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Invited Paper

Use of microwave energy for accelerated curing of concrete: a review

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Abstract

Microwaves (MWs) are one of the most popular energy sources to heat dielectric materials in various industrial processes. One application is the rapid thermal cure of concrete. Due to the advantages of volumetric heating, MWs can be implemented in a reasonable way to improve the rate of strength development. However, these fields have been grown only gradually, as there has been not much research and practical work over the last years. The climate change issue and the discussion around the non-renewable energy resources triggered a change for better energy-utilizing systems. One is the use of clean energy in the cement and concrete production. Nevertheless, simultaneously efforts also needed to make towards an improvement of concrete properties. Therefore, suitable MWs curing method and processes involved are indispensable factors for research and subsequent developing into applications. The present paper reviews the historical evolution of the MWs energy implementation to cure concrete. It further provides a deeper understanding of this technology and proposes suitable points for future study and development. The first part describes the necessity of thermal curing on the strength development of concrete at early age and then discusses its factors affecting. Also curing criteria and the disadvantages of the conventional methods used to accelerate the rate of hydration reaction of concrete are summarized. The second part reports the implementing method for achieving this purpose covering dielectric properties involved and related heating mechanisms. Finally, some aspects for future studies are proposed to build a forward-complementing knowledge from the current one.

Keywords: concrete, curing, microwave, properties, review

1. Introduction

Having a relatively high compressive strength, being more durable and economical, concrete is a key material for mankind. At present, it is widely used in civil work, such as buildings, pavements, architectural structures, roads, bridges, brick/block walls, and footings for gates and fences. For example, around the world over one-fifth of a ton of cement per capita which is a main constituent of concrete, is produced in 1989 (CEMBURO) and this increases with a yearly rate of app. 4.5% as shown in Figure 1.

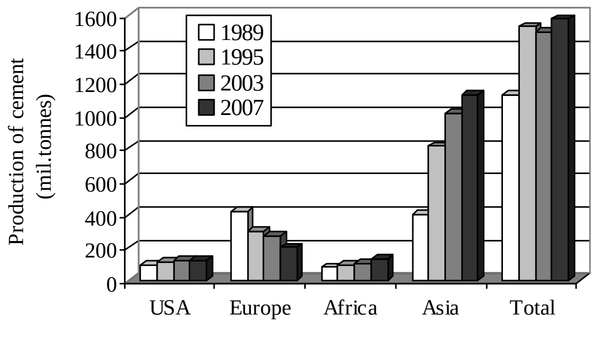

Figure 1. Production of cement 1989 and 1995 (Dhir, 1999) whereas cement production in the years of 2003 and 2007 are surveyed by the authors.

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Conventionally, concrete is made from hydraulic cement, water, and aggregates. The cement is a mixture of calcareous-, silica- and alumina-based minerals. After manufacturing, which consists of grinding raw materials, mixing them in certain proportions and burning them at temperatures of up to 1450°C, granular clinker is formed that comprises tri-calcium silicate ($3CaO.SiO_2$), di-calcium silicate ($2CaO.SiO_2$), tri-calcium aluminate ($3CaO.Al_2O_3$), and tetra-calcium alumino ferrite ($4CaO.Al_2O_3.Fe_2O_3$). It is then ground to a fine powder and added a few percent of calcium sulfate to make in the commercial Portland cement product and ready to react with water.

When cement grains come in contact with sufficient mixing water molecules suddenly a variety of reactions occur, in which hydration products are formed, i.e. calcium silicates hydrate gel (CaO_x-SiO_{2y}-H_2O_z) as shown in the reactions in Equation 1. It means that the strength develops continuously A typical kinetic reaction is shown in Figure 2. Immediately after the cement-water mixing, the ($3CaO.Al_2O_3$) phase reacts with the water to form an aluminate-rich compound. An associated process, the hydration of calcium sulfate hemihydrate to dehydrate, may also contribute to this exothermic peak (Stage 1). Consequently, gel reacts with sulfate in solution to form ettringite ($3CaO.Al_2O_3$). The hydration is an exothermic reaction but it does not last long, typically only a few minutes; this is called the dormant period (Stage 2). At the end of this period, the $3CaO.SiO_2$ and $2CaO.SiO_2$ in the cement begin to hydrate with the formation of calcium silicate hydrate (CaO_x-SiO_y-H_2O_z) and calcium hydroxide ($Ca(OH)_2$). This corresponds to the main period of hydration (Stage 3), which over time leads to the increase in concrete strengths. The cement grains react from the surface inwards, and un-reacted grain particles become smaller. The period of maximum heat evolution occurs between 6 and 24 hrs after mixing and then it decreases gradually within about a month (Stages 4 and 5; Mindress *et al.*, 2002).

$$3CaO.SiO_2+H_2O \rightarrow CaO_x\text{-}SiO_{2y}\text{-}H_2O_z+Ca(OH)_2+\Delta Heat$$

$$2CaO.SiO_2+H_2O \rightarrow CaO_x\text{-}SiO_{2y}\text{-}H_2O_z+Ca(OH)_2+\Delta Heat$$

$$2(3CaO.Al_2O_3)+18H_2O \rightarrow 2CaO.Al_2O_3.8H_2O+4.CaO.Al_2O_3.10H_2O+\Delta Heat$$

$$2(3CaO.Al_2O_3)+32H_2O+3(Ca^{2+}_{(aq)}+SO_4^{2-}{}_{(aq)}) \rightarrow 6CaO.Al_aO_3.3SO_3.32H_2O+\Delta Heat$$

$$6CaO.Al_aO_3.3SO_3.32H_2O+23CaO.Al_2O_3 \rightarrow 3(4CaO.Al_aO_3.SO_3.12H_2O)+\Delta Heat \quad (1)$$

Compressive strength is considered a valuable property and is invariably a vital element of the structural design. Especially high early strength development can benefit to concrete production, such as reducing constructing time and labor, saving the formwork and energy, having a small impacting to the environment. As a matter of fact, it is influenced by several factors as shown in Figure 3, including water-cement ratio, cement type, age of paste and curing

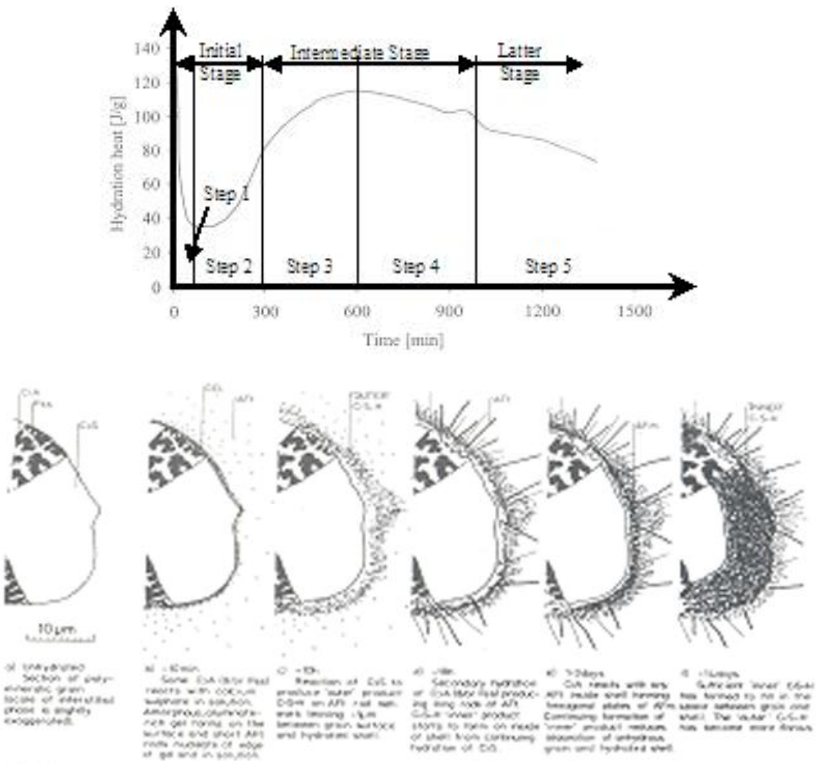


Figure 2. A typical kinetics of heat evolution from hydration reactions of cement (Èerný and Rovnaníková, 2001 and Mindress *et al.*, 2002).

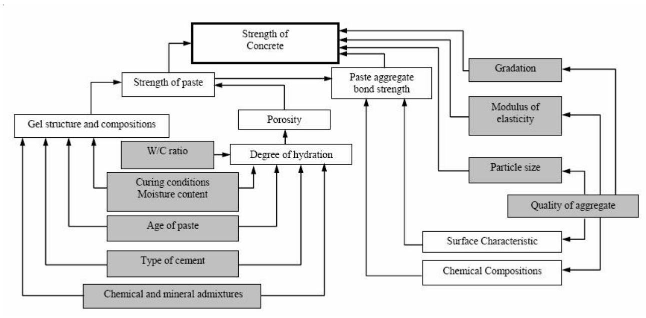


Figure 3. Factors affecting compressive strength of concrete at early age.

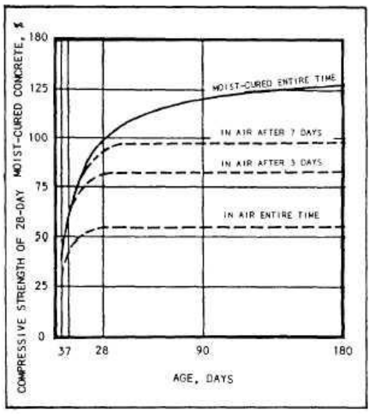


Figure 4. Strength developments at different curing conditions. (Neville, 1995)

methods employed (Neville, 1995). All things being equal, a concrete with a lower water-cement ratio makes a stronger concrete than one with a higher ratio. The total quantity of cement materials and types can affect the strength, especially in the early age.

At present, there are various curing methods for accelerating the strength of concrete at early age. Basically curing is an admiral method, which is the maintenance of adequate moisture content and a favorable temperature in concrete through curing. By this it is ensured that the degree of hydration is sufficient to reduce the porosity to a level in such way that the desired properties of concrete can be attained. For examples, cured by water and air at a specific time is affecting the rate of strength development as shown in Figure 4. In addition, acceleration strength gains by supplying heat and additional moisture to the concrete. For example, steam curing is advantageous where a development of early strength in concrete is desired or where additional heat is required to accomplish hydration, like in cold weather. Two methods of steam are used: live steam at atmospheric pressure and high steam in autoclaves. However, the conventional curing methods have many limitations, which are summarized in Table 1. For example, long time consumption to reach the strength required in case of water curing, non-uniform hydration products due to the inherent thermal insulation of concrete caused by temperature differences taking place within the processed concrete under high stream and temperature curing, and concrete may face difficulties in durability properties when using curing compound admixtures.

From this, following questions arises: Can microwave heating be applied in the concrete industry? The possible answer based on a theoretical feasibility study is yes. This is because concrete-making materials, like hydraulic Portland

Table 1. Summary of the disadvantages of various curing methods

Methods of curing	Disadvantages
Water	1. Lack of water also causes the concrete to shrink which leads to tensile stresses within the concrete. As a result, surface cracking may occur, especially if the stresses develop before the concrete attains adequate tensile strength. 2. Long time to reach sufficiently the strength required such as (2.1) The AASHTO Guide Specifications for Highway Construction requires 3 days of curing, without comment on temperature. (2.2) ACI 318 (Building Code).7 days at temperature 10^{o}C, or 3 days at temperature 10^{o}C for high early-strength concrete (2.3) ACI 301 (Standard Specification for Structural Concrete). 7 days or 3 days for high early strength concrete (2.4) ACI 330 R (Guide for Design and Construction of Concrete Parking Lots)-3 days for auto traffic, 7 days for all other traffic
Heat with/ without steam	1. Too much heat reduces the long term concrete strength. Selecting an appropriate curing process helps in temperature control during hydration
Admixture	1. Amount of detail involved in specification-compliance issues and of application procedures required to insure proper performance. 2. Long term durability problem

cement, aggregates, water, and admixtures are dielectric materials, and therefore they are able to absorb microwave energy. Especially water has a relative dielectric constant (ε_r') and a relative loss tangent $(tan\,\delta_r)$ that is higher than of the other components. As a result, when the electric field $(\vec{E})$, which is a main part of the electromagnetic field, interacts with concrete constituents, energy is transferred and converted from the fields to water molecular bonds of materials by means of ion conduction and polar rotation. These mechanisms cause these bonds to vibrate and then the energy is dissipated as heat and transferred within processed concrete, yielding elevated temperatures and hydration reactions are excited and accelerated. Consequently, the part of free water molecule in capillary pores of concrete can be quickly removed from internal concrete structure before setting, which means induced plastic shrinkage is taken place leading to the collapse of capillary pores or the microstructures of concrete are simultaneously densified.

2. Characteristics of microwaves

It is generally accepted that microwaves are electromagnetic waves having frequencies in a range of 300 MHz (10^6 Hertz) to 300 GHz (10^9 Hertz) or wavelengths ranging from 1.0 meter (m) to 1.0 millimeter (mm) as shown schematically in the frequency spectrum in Figure 5.

Microwave (MWs) energy is today a mature technique having a wide range of applications in various industrial processes. Especially, the frequencies at 0.915±0.013 and 2.45±0.05 GHz, which are assigned by the International Microwave Power Institute (IMPI) as the two principal microwave frequencies, are utilized for industrial, scientific, and medical (ISM) purposes (Osepchuk, 1984, 2002). With fast and volumetrically internal heating, it has been widely utilized to heat, to dry, and to melt various dielectric (non-conducting) materials, such as paper, concrete, wood, rubber, and others. Some of the achievements of microwave energy, for example, are the tempering of frozen meat (Peyre, 1997; Basaran-Akgul, 2008), vulcanization of rubber (Martin, 2002; Sombatsompop and Kumnuantip, 2006; Doo-ngam, 2007), curing of adhesives for lumber (Beall, 2007), quickly heating of food (Orsat *et al.*, 2006; Chen, 2008), bonding of composite sheets (2007; Ku *et al.*, 2003; Sgriccia and Hawley), removal of contaminated surface (Lagos, 1995; Li, 1995; Bažant *et al.*, 2003), and hyperthermia (Tayel, 2006; Cresson, 2007; Arunachalam, 2008).

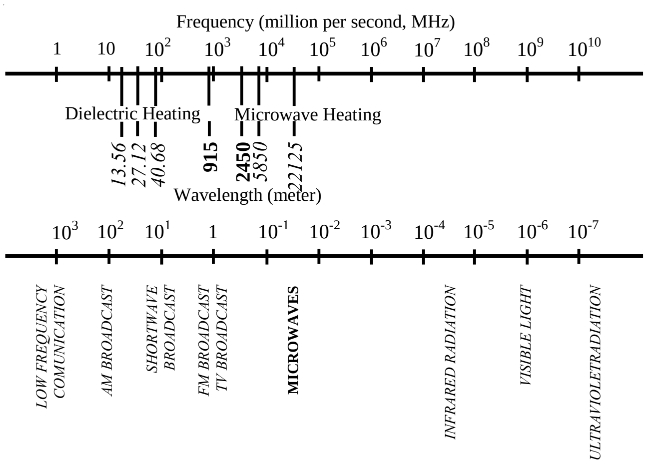


Figure 5. Electromagnetic spectrum.

3. Principles of microwave heating mechanism

A term of microwave heating is equally applicable to microwave systems in both cases; the heating is due to the fact that a dielectric material, which is a material with a small but finite electrical conductivity, absorbs energy when it is placed in a high frequency electric field. Consequently, electrically dipole polarization and conduction will be generated within dielectric materials, which are composed of polar molecules with positive ⊕ and negative ⊙ poles. These orderly dispersed polar molecules vibrate instantaneously and violently in correspondence to the alternative high frequency electric field of microwaves as shown in Figure 6. It is necessary to overcome the resistance of molecular attraction and motion. The friction generated heat results in a simultaneously temperature increase of the material.

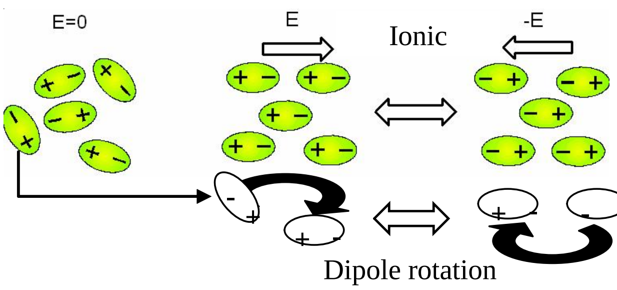


Figure 6. Mechanisms of microwave heating.

The root-mean-square value of the electric field intensity $\vec{E}$ is normally used to evaluate the microwave energy absorbed. Based on the Lambert's law, the microwave energy absorbed can be defined in Equation 2 (Ratanadecho, 2002).

$$Q=\sigma\left|\vec{E}\right|^2=2\pi f\varepsilon_0\varepsilon_r'\left(tan\sigma\right)E^2 \qquad (2)$$

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

When microwaves travels inwards dielectric materials, the wave strength fades away exponentially because the microwave energy is absorbed into dielectric materials and changed to heat. In general, the penetration depth (D_p) denotes the depth where the power density has decreased to 37% or (1/e) of its initial value and is defined as shown in

Equation 3.

$$D_p = \frac{1}{\frac{2\pi f}{\upsilon_p}\sqrt{\frac{\varepsilon_r'\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1}{2}}} = \frac{1}{\frac{2\pi f}{\upsilon_p}\sqrt{\frac{\varepsilon_r'\sqrt{1+(\tan\delta)^2}-1}{2}}} \quad (3)$$

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

As concrete is a dielectric material, its intrinsic properties affect the way how it is interacting with electric and magnetic fields of microwaves. It can be characterized by two independent electromagnetic properties i.e., the complex (electric) permittivity ε^* and the complex (magnetic) permeability μ^*. However, most common concrete materials are non-magnetic, having a permeability that is very close to the permeability of the free space ($\mu_o = 4\pi\, x10^{-7}$ *Henry/meter*) (Rhim and Büyüközürk, 1998). Thus, this study focuses upon the complex comprising real and imaginary parts, which can be defined in a relationship shown in Equation 4.

$$\varepsilon_r^* = \varepsilon_r' - \bar{j}\varepsilon_r'' \quad (4)$$

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

The real part of the relative complex permittivity, so-called commonly dielectric constant, ε_r' is a quantity, which measured how much energy transferring from an external electric field is stored in a material. The imaginary one ε_r'' is a measure of how much is lost from the material to an external electric field and it is referred as the relative loss factor. Moreover, an essential ratio that shows the energy lost (relative loss factor) to the energy stored (relative dielectric constant) in a material is given as a loss tangent $\tan\delta$ as shown in Equation 5.

$$\tan\delta = \varepsilon_r'' / \varepsilon_r' \quad (5)$$

According to the heating mechanism as discussed above, the dielectric properties play an important role for predicting rates that describe the behavior of concrete materials when subjected to a microwave electric field. In order to understand these properties, many techniques have been developed to measure continuously, such as transmission/reflection line, perturbation, free-space, and open ended probe. Table 2 summarizes the characteristics of each measuring technique (Hasted and Shah, 1964). The choices of measurement equipment and sample holder design depend upon the dielectric materials to be measured, the available equipment and resources. A Vector Network Analyzer (VNA) is expensive but very versatile and useful if studies are extensive where as scalar network analyzers (SNA) and impedance analyzers are relatively less expensive but still too expensive for many studies (Rohde and Schwarz, 2001).

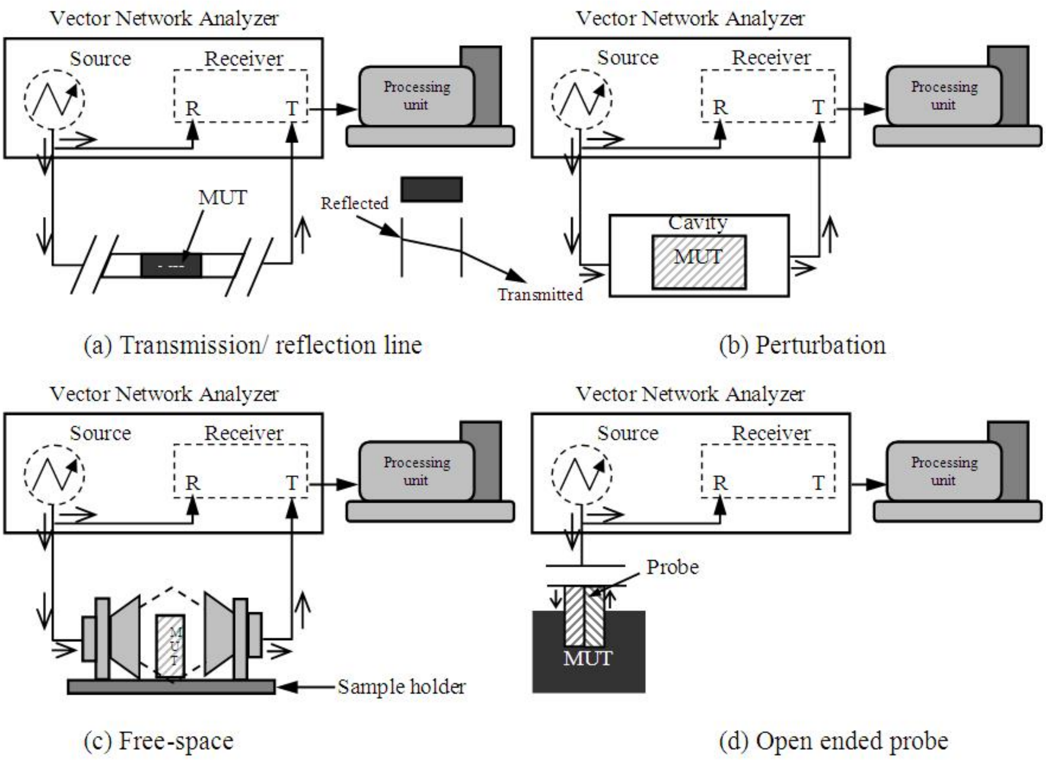


Figure 7. Schematic drawings of dielectric properties measurement techniques. (R = reflected power, T = transmitted power).

Table 2. A summary of the technique for measuring dielectric properties (Rohde and Schwarz, 2001; Venkatesh and Raghevan, 2005)

Technique	Characteristic	Advantages	Disadvantages	Dielectric properties parameters
Transmission/ reflection line	The material under test (MUT) must be made into slab geometry. At 2.45 GHz, the sample size is somewhat large. For measurements at 0.915 GHz, only the coaxial line technique is practical due to the large size of the waveguide required (Nelson *et al.*, 1973).	1. Common coaxial lines and waveguide 2. Used to determine both ε_r, μ_r of the MUT	1. limit by the air-gap effect 2. limit to low accuracy	ε_r, μ_r
Perturbation (Cavity) (Resonant)	The resonant cavities are designed in the standard TM (transverse magnetic) or TE (transverse electric) mode of propagation of the electro-magnetic fields. It is based on the shift in resonant frequency and the change in absorption characteristics of a tuned resonant cavity, due to insertion of a sample of target material. The measurement is made by placing a sample completely through the center of a waveguide (rectangular or circular) that has been made into a cavity. The sample provides information to calculate the dielectric	1. Simple 2. Easy data reduction 3. Accuracy 4. High temperature capability 5. Suite to low dielectric loss materials	1. Need high frequency resolution vector network analysis (VNA) 2. Limit to narrow band of frequency band only	ε_r, μ_r
Free-space	The sample is placed between a trans-mitting antenna and a receiving antenna, and the attenuation and phase shift of the signal are measured. The results of which can be used to translate the material dielectric properties. The usual assumption made during this technique is that a uniform plane wave is normally incident on the flat surface of a homo-genous material, and that the planar sample has infinite extent laterally, so that diffraction effects at the edges of the sample can be neglected.	1. Used for high frequency 2. Allow non destructive measurement 3. Measure MUT in hostile environment 4. Evaluation both ε_r, μ_r	1. Need large and flat MUT 2. Multiple reflection between antenna and surface of sample 3. Diffraction effects at the edge of sample	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. Care must be exercised with this technique because errors are introduced at very low frequencies and at very high frequencies, as well as for low values of dielectric constant and loss factor. This technique is valid for 0.915 and 2.45 GHz, for materials with loss factors greater than 1.0 (Sheen and Woodhead, 1999; HP, 1992)	1. Easy sample preparation 2. After calibration, can be routinely measured in a short time 3. Measure can be performed in a controll-ing temperature	1. Available for reflect-ion measurement 2. Affected by the air-gap effect	ε_r

A number of research work has been continuously investigating basic dielectric properties. Watson (1961) used microwave absorption measurements to determine the evaporable moisture content (free water) in building materials. Later Hasted and Shah (1964) used the Robert and von Hippel Method to study the standing wave in a guide and found that the dielectric properties of cement paste depend on the inside water in the same state, which produces the low frequency loss, rather than from the rotation of free water. Wittmann and Schlude (1975) studied the absorption of microwaves of hardened cement paste in the frequency of 8.5 and 12.3 GHz (X-band). They proposed a new method to determine the complex permittivity from the experimentally obtained absorption data. The high attenuation of microwaves with a frequency of 10.0 GHz in hardened cement paste is caused mainly by the evaporable water. Furthermore, at relatively high moisture content the complex permittivity was strongly influenced by a certain amount of water. Gorur *et al.* (1982) proposed a new method to monitor hydration kinetics and to estimate the degree of hydration for a small sample of cement paste. The dielectric properties of hydrating cement are closely related to its free water content. Moukwa *et al.* (1991) measured the conductivity and permittivity of Portland cement, Type I, II, and III, during the first 24 hours of the hydration period at a frequency of 10.0 GHz using the finite sample method. The results showed the conductivity and relative permittivity for the cement paste at a water-to-cement (w/c) ratio of 0.40; the initial conductivity was relative high and changed very little during the dormant period and when the reactions started again the conductivity decreased. Zhang *et al.* (1995) analyzed the dielectric constant (ε_r) and electrical conductivity of cement paste by using microwave techniques at operating frequencies between 8.2 and 12.4 GHz during the early stage of the hydration reaction. Rhim and Büyüközürk(1998) studied the electromagnetic properties of concrete over a microwave frequency range from 0.1 to 20 GHz by means of an open-ended coaxial probe method. Also Haddad and Al-Qadi (1998) evaluated the effect of the dielectric properties of Portland cement concrete over the microwave frequency range of 0.1 to 1.0 GHz. Robert (1998) designed and constructed a new dielectric measurement device for measuring the permittivity of concrete consisting of aggregates with 30 mm in diameter between 0.05-1.0 GHz. Wen and Chung (2001) investigated the effect of admixtures upon the dielectric constant of cement paste. Leon (2007) studied the effect of composition and time on dielectric constant of fresh concrete. Furthermore, the obtained experimentally data of concrete constituents by using a network analyzer open ended probe (Figure 8) by the authors are shown in Figures 9 and 10.

4. Evolution of use of microwave energy to cure concrete

4.1 Multi mode system with stationary workpiece

Xuequan *et al.* (1987) were probably the first ones who developed a new kind of curing technique of concrete by using microwave desiccation. One aspect could be noted that the strength under this technique begins to decrease when the final water-to-cement ratio of the microwave-cured specimen is less than 0.40. Hutchinson *et al.* (1991) indicated that microwave energy was a fully potential source for accelerating the strength development rate of OPC mortar without changing the long term strength of the mortars. By applying a

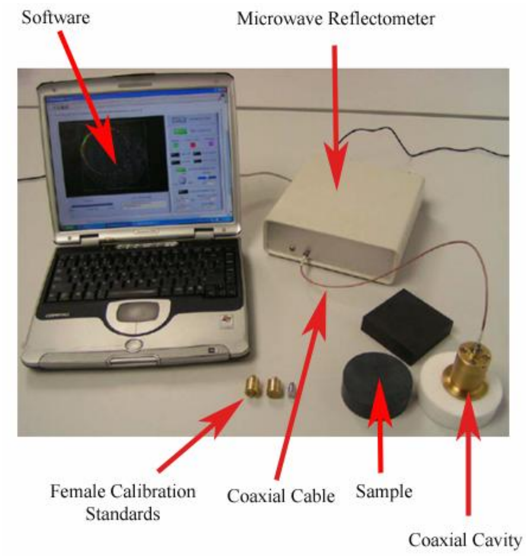
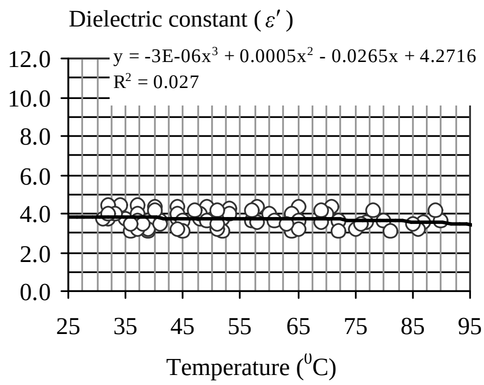


Figure 8. A network analyzer (open-ended probe technique).



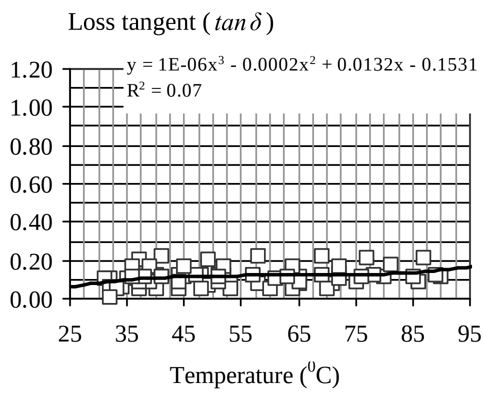


Figure 9. Dielectric properties of Type I Portland cement (Blaine fineness at 3250 cm^2/g)

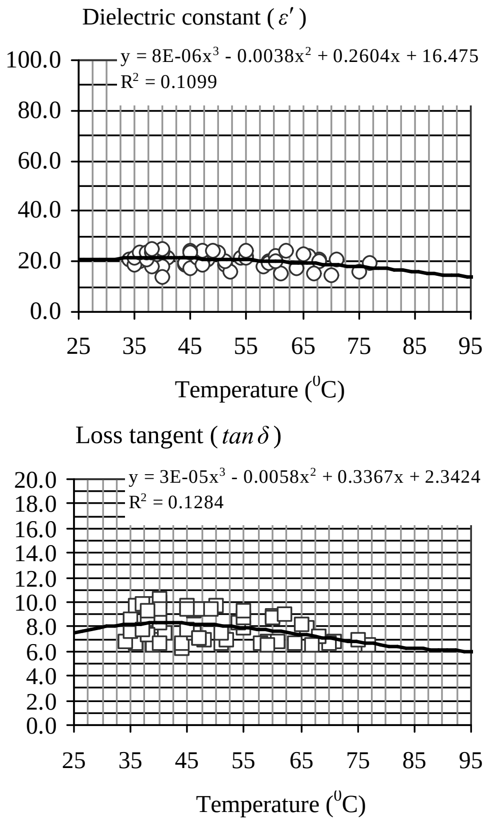


Figure 10. Dielectric properties of superplasticizer (Polycarboxylic based)

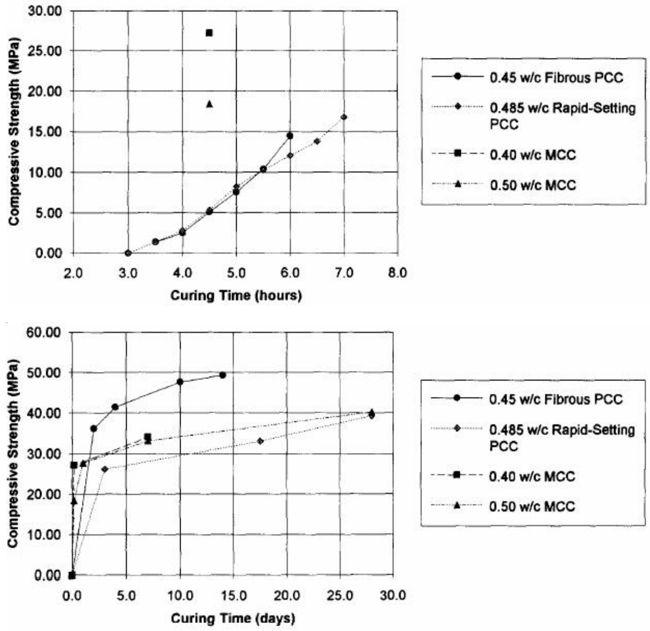


Figure 11. Comparison between microwave cured concrete and rapid setting Portland cement concrete with w/c =0.485 (Leung and Pheeraphan, 1995).

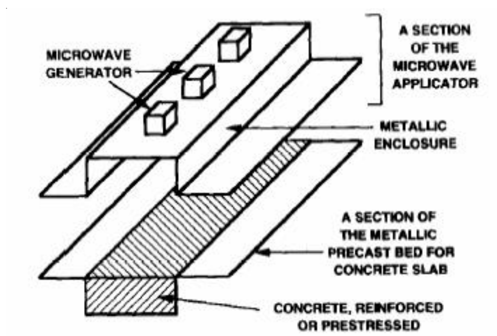


Figure 12. A plausible microwave applicator for precast concrete slab (Leung and Pheeraphan, 1995).

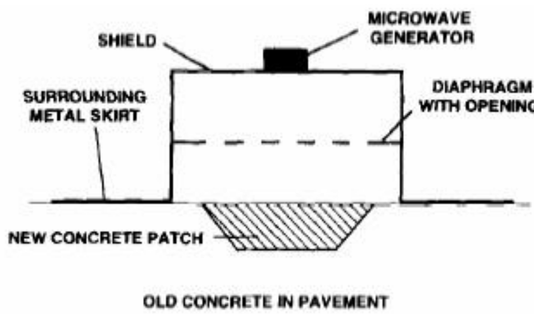


Figure 13. A plausible microwave configuration for pavement repair (Leung and Pheeraphan, 1995).

housing microwave oven to accelerate the mortar specimens at varying microwave levels, microwave energy acts as accelerator only during the first 24 hours in relation to the degree of hydration and reduces the induction period. Bella *et al.* (1994) used microwaves for the hyper-accelerating of the setting and curing process of concrete and ensured a significant improvement with respect to the present concrete curing technologies, which make use of the heat application. Dongxu and Xuequan (1994) applied a vacuum microwave composite to dewater concrete engineering. The optimum curing time was found to be 45 minutes at a temperature of 60°C and the final w/c ratio of concrete was decreased to about 0.38. Leung and Pheeraphan (1995) studied the suitable process for accelerating early-age strength development with microwave energy. They suggested that heating rate, power level, water-to-cement ratio, and delay time before microwave application are taken into consideration to evaluate the performance of microwave treatment. The test results showed that the microwave cured concrete has very high early strength, almost 20 MPa for the 0.55-w/c concrete, while the 0.45-w/c concrete of 27.5 MPa was achieved with a curing time of 4.5 hours as shown in Figure 11. In addition, the 7-days compressive strength of microwave cured concrete has similar to normal cured concrete. Leung and Pheeraphan (1996) investigated the feasibility of microwave curing in practical applications as shown in Figure 12 and 13. With microwave curing, Type III Portland cement concrete can develop early strength and later age strength, which is more favorable in comparison to commercially available rapid hardening concrete as well as concrete containing accelerating admixtures. Sohn and Johnson (1999) found that the microwave energy can be applied to cure cementitious material where the optimal curing condition should be limited at 40°C and 60°C. Lee (2007) preliminarily investigated the effects of steam and microwave curing on the strength development of concrete. The test results indicated that microwave heating could further increase the early strength of concrete, but did not increase the concrete deterioration that is related to the steam-cured concrete.

4.2 Multi mode system using a continuous microwave belt processor

Mak *et al.* (1997; 1998) indicated that the microwave accelerated processing (MPA) is an efficient heating technique for accelerating the early age curing of concrete with various potential applications in the concrete industry such as precast operations. They also discussed some of the requirements for production efficiency and product performance of precast concrete and described the temperature distribution and moisture content within concrete slab elements subjected to microwave heating. Mak *et al.* (1999) discussed the impact of heat curing on the performance of a selected range of structural concrete for bridge construction by focusing on the thermal response of supplementary cementitious materials, early age strength development, durability, creep, and shrinkage. Mak *et al.* (2001) showed the results for the same bulk heating rates. Microwave heating produces significantly lower temperature gradients when compared to steam heating. Using rapid curing cycles of less than six hours, compressive strengths in excess of 25 MPa can be achieved in high-quality precast concrete. Doubling the bulk heating rate using microwaves does not result in any deterioration of the near-surface quality as was the case with conventional steam heating. In 2002, they also showed that microwave curing cycles of less than six hours can provide sufficient strength for formwork removal and prestressing without impairing concrete quality. Rattanadecho *et al.* (2008) used a continuous microwave thermal processor to develop the compressive strength of cement paste. In this study, the acceleration of cement paste curing with microwave energy by using continuous belt drier is investigated. The microwave power was generated by means of 14 compressed air-cooled magnetrons of 800 Watts each for a maximum of 11.2 kW as shown in Figure 14. The power setting could be adjusted individually in 800 Watts steps. The test results showed that microwave energy accelerated the early-aged compressive strength of cement paste and did not have an effect upon later-aged strength.

5. Further research and development

Many previous researchers concentrated on microwave curing as shown in the above summary. However, some essential points that indicate the performance of the microwave heating method are not taken deeply into account. Therefore, in this part some essential points for future research are proposed as follows:

5.1 The first point is the time dependent dielectric properties and thermal properties of concrete on microwave heating mechanisms. The dielectric property is a primary factor for determining the performance of microwave energy interacting to the dielectric material to be processed. With regarding to microwave heating mechanism, the performance ways in which physical processes in a given concrete can effect the wave electric field are depended and can be described through the complex permittivity ($\varepsilon^* = \varepsilon' - \bar{j}\varepsilon''$). However, when the temperature within the concrete is elevated by microwave energy the dielectric properties are

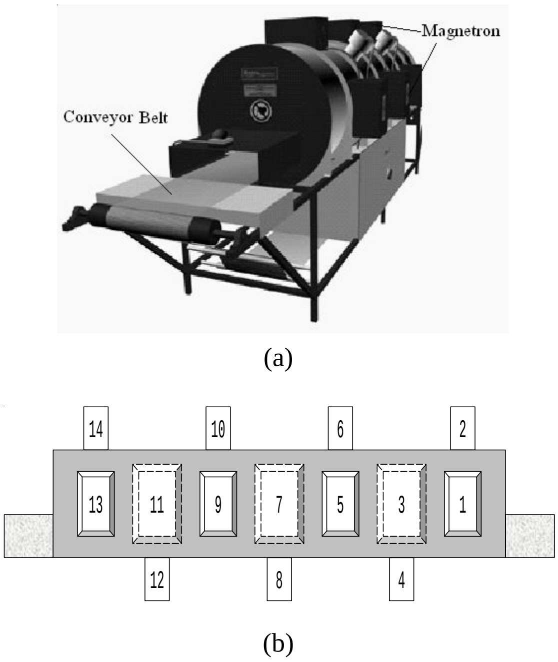


Figure 14. (a) Continuous microwave belt drier for drying tableware product, (b) Location of magnetrons (Rattanadecho *et al.*, 2008).

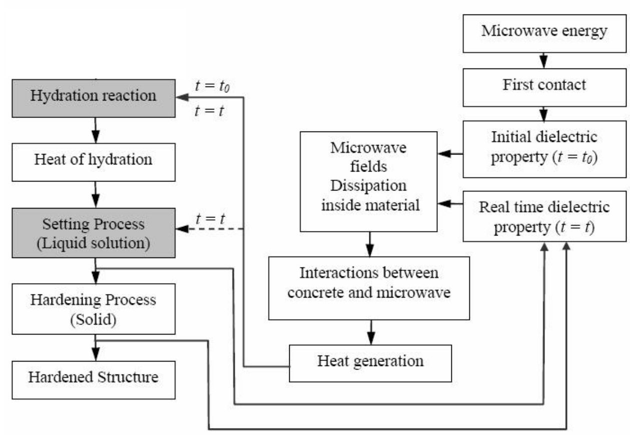


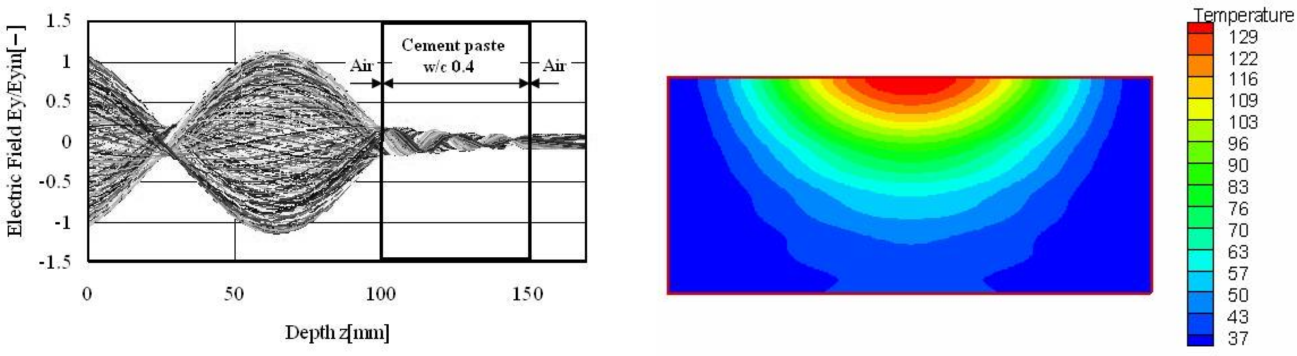
Figure 15. Effect of time dependent dielectric properties on hydration reaction.

changed simultaneously, which affects reversely instantaneously the interaction of microwave and concrete as shown in Figure 15.

5.2 The second point is the heat and mass transfer mechanisms within the heated concrete during curing by microwave energy. A number of works have been proved noticeably that generating and transporting of heat and mass within the heated concrete material are key factors indicating microwave energy efficiency. This is due to its inherent mechanism of the energy that generates heat inside out as volumetrically. However, the assumptions define that no chemical reactions occur within the concrete, but it is not. The hydration and pozzolanic reactions take place in nature. Therefore, the difficulty of this task, maybe a defined point of microwave-cured development, is when and how to apply microwave energy in a suitable process corresponding to the cement reaction.

5.3 The fourth point is the numerical tools to predict heat and mass transfer during heating by microwave energy. In almost all case studies in microwave energy, numerous models are developed covering various aspects such as the work of Ratanadecho (2008). He used a three dimensional Finite Difference Time Domain (FDTD) scheme to determine the electromagnetic fields (TE_{10}-mode) and the absorbed power by solving the transient Maxwell's equations taking place in microwave with a rectangular waveguide (Figure 16(a)). Further he evaluated the variations of temperature with heating time (Figure 16(b)) at different frequencies and sample sizes of the cement paste with the water-to-cement ratio (w/c) by weight of 0.4. The developed model is an example for efficient computational prototyping.

5.4 The last point here is the characterization of single-mode and multi-mode applicators of microwave system associating with multi-feed hot air system on heating mechanisms of concrete (Figure 17). In the use of microwave energy to concrete, the compatibility of microwave heating mechanisms and suitable equipments and systems should be considered. In other words, these components should be closely compatible to the concrete material to be processed. Heating mechanisms taking place inside a multi mode cavity are somewhat more complicated than that those mechanisms that occur in a single mode one. However, the microwave



(a) (b)

Figure 16. (a) The electric field distribution (b) and temperature distribution (°C) at a heating time for 20 seconds (Ratanadecho, 2008).

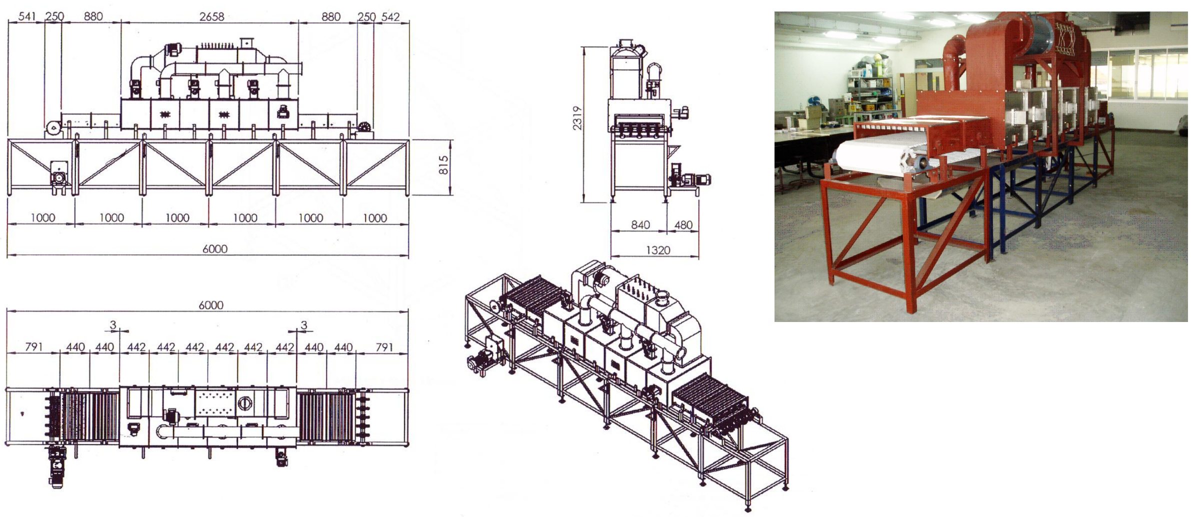


Figure 17. A combined multi feed microwave-hot air heating with continuous belt system (multi mode applicator).

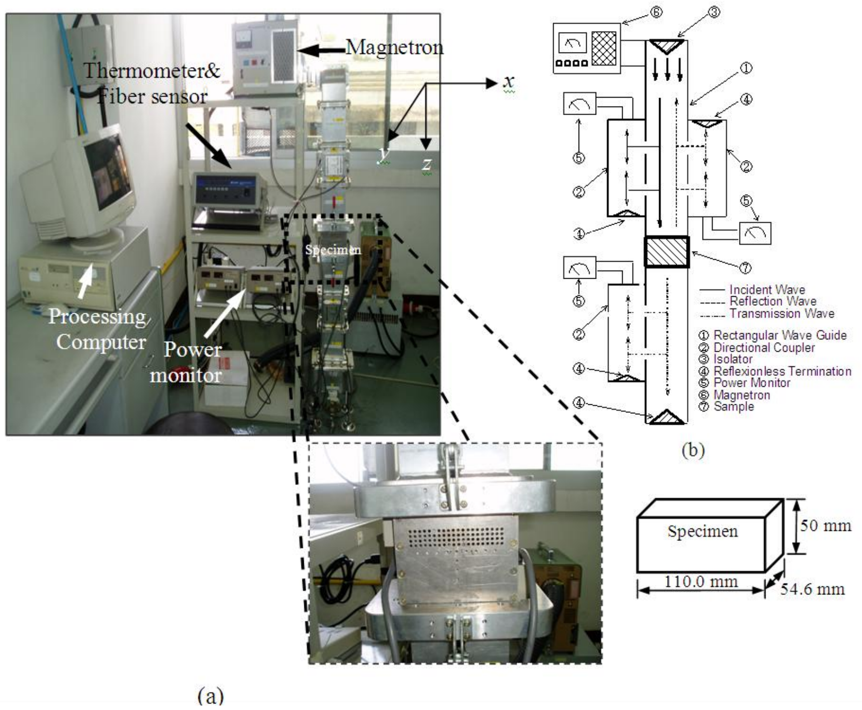


Figure 18. A microwave heating system with a rectangular wave-guide (single mode applicator).

systems with multi mode are generally used in the industry. The way to solve this problem is to extrapolate the results of a single mode (Figure 18) and hen from there to predict the phenomena that occur in a multi mode cavity as good as possible.

6. Conclusions and outlook

The current trends in clean energy parallel with a more sustainable development and more environmental friendly processes microwave energy (MW) is becoming a more popular energy source for heating and drying in various industrial applications. However, this application has been grown only gradually due to a lack of basic knowledge and due to serious concerns regarding radiation safety and hazards of microwave heating to biological tissue. Thus, these issues together with the societechnical questioning of this method need to be clarified,

Still, in the future, there will be applications requiring industrial scale instead of the conventional curing methods. Therefore further research is needed, especially regarding the time dependent dielectric properties and thermal properties. Further issues are the compatibility of mixed concretes and curing conditions, heat and mass transfer mechanisms, and numerical tools to predict heat and mass transfer during heating by microwave energy.

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