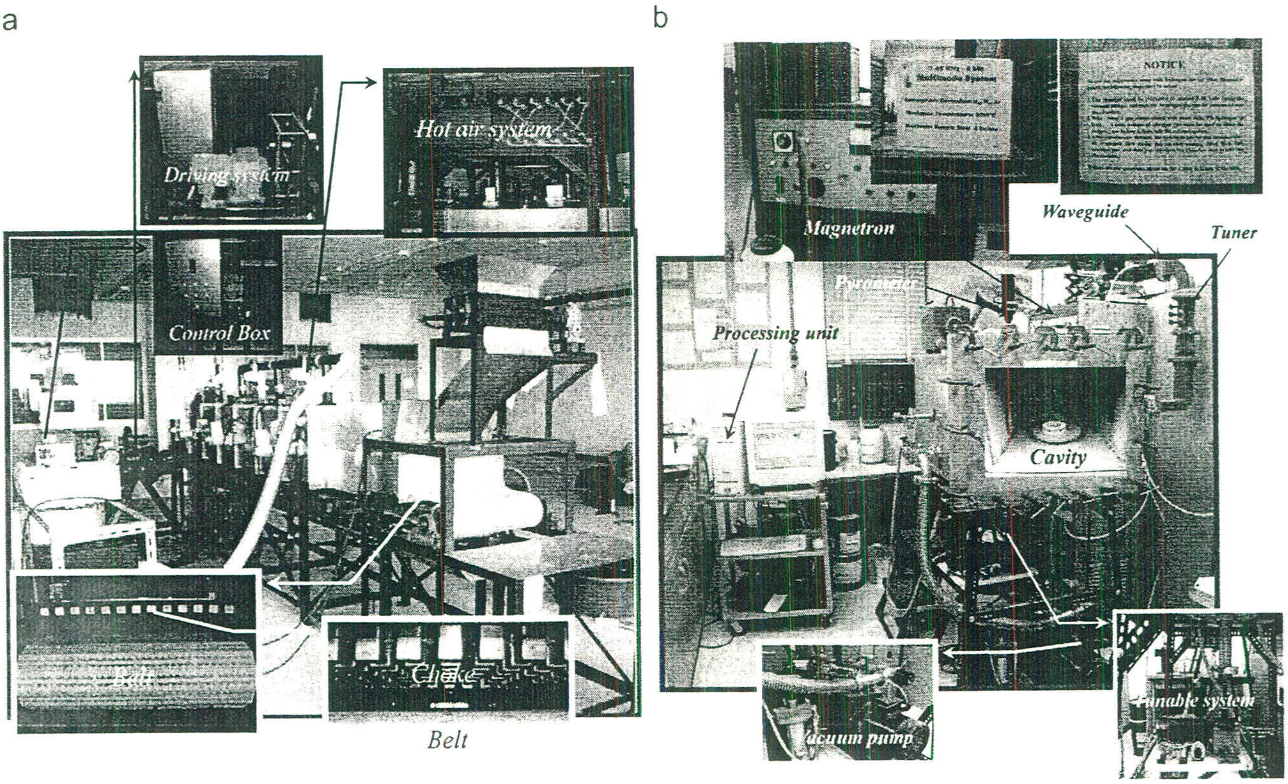


Fig. 7. (a) Experimental set up, (b) schematic showing direction of microwave components (Incident wave, reflected wave, and transmission wave) [46,47].



g. 8. Microwave system typed multimode resonant cavity: (a) A combined multi-feed microwave-hot air heating with continuous belt system (low temperature multi-node microwave system) [48] and (b) high temperature multi-mode microwave system [49].

12 compressed air-cooled magnetrons. The maximum microwave capacity was 9.6 kW with a frequency of 2.45 GHz. The power setting could be adjusted individually in 800 W/steps. In the continuous processing equipment, two open ends were essential, through which the material to be heated up on the belt conveyer was put in and taken out. In this equipment, leakage of microwaves was prevented by the countermeasure in double with a combination of mechanical blocking filter (corrugate choke) and microwave absorber zone filter was provided at each of the open ends. The multiple magnetrons (12 units) were installed in an asymmetrical position on the rectangular cavity (Fig. 8(b) [49]). The microwave power was then directly supplied into the drier by using waveguides. An infrared thermometer (located at the opening ends) was used to measure the temperature of the specimens (accurate to ±0.5 °C). An example is high temperature microwave system. It can generate microwave energy at a frequency of 2.45 GHz and maximum power of 6.0 kW with a multi-mode system. This results in a temperature of 2000 °C being induced in the material.

4. Applications of microwave to cement

Cement is a complicated mixture of calcareous-, silica-, and alumina-based minerals with specific compositions. The manufacturing process consists of grinding and mixing the raw materials, and then roasting at temperatures up to 1450 °C. During this process, a granular clinker is formed, which is composed of tricalcium silicate ($3CaO \cdot SiO_2$ or C_3S), dicalcium silicate ($2CaO \cdot SiO_2$ or C_2S), tricalcium aluminate ($3CaO \cdot Al_2O_3$), and tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$). To generate commercial Portland powder, clinkers are ground to a fine powder and 4–5% calcium sulfate is added. The resulting product is ready to be reacted with water.

In the following sections, various applications of microwave energy to cement are presented, covering the use of microwave energy to synthesize cement and to improve cementitious properties.

4.1. Cement synthesis

Microwaves have been utilized at 2.45 GHz to assist in the clinkerization of cement nodules, producing clinkers with similar characteristics to those of conventionally produced industrial cement clinkers. During microwave heating at a maximum temperature of 1450 °C [50;51], the dielectric losses of different cement constituents were adequate to preserve the heating rate and ensure clinkerization, as confirmed by Sutton [52]. In a later work [53], microwave energy at 2.45 GHz was capable of synthesizing regular and colored cement clinkers. Clinkering temperatures required by microwave processing were about 100 °C less than those required for fast-heating by the electric furnace method. Another microwave sintering method involved heating the sample by electric heating to 1500 °C, and then using microwave-assisted heating for 30–60 min to induce C_3S formation [54]. Ion oxides played a very important role in C_3S formation in conventional sintering [55].

Microwave heating has been used to sinter Class F fly ash at temperatures from 800 to 1000 °C for 10 to 20 min. Samples sintered by microwave were denser and had better mechanical properties than samples sintered by conventional processes at the same sintering temperature and for the same time. The sintered cement nodules were mainly composed of mullite ($Al_6Si_2O_{13}$). At the same heating rate during clinker formation, microwave-assisted sintering improved the formation of C_3S compared to the conventional sintering methods [56–58].

In addition to the use of only microwave heating for cement sintering, a combined electric and microwave clinkering method has been applied for Portland cement. After raw materials had been heated by electric energy to 1000–1200 °C, they were sintered by microwave energy for 1–2 min. The sintering time was reduced by using higher temperature samples in the microwave-sintering step. The same combined method was also applied to make sulphoaluminate belite (SAB) cement clinkers from a raw sulfoaluminate precursor [59]. The combined use of electric heating and microwave processing significantly accelerated the clinkering reaction. For samples that were heated at 1300 °C for 1 h, the free CaO of the obtained clinkers was as high as 1.03–4.78%. When samples of the same composition were heated by microwave alone for 25 min, the $CaCO_3$ in the raw materials did not completely decompose.

4.2. Improving cementitious properties

Microwave can be utilized to improve the cementitious properties of pozzolan materials. For example, rapid sintering of Rice Husk Ash (RHA) at 800–1200 °C by microwave at 2.45 GHz enhanced the cementitious properties of the cementing material. The sintered and ground RHA contained the cristolbalite phase. The strength index of 28-day-old microwave-sintered RHA paste sintered at 800 °C was increased by 30% compared to the index before sintering [60].

5. Applications of microwave to concrete

This section presents various applications of microwave energy to concrete, including microwave-accelerated curing, the decommissioning of decontaminated concrete, nondestructive monitoring, and the drilling/melting of concrete.

5.1. Acceleration of curing

After cement grains are mixed with sufficient water, various reactions occur that result in hydration product formation (e.g. calcium silicate hydrate gel, C_x–S_y–H_z) (Eq. (4)). Due to the nature of the cement grains and the reaction kinetics, the strength of the concrete continually increases over time. Immediately after the cement and water are mixed, the $CaO\cdot Al_2O_3$ phase reacts with water to form an aluminate-rich material, and calcium sulfate hemihydrate is converted to its dihydrate form. Both of these reactions contribute to a brief exothermic peak. Subsequently, the gel reacts with sulfate in solution to form ettringite ($3CaO\cdot Al_2O_3$) and, thereafter, enters a dormant period [61].

At the end of the dormant period, $3CaO\cdot SiO_2$ and $2CaO\cdot SiO_2$ in the cement begin to hydrate, forming calcium silicate hydrate (CaO_x–SiO_y–H_2O_z) and calcium hydroxide ($Ca(OH)_2$). This step corresponds to the main period of hydration, when much of the increase in strength occurs. The cement grains react from the surface inwards, and unreacted grains become fewer and eventually are consumed. The period of maximum heat evolution occurs between 6 and 24 h after mixing, followed by a gradual decrease approximately over 1 month period. The sequence of reactions is shown below:

$$\left.\begin{array}{l}
3CaO\cdot SiO_2+H_2O\rightarrow CaO_x-SiO_{2y}-H_2O_z+Ca(OH)_2+\Delta Heat\ (500\ J/g)\\
2CaO\cdot SiO_2+H_2O\rightarrow CaO_x-SiO_{2y}-H_2O_z+Ca(OH)_2+\Delta Heat\ (260\ J/g)\\
2(3CaO\cdot Al_2O_3)+18H_2O\rightarrow 2CaO\cdot Al_2O_3.8H_2O+4CaO\cdot Al_2O_3\cdot 10H_2O+\Delta Heat\ (866\ J/g)\\
2(3CaO\cdot Al_2O_3)+32H_2O+3(Ca^{2+}_{(aq)}+SO^{2-}_{4(aq)})\rightarrow CaO\cdot Al_2O_3\cdot 3SO_3\cdot 32H_2O+\Delta Heat\ (420\ J/g)\\
6CaO\cdot Al_2O_3\cdot 3SO_3\cdot 32H_2O+23CaO\cdot Al_2O_3\rightarrow 3(4CaO\cdot Al_2O_3\cdot SO_3\cdot 12H_2O)
\end{array}\right\} \quad (4)$$

Although cement can react with water under conditions of room temperature and pressure, such cement will require more time to reach an adequate strength for industrial uses [61]. Consequently, various curing methods are used to accelerate strength development in cement-based materials during the early-age phase.

Strength is a crucial factor in structural design. High early strength can benefit concrete production by reducing the construction time, labor, formwork, energy, and environmental impact. Early strength development is strongly influenced by several factors, including the water/cementitious material ratio, cement type and content, age of the paste, and curing method. For example, use of a lower water/cementitious materials ratio (w/c) makes a stronger concrete.

Many methods [61] are available for increasing the early strength of concrete. Curing involves maintaining favorable moisture and temperature conditions to ensure that the degree of hydration is sufficient to reduce the porosity to a level at which the desired properties (e.g. strength and flexibility) can be attained. Curing affects the rate of strength development. Accelerated gains in strength may be achieved by supplying heat and moisture to the concrete. For example, curing with steam at atmospheric pressure (live steam curing) or at high pressure in an autoclave (high-pressure steam curing) is advantageous when high early strength is necessary or when additional heat is required to accomplish hydration (e.g. in cold weather).

Conventional curing methods have many limitations. For instance, when water curing is used, long periods are needed to reach the required strength. With steam curing, non-uniform temperature distributions can occur, resulting in non-homogeneous curing. When admixtures are employed, durability problems may occur. Thermal curing methods are especially susceptible to negative effects on durability in both the early and long-term stages. For example, high-temperature curing at atmospheric pressure was shown to result in reduced long-term strength and durability problems [62,63]. Although the reasons for these problems are not wholly understood, they might include an increase in microcracking and delayed ettringite formation. As mentioned in Verbeck and Helmuth [63], rapidly accelerated hydration during curing can lead to the encapsulation of the anhydrous cement grains by a layer of product with low porosity, which further slows the hydration. Hydration products act as insulating (dielectric) materials that transfer heat at a low, non-uniform rate, resulting in poor properties after curing.

Moving the heat source from the outside surface of a heated cementitious material to the internal structure (e.g. through the interaction between the microwave field and the heated material) can result in a violent cement–water interaction and volumetric heat generation [64,65]. This concept serves as the basis of one method of accelerated curing (microwave curing). The Portland cement–water system inherently reacts to a complex multicomponent system and repletion-coupled temperature- and composition-sensitive hydration products. Therefore, to develop the accelerated curing method further, Portland cement-based materials subjected to high-temperature curing by microwave energy will need to be characterized from a microstructural perspective.

Given the adverse short- and long-term effects that thermal-curing methods have on the properties of concrete, a crucial question is whether microwave heat can be applied in the concrete industry. Theoretically, this application is possible because the materials used to make concrete (*e.g.* hydraulic Portland cement, aggregates, water, and admixtures) are dielectric (*i.e.* they can absorb microwave energy). In particular, the relative dielectric constant (ε_r') and loss tangent (tan δ) values for water are higher than those of the other components of cement. As a result, when the electric part of the electromagnetic field ($\vec{E}$) interacts with the constituents of concrete, energy is transferred from the electric and magnetic fields and converted (through ion conduction and polar rotation) to the molecular bonds of the water, which is part of the microwave-irradiated material. This mechanism causes the bonds to vibrate. Energy is dissipated as heat and transferred within the concrete, increasing the temperature and accelerating hydration. Free water molecules in the capillary pores of the concrete are quickly removed from the internal concrete structure before setting. Thus, plastic shrinkage occurs, which leads to collapse of the capillary pores and densification of the microstructure [66].

Studies on the use of microwave-assisted curing have numerous aspects. A paper by Watson [67] was the first to extend a microwave dehydration method to concrete. Use of microwave energy accelerated strength development in Portland cement mortar without decreasing the long-term strength of the concrete. The strength of the concrete specimens began to decrease when the final *w/c* ratio was less than 0.40 [68]. In another study, microwave-assisted curing during the first 24 h reduced the induction period of hydration [69]. Key parameters for microwave curing include the microwave power, application time, duration of microwave heating [66], thermal runaway, and overheating within the sample [70]. When optimal microwave power was applied in a discretized fashion through feedback temperature control, very good results were obtained for concrete [71]. The work of Sohn and Johnson [72] obtained the optimal microwave-curing of type 1 Portland cement mortars at 40 and 60 °C, whereas other temperatures were incompatible with curing.

Microwave curing appeared to damage the freeze-thaw durability of high *w/c* concrete, but not low *w/c* concrete [8,73]. In terms of the microstructural characteristics of cement-based materials subjected to microwave energy, microwave-cured paste demonstrates some ettringite. In two studies, the ranges of the *Si/Ca* and *Al/Ca* ratios in the autoclave-cured paste were 0.039–0.052 and 0.207–0.234, respectively, whereas the ratios in the microwave-cured paste ranged from 0.079 to 0.091 [65,74].

Apart from conventional concrete, microwave heating can also be used to cure metakaolin-blended cements. For instance, the pozzolanic activity of metakaolin was improved under microwave curing. Microwave-cured 15% metakaolin was free of $CaOH_2$, whereas 30% or 40% metakaolin was needed for similar outcomes in room-temperature curing [75]. Concrete samples containing 10% silica fume responded well to microwave curing. Microwave heating for 40 min appeared to be the optimal curing time [73].

Microwave energy can also be used in association with a vacuum system, in order to dewater or dehydrate the concrete. The optimal microwave curing time has been shown to be 45 min at a maximum temperature of 60 °C, with a final *w/c* ratio of around 0.38. In this process, microwave curing decreases the amount of free water while increasing the hydration rate of cement, resulting in a compacted/less porous concrete [76]. When microwave energy was applied with a continuous belt drier consisting of 14 compressed air-cooled magnetrons of 800 W each (maximum of 11.2 kW), the microwave energy accelerated the early-age compressive strength of the cement paste, but did not affect the later-age strength. Microwave curing reduced the energy consumption and curing time [77].

Practically, microwave-assisted curing has been shown to be a useful technique for construction applications [6] and for repairing damaged concrete pavements. Leung and Pheeraphan [71] compared the early-age and long-term compressive strengths of concrete specimens developed from microwave-cured type 3 Portland cement to those of commercially available rapid-hardening concrete containing accelerating admixtures. The compressive strength of microwave-cured concrete (*w/c* ratio of 0.55) that was cured for 45 min increased to 19.2 MPa at 4.5 h [71]. Studies based on research by the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia [78–83] found that the use of microwave curing cycles of less than 6 h permitted adequate strength for formwork removal and wire-strand prestressing, without impairing the concrete quality.

Microwave heating offers efficient production and high product performance for precast concrete. Heat curing impacts the performance (*i.e.*, thermal response, early-age strength, and durability) of a selected range of concrete materials for bridge construction. Microwave heating produces considerably lower temperature gradients compared to steam heating. For example, when rapid microwave curing cycles of less than 6 h were used, compressive strengths of up to 25 MPa were achieved in high-quality precast concrete. Replicating the bulk heating rate with microwave heating did not cause any deterioration in the near-surface quality, unlike in conventional steam heating.

Several inventions have been developed for the application of microwave-accelerated curing. Mario and Sergio [84] developed a process and device for accelerating the drying of cement mixtures, such as those containing prestressed and non-prestressed concrete components. Ludewig and Steinbach [85] invented a method and device for removing water from buildings, parts of buildings, and/or fixed structures, including those outside buildings, for construction purposes. Birch-Rasmussen et al. [86] invented a process for curing and drying wet reinforced concrete. In their process, the concrete is subjected to short-term electromagnetic heating (for seconds to a few minutes), which increases the temperature of the concrete from 10–25 °C to 50–80 °C. Furthermore, Engelbrecht and Soeren [87] proposed a process for curing and drying concrete by electromagnetic radiation, and a multistep process for accelerating the curing and drying of reinforced concrete products. In their proposals, the cast concrete elements are consecutively subjected to an inductive alternating magnetic field, high-frequency electromagnetic radiation, and electromagnetic microwave radiation.

Although the initial cost of the microwave equipment might be expensive, microwave curing can reduce the amount of cement used in concrete and can accelerate early-age concrete curing in various applications. However, this curing method could have negative impacts on the performance (*i.e.*, thermal response, early-age strength, and durability) of some concrete mixtures. Therefore, a suitable microwave system and appropriate curing procedures need to be determined.

5.2. Decontamination and decommissioning of concrete

Microwave energy has been applied to the decontamination of concrete surfaces [88], including radioactively contaminated surfaces [90,91], and concrete layers, in the case of biological shields [89].

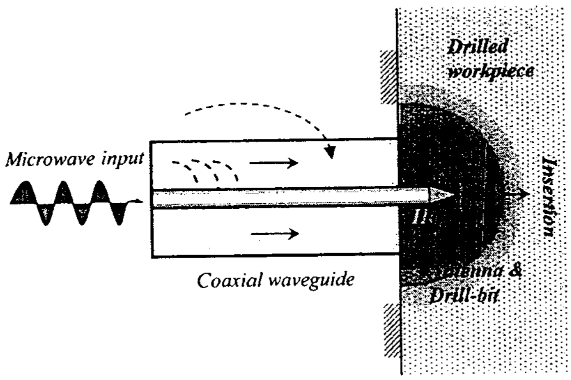


Fig. 9. A typical microwave drill operating system [12].

When a targeted dielectric material is irradiated by microwave energy, the energy is transferred from the electric field to the molecular bonds of the concrete, leading to vibration of molecules within the bond. Due to the nonuniform temperature distribution under the concrete surface, water beneath the surface evaporates, generating a high vapor pressure on the surface. When the accumulated pressure exceeds the tensile strength (maximum tensile stress) of the concrete, the concrete surface will spall off the bulk concrete.

A series of studies investigated the decontamination of concrete by microwave technology [92–94] under operating frequencies of 0.896, 2.45, 10.6, and 18.0 GHz. For microwave frequencies at or above 10.6 GHz, the microwave power dissipation was shifted towards the front surface of the concrete. This finding was verified in theoretical studies by Lagoset al. [95]. When higher microwave frequencies were used, less power was needed to increase the temperature or thermal stress to the same value in the same period of time compared to experiments under lower frequencies. These results are consistent with the findings of Bažant and Zi [11,96], who used microwave to spall off a thin layer of concrete surface that had been contaminated with radionuclide.

More investigations are needed into the use of microwave energy to spall off targeted concrete surfaces for decontamination. The decontamination of steel-reinforced concrete needs to be studied carefully because steel can reflect microwave energy, causing overheating and damage of the bulk concrete. Moreover, the decontamination of the concrete surface to make a break at a specific point or area requires careful analysis. Specifically, the design of an apparatus or machine to control the breaking region should be carefully considered. Finally, the safety of the worker should be taken into consideration.

5.3. *Nondestructive monitoring*

The early strength and accelerated curing parameters of microwave-cured concrete have been used to predict the 28-day compressive strength of concrete [97]. The 7-day strength of concrete made with rapid-hardening Portland cement and the 28-day strength of concrete made with ordinary Portland cement were predicted from the accelerated strength of concrete by microwave energy. Prediction results were within 15% agreement with actual test results [98].

Near-field microwave-sensing techniques can be used to determine the hydration state of cement paste or concrete [99]. For example, microwave energy has been applied to determine the natural moisture content, percent absorption, and bulk specific gravity values of aggregates [100], to study the hydration kinetics [101], to observe the hydraulic reaction of fresh pastes of C_3S for the first 30 h of hydration [102], and to determine the water content of fresh concrete [103]. The compressive strength of hardened concrete can be estimated from the apparent activation energy using a microwave technique [104,105]. This technique determines the strength in a nondestructive manner, without contacting the sample. In addition, microwave has been used to monitor the residual moisture content in the early hydration stages of cement paste. The residual moisture content decreased in rough proportion to the stage of the hardening process [106–108].

In the case of reinforced or prestressed concrete, microwave can indicate the presence of water, which is important for the diagnosis of concrete. The propagation of electromagnetic waves in concrete is controlled by the electromagnetic properties of the material itself, which are mainly influenced by the presence of water. Concrete-independent linear relationships were observed between the water volume and the propagation velocity of the direct wave and its attenuation [109].

For damaged concrete, microwave can be used to distinguish mortars containing Alkali-Silica Reactive (ASR) aggregate from nonreactive aggregate. Variations in measurements were linked to the production of ASR gel and its tendency to attract free water from its environment. ASR gel in cement-based materials can also be detected by material characterization methods [110,111]. In order to utilize microwave to measure the concrete properties, the status of free and fixed water must be considered. The temperature of free water can increase due to the increase in heat when the concrete interacts with the electromagnetic field. Thus, some of the free water is evaporated, leading to the misinterpretation of the amount of remaining water in the concrete.

5.4. *Drilling/melting of concrete*

An innovative application of microwave to concrete is the microwave-assisted drilling or melting of concrete [12,13]. High-energy microwave is applied to an area that is much smaller than the wavelength of the microwave (0.001–1.0 m). The microwave behaves like a "focusing injection," with a monopole antenna conveying the material to be drilled (*e.g.*, concrete, ceramic, *etc.*; Fig. 9). The high-energy microwave energy penetrates the small area of the surface of the material, generating a high temperature locally until the material softens or melts. When a near-field radiator is used to induce microwave energy into a small volume on the surface of the material, a hot spot progresses in a rapid thermal runaway process. This process should be taken into account when determining the microwave drilling spot.

6. Theoretical investigations of microwave processing

This section describes an important theoretical investigation point of view of use of microwave in cement and concrete. It consists of electromagnetic theories involved microwave heating by applying Maxwell's equations, electromagnetic power flow by Poything vector, and the local volumetric heat-generation term based on Lambert's law. In addition, numerical techniques and simulation of microwave heating are presented involving Partial Differential Equations (PDEs) of the Maxwell's equations and the heat transport equations.

6.1. *Electromagnetic theories*

In essence, the numerical simulation/modeling of microwave heating involves the analysis of multiphase coupling. The mathematic model consists of the electromagnetic field equations (*i.e.* Maxwell's equations) and the heat transport equations, which are interrelated. To capture the interrelationship between the electromagnetic field and heat transport, the heat transport equation contains at least one inhomogeneous term that reflects the heating source provided by the microwave-dissipated power. Temperature variations during heating can cause changes in the complex permittivity, which can lead to space and time variations of the electromagnetic field. To simulate the microwave heating process, the electromagnetic and heat transport equations with their coupled relationships must be modeled together and solved by suitable numerical methods.

The microwave field includes electric ($\vec{E}$) and magnetic ($\vec{H}$) fields that move simultaneously through space. The relationship between these time-varying fields can be described macroscopically with Maxwell's equations, revealing the following important observations: (a) the displacement current density is the rate at which the electric flux density (D) varies with time; (b) time variations in the electric field create time variations in the magnetic field, due to the action of ($\partial \vec{D}/\partial t$) as a source of the magnetic field; and (c) the time-varying magnetic and electric fields are interdependent. With the help of boundary characteristics, the propagation conditions of plane waves can be assumed as follows: (a) the components of the field quantities ($\vec{E}$ and $\vec{H}$) lie in a transverse plane that is perpendicular to the direction of wave propagation; and (b) the attenuation of the wave amplitude is reduced by a factor of e^{-1} (0.368) in a dielectric medium (*i.e.* a material that can absorb microwave energy and then can be converted partially into other form of energy), by creating ionic oscillations and continuing dipole relaxation.

The electromagnetic (microwave) waves propagate in free space at the speed of light. Further information on the form of these waves can be obtained by noting that the electric and magnetic fields must also satisfy Maxwell's equations. Although the results derived are general, a specific type of wave is considered: the wave is an unbounded plane, indicating that there exist planes (or wave fronts) that are perpendicular to the direction of propagation, over which all quantities of the wave are constant.

Importantly, Maxwell's equations can be used to predict electromagnetic waves by considering the compacted forms of four equations. The validity of these equations has been proven by their consistency with all existing experiments of electromagnetic phenomena. The physical meanings of these equations are indicated via their specific differential forms below:

$$\text{(a) } \textit{Gauss's law}: \nabla \vec{D} = q \tag{5}$$

$$\text{(b) } \textit{Faraday's law}: \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{6}$$

$$\text{(c) } \textit{AmpÓre's law}: \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{7}$$

$$\text{(d) } \textit{Maxwell's equations}: \nabla \vec{B} = 0 \tag{8}$$

where $\vec{E}$ is the electric field intensity (V/m), $\vec{H}$ is the magnetic field intensity (A/m), $\vec{D}$ is the electric flux density (C/m), $\vec{B}$ is the magnetic flux density (Wb/m^2), t is time, and q is the electric charge density (C/m^3).

Constitutive relations that relate $\vec{H}$ and $\vec{B}$, $\vec{E}$ and $\vec{D}$, and $\vec{E}$ and $\vec{J}$ are shown in Eqs. (9)–(11), respectively. Substituting Eqs. (9)–(11) into Eqs. (5)–(8) results in Eqs. (12)–(15):

$$\vec{B} = \mu \vec{H} \tag{9}$$

$$\vec{D} = \varepsilon \vec{E} \tag{10}$$

$$\vec{J} = \sigma \vec{E} \tag{11}$$

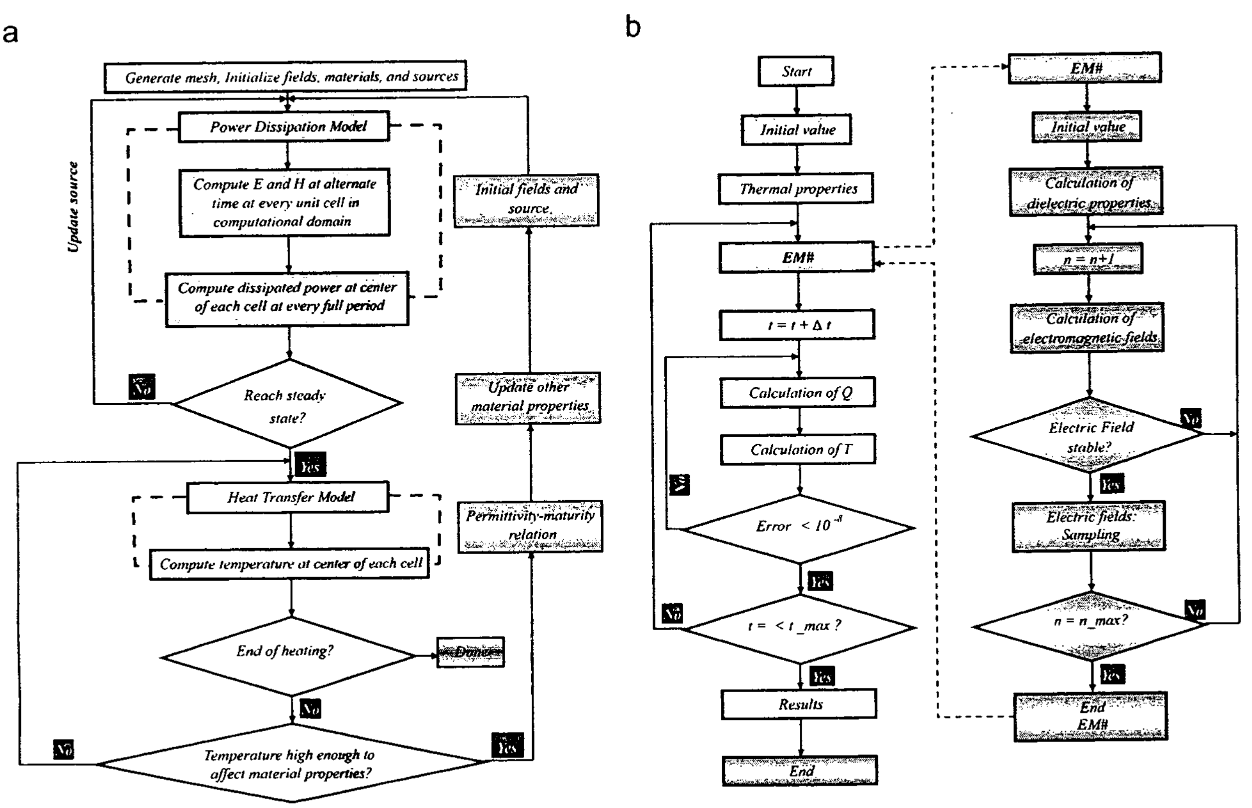


Fig. 10. Microwave heating model. (a) Multi-mode cavity [115] (b) Single mode cavity [46].

where μ is the magnetic permeability (H/m), σ is the electric conductivity (1/Ohm), and ε is the dielectric constant (F/m).

$$\nabla \dot{E} = \frac{q}{\varepsilon} \tag{12}$$

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} \tag{13}$$

$$\nabla \times \dot{H} = \sigma \dot{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \tag{14}$$

$$\nabla \dot{H} = 0 \tag{15}$$

During microwave heating, electromagnetic energy is converted into heat, which is liberated into or from the dielectric material. Therefore, the power that flows through a closed medium surface can be calculated from the Poything vector, as shown in integral form in Eq. (16).

$$\vec{P} = \bar{E} \times \vec{H} \tag{16}$$

However, by definition, the average power is given by Metaxas and Meredith [5]

$$P_{av} = -\tfrac{1}{2} \int_S \mathrm{Real}(E \times H') dS' = -\tfrac{1}{2} \omega \varepsilon_0 \varepsilon'' \int_V (E \overset{*}{E}) dV \tag{17}$$

The temperature change of the processed cement paste during microwave treatment can be obtained by solving the heat-conduction transport equation, in which the microwave power is included as a local electromagnetic heat-generation term:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{Q}{\rho \cdot C_p} \tag{18}$$

In this equation, T is the temperature (°C), a is the thermal diffusivity (m^2/s), ρ is the density (kg/m^3), and c_p is the heat capacity at constant pressure (J/(kg K)). The local electromagnetic heat-generation term Q depends on the electric field distribution and based on Lambert's law, the microwave energy absorbed or the local volumetric heat-generation term, defined as in Eq. (19).

$$Q = \sigma |\bar{E}|^2 = 2\pi f \varepsilon_0 \varepsilon_r' (\tan \delta) |\bar{E}|^2 \tag{19}$$

where Q is the microwave energy, σ is the effective conductivity, f is the frequency (Hz), ε_0 is the permittivity of free space (8.8514×10^{-12} F/m), ε_r' is the relative dielectric constant, $\tan \delta$ is the loss tangent coefficient, and $\vec{E}$ is the electric field intensity (V/m).

When microwave energy penetrates a dielectric material, the wave strength fades away exponentially because the microwave energy is absorbed by the dielectric material and is converted to heat. This absorbed ratio varies with frequency and dielectric properties. In general, the penetration depth (D_p) is used to denote the depth at the power density. It decreased to 36.8% or (e^{-1}) of its initial value at the surface [46] and is defined in Eq. (20):

$$D_p = \frac{1}{(2\pi f/\upsilon)\sqrt{\varepsilon_r'(\sqrt{(1+(\varepsilon_r''/\varepsilon_r')^2)}-1)/2}} = \frac{1}{(2\pi f/\upsilon)\sqrt{(\varepsilon_r'(\sqrt{(1+(\tan \delta)^2)}-1)/2)}} \tag{20}$$

where D_p is the penetration depth, ε_r'' is the relative dielectric loss factor, and υ is the microwave speed in the dielectric material that can be evaluated by $c/\sqrt{\varepsilon_r'}$.

6.2. Numerical techniques and simulation

The numerical simulation of microwave heating involves an analysis of at least two kinds of interrelated Partial Differential Equations (PDEs): the electromagnetic field equations (i.e. Maxwell's equations) and the heat transport equations. Additional differential equations may also be needed; for example, the mass transfer equation may be required for a model of drying porous materials.

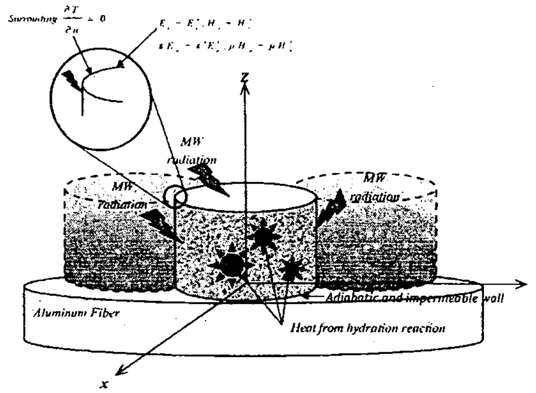


Fig. 11. A physical model and boundary conditions of 0.38-w/c cement paste subjected to microwave energy using a multi-mode cavity [116].

To obtain an accurate solution for the above coupled equations, analytical methods cannot be used. Various numerical methods have been applied to simulate microwave heating of cement and concrete. Popular methods include Finite Difference (FD) methods (e.g. Finite Differential Time Domain/FDTD method) [112,113], Finite Element Method (FEM), the Moment of Method (MoM), Transmission Line Matrix (TLM) method, Finite-Volume Time-Domain (FVTD) method, and others. Remarkable progress has been achieved in recent years in the numerical simulation of microwave heating. As more refined models, faster numerical methods, and more complete descriptions of the complex permittivity of more materials are developed [114], this progress will continue to accelerate. With the aid of numerical simulation, the complex interaction between microwaves and materials will be better understood, and the critical parameters influencing the process will be identified, allowing for the rapid design of optimized and controllable applicators.

To study the microwave heating process in cement and concrete, this process can be separated into a heat transfer model and a microwave power dissipation model, as shown schematically in Fig. 10(a) [115]. FDTD is a powerful numerical method for solving Maxwell's equations. The FDTD method described by Rattanadecho et al. is a useful approach for solving models in the single-mode cavity, as shown schematically in Fig. 10(b) [46]. Natt et al. [107] used the FEM method to solve Maxwell's equations and heat transfer in the cement paste during microwave curing in the multimode cavity (Fig. 11) [116]. However, Lambert's law cannot be used in numerous situations, such as instances with standing waves.

7. Health and safety of microwave processing

Health and safety of microwave processing cannot be neglected when microwave operates with human and environments. Therefore this issue is explained in this section that entails on the limitations and conditions of microwave exposure regulated by associations relating to the use of microwave energy.

Microwave processing of cement and concrete materials may involve a risk of exposure of microwave to human and biological tissues if certain precautions are not taken. Therefore, the Federal Communication Commission (FCC) and Occupational Health and Safety Administration [117] have provided exposure limits for microwave. These organizations have considered the effects of microwave radiation on human health from the perspectives of

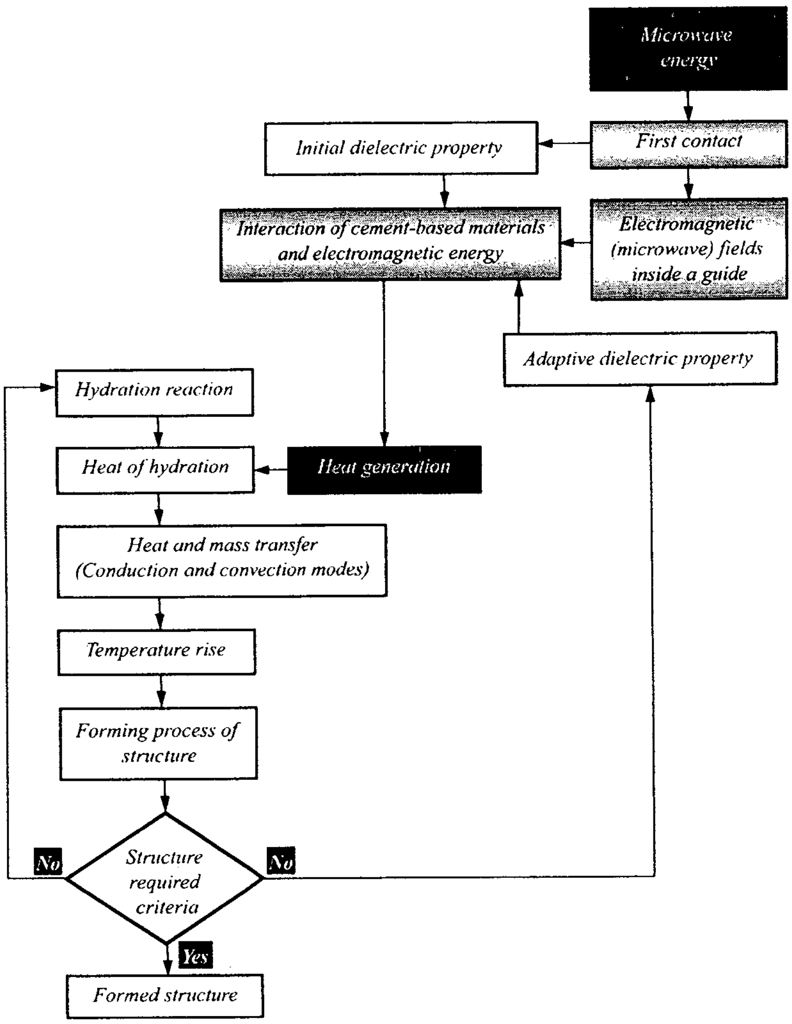


Fig. 12. A proposed schematic model of cement and concrete subjected to microwave energy.

exposure source (*e.g.* medical devices, amateur radio, cellular phone base stations, hand-held cell phones, heating and sealing devices, microwave ovens, radio broadcast antennae, traffic radar devices, *etc.*), hazard location, exposure time and solution.

The absorption and distribution of microwave exposure are strongly dependent on body size and orientation, as well as on the frequency and polarization of the incident radiation. In particular, the Specific Absorption Rate (SAR) refers to the power absorbed by a body when exposed to EM radiation. The current SAR limit is 4 W/kg. To be conservative, organizations generally use 1/10 of this value for setting standards, especially for Radio Frequency (RF) and microwave exposure limits. For occupational exposure, the field strength is averaged over a 6-min time period. For public exposure, the field strength is averaged over a 30-min period, as recommended by the International Radiation Protection Association (IRPA) Guidelines [118], IEEE Standards [119,120], National Radiological Protection Board (NRPB), and the Health Protection Agency [121]. It is strongly recommended that the microwave systems in the laboratory and industry are periodically tested for any leakage, and if any substantial leakage is observed, suitable measures must be taken to stop the leakage before the system is further used.

8. Conclusions

8.1. Major review findings

In this review paper, we have described applications of microwave energy in the cement and concrete field. Microwave heating is a high-performance volumetric heating method suitable for dielectric materials used in various concrete industrial processes. Applications of microwave heating in these systems include cement synthesis, accelerated curing, decommissioning of decontaminated concrete, nondestructive monitoring, and concrete drilling/melting. Numerous studies have experimentally and numerically investigated these processes, to utilize microwave heating to its fullest potential in cement and concrete applications. The following conclusions can be drawn from this review:

- Microwave heating is commonly performed at 2.45 GHz. Concrete mixtures can be monitored during the hydration process with a custom-designed parallel-plate setup using a network analyzer.
- The dielectric permittivity of cement-based materials is affected by the initial *w/c* ratio, cement type, mineral admixture, and

aggregate. Although the volumetric fractions of water and superplasticizer in a given mixture are small, these components strongly affect the dielectric permittivity.

- The dielectric permittivity is relatively high and remains constant during the dormant period of each process. The dielectric permittivity decreases rapidly when the hydration reaction resumes, and it continues to decrease during the acceleratory period. Thus, the dielectric property is related to the temperature rise and setting time behaviors of cement-based materials. This information can be used to accelerate the early strength of the concrete by choosing a suitable curing time (*e.g.*, start time and end time for applying microwave energy).
- The clinkering temperatures required by microwave processing were about 100 °C less than those required for fast-heating by the electric furnace method.
- Microwave-assisted heating for 30–60 min induced C_3S formation. Ion oxides played a very important role in C_3S formation in conventional sintering.
- Microwave-assisted sintering improved the formation of C_3S compared to conventional sintering methods.
- Microwave can be utilized to improve the cementitious properties of RHA-incorporating cement, especially cement that is microwave-sintered at 800 °C.
- Use of microwave energy accelerated strength development in Portland cement mortar without decreasing the long-term strength of the concrete. The strength of the concrete specimens began to decrease when the final *w/c* ratio was less than 0.40.
- Key parameters for microwave curing include the microwave power, application time, duration of microwave heating, thermal runaway, and overheating within the sample.
- Microwave energy at operating frequencies of 0.896, 2.45, 10.6, and 18.0 GHz can be used to decontaminate a concrete surface. At or above 10.6 GHz, the microwave power dissipation was shifted towards the front surface of the concrete.
- Microwave energy can be used for near-field microwave-sensing techniques, such as for determining the natural moisture content, percent absorption, bulk specific gravity of aggregates, hydration kinetics of cement, and water content of fresh concrete.
- High-energy microwave energy (wavelength range: 0.001–1.0 m) is useful for drilling/melting of concrete.
- The numerical simulation of microwave heating involves the analysis of electromagnetic field equations (*i.e.*, Maxwell's equations) and heat transport equations. Simulations should be separated into heat transfer and microwave power dissipation models. FDTD is a powerful numerical method for solving Maxwell's equations.
- The Specific Absorption Rate (SAR) refers to the power absorbed by a body when exposed to electromagnetic radiation. The current SAR limit is 4 W/kg.

8.2. Future trends of research and development

Microwave heating is a high-performance volumetric heating method suitable for the dielectric materials used in various concrete industrial processes. Numerous studies have experimentally and numerically investigated this process, in order to utilize microwave heating to its fullest potential in cement and concrete applications. Some of the investigated topics are outlined as follows:

- The dielectric properties of cementitious materials should clarify the effects of the time-dependent dielectric properties and thermal properties of concrete on microwave heating mechanisms. The dielectric property is a primary factor for determining the interaction of the microwave energy with the material. Theoretically, the complex permittivity comprises the normal dielectric constant ε', which is a measure of how much energy from an external electric field is stored in a material, and the loss factor ε'', which is a measure of how much energy a material loses to an external electric field. In addition, concrete is a heterogeneous material with pores that are partially filled by Si^{3+}, Ca^{2+}, and OH^- ion-rich solution. The ion concentration parameters can vary throughout the hydration and pozzolanic reactions. However, heating concrete by microwave energy leads to a simultaneous change in the dielectric property, which instantaneously affects the interaction between the microwave energy and concrete. Thus, the dielectric property needs to be understood, in order to determine the compatibility of microwave applications with the material's time-dependent concrete properties and thermal properties.
- Studies should investigate the influences of different concrete mixtures and curing conditions on the characteristics of microwave heating, as these conditions strongly affect the strength development of concrete. The primary parameters that characterize a given concrete sample include the *w/c* ratio, the chemical composition of the cement, the "fineness" of the cement (*e.g.* type 1 – normal purpose; type 2 – moderate heat- and sulfate-resistant; type 3 – high early strength; type 4 – low heat; and type 5 – sulfate-resistant), the nature and proportions of aggregates, and the use of chemical and mineral admixtures, among others. Admixtures are increasingly being used in the concrete construction industry. For example, type I cement can be replaced, in part, by silica fume, producing a concrete with high early strength.
- As shown in Fig. 12, Heat and mass transfer mechanisms within the heated concrete during microwave heating should be clarified. Studies have consistently shown that the generation and transport of heat and mass within the heated concrete material are key factors influencing the efficiency of microwave heating. In this process, heat is generated inside the concrete structure, and volumetrically transported towards the outside. These studies assume that no chemical reactions occur within the concrete under consideration. This assumption is not true, however, as hydration and pozzolanic reactions take place. Given the difficulty of this task, one may choose to perform the analysis at specified coupled chemical reactions during microwave curing. Heat generated by the microwave ($Q = \sigma|\vec{E}|^2 = 2\pi f \varepsilon_0 \varepsilon_r' (\tan\delta)|\vec{E}|^2$) must be applied in synergy with the heat liberated by the hydration (Q_{Hyd}^{Total}) and pozzolanic (Q_{Pozz}^{Total}) reactions ($Q_{Reaction}^{Total} = Q_{Hyd}^{Total} + Q_{Pozz}^{Total}$). These heat sources should be considered from the perspectives of the setting and hardening processes of concrete, which are influenced by the internal energy from hydration and the external energy from microwave energy. Simply speaking, when external energy is added to the concrete after the final setting time, the energy leads to the generation and expansion of microcracks.

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pursuits including his pioneering contributions to advance the field of materials science.

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