TEMPERATURE AND PORE PRESSURE DISTRIBUTION IN A CONCRETE SLAB DURING THE MICROWAVE DECONTAMINATION PROCESS

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10th Int. Heat Transfer Conf.
Brighton, England

August 14-18, 1994

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5. **Li, W., Ebadian, M. A., White, T. L., Grubb, R. G., and Foster, D.**
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During the Microwave Decontamination Process"**
10th Int. Heat Transfer Conf., Brighton, England, August 14-18, 1994.

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ABSTRACT

As an application of microwave engineering, the new technology of concrete decontamination and decommissioning using microwave energy has been recently developed. The temperature and pore pressure within the concrete are studied theoretically in this paper. The heat and mass transfer within the porous concrete, coupled with temperature dependent dielectric property are investigated. The effects of microwave frequency (f), microwave power intensity ($Q_{0,\text{mic}}$), concrete porosity (ϕ) on the temperature and pore pressure distributions and their variations are fully discussed. The effects of the variation of complex dielectric permittivity (ϵ^*) and presentation of different steel reinforcements are also illustrated.

1. INTRODUCTION

The use of microwaves as a source of thermal energy is growing rapidly. The food industry is the largest consumer of microwave energy. Some successful applications are for the thawing of frozen meat, cooking bacon, and drying pasta. Microwaves are also widely used in the vulcanization of rubber (Copson, 1975) and ceramic processing for drying and sintering (Bruce, 1988). Microwave technology is also employed in the drying of paper, forest products and textiles. More recently, microwave energy has been applied to the decontamination of concrete. Several groups in Japan, Yasunaka et al. (1987), in Europe, Hills (1989), and in the United States, White (1992), Li et al. (1993a), have begun developing new processes that use microwave energy for thermally treating radioactive wastes.

To model the transient temperature distributions, the dissipated electric energy is deduced by solving Maxwell's equations and is then incorporated as a source term in the transient energy equation. In several computational studies of microwave heating, the heat dissipation within foods has been modeled by Lambert's law, in which the microwave power is attenuated exponentially as a function of the distance of penetration into the sample (Data, 1990). Lambert's law is valid for semi-infinite samples and has been used to predict temperature profiles during microwave heating (Wei et al. 1985). Ayappa et al. (1990) showed that Lambert's law fails for samples thinner than three times the characteristic penetration depth of the microwave. Li et al. (1993a) illustrated a standing wave solution of the electromagnetic field for a multi-layer concrete slab in which a steel reinforcement layer was also considered. The assumption of constant dielectric and thermal properties results in a linear problem, decoupling the wave propagation from the accompanying heat transfer.

As recently measured by Ebadian and Li (1992), the dielectric properties of concrete are also very sensitive to temperature. Therefore, the nonlinear electromagnetic field must be coupled with the heat transfer process. To describe the dynamic phenomena occurring in heated porous materials, Wei et al. (1985) derived equations for the different materials having a simple model of microwave heating according to Lambert's law.

In the current paper, the temperature-dependent dielectric properties within the porous concrete are considered. The concrete dielectric properties measured by Ebadian and Li (1992) were employed. Based on porous concrete model with temperature-dependent dielectric properties, the effect of microwave frequency (f) on the temperature and pore pressure distributions is discussed. The effects of concrete porosity (ϕ) on the maximum temperature and pressure are examined. The difference between constant and temperature-dependent dielectric property models is also illustrated. Finally, the effect of presence of different steel reinforcements on the temperature and pressure distributions is also investigated.

2. ELECTROMAGNETIC FIELD

The concentration of ferromagnetic material in concrete is negligible. Hence, the value of concrete permeability (μ_{con}) can be assumed to be equal to the value of the air (μ_{air}), which is a constant not influenced by temperature and frequency. The measurement of the variation of complex concrete dielectric permittivity with temperature has been conducted by Ebadian and Li (1992), and is employed in the current analysis.

2.1 Maxwell's Equations

During the decontamination process, the front surface of a concrete slab ($z=0$) is directly exposed to the microwave source, and the steel reinforcement mesh is located at a distance (L_s) from the front surface of the concrete slab with a total length (L), Fig. 1. The steel reinforcement within the concrete is treated as an infinite thin layer, and has no dielectric loss ($\epsilon''_{\text{steel}}=0$), $\mu_s=\mu_{\text{air}}$, and has a certain dielectric constant, ϵ'_s . The layer thickness (δ) is very small and is totally neglected in the heat and mass transfer. The fraction of reflection caused by the steel reinforcement (β) is assumed to be equal to a fraction of the cross-sectional area of the concrete taken up by the steel mesh (Li et al., 1993b). The concrete slab is further divided into N subdivisions. It is assumed that the concrete dielectric permittivity, $\epsilon^*(\epsilon'-j\epsilon''_{\text{eff}})$, is uniform in each small subdivision, and is a function of the local temperature and the microwave frequency only.

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Fig. 1. Geometry of the concrete slab.

The governing equation for the electromagnetic fields in the i -th ($i=0, \dots, N+1$) subdivision can be simplified as follows for the time harmonic plane microwave (Johnk, 1988):

$$\frac{dE_z^i}{dz} = -j\omega\mu H_y^i \quad (1)$$

$$\frac{dH_y^i}{dz} = -j\omega\epsilon_i E_z^i \quad (2)$$

with the general solution, as:

$$E_z^i = E_0^+ (E_1^+ e^{-\gamma_i z} + E_1^- e^{\gamma_i z}) \quad (3)$$

$$H_y^i = \frac{E_0^+}{\eta_i} (E_1^+ e^{-\gamma_i z} - E_1^- e^{\gamma_i z}) \quad (4)$$

in which

$$\gamma_i = j\omega\sqrt{\mu_i\epsilon_i} \quad \text{and} \quad \eta_i = \sqrt{\mu_i/\epsilon_i} \quad (5)$$

where E_z and H_y are the electric and magnetic field potential, and μ_i and ϵ_i are the magnetic permeability and complex dielectric permittivity at the i -th division of the concrete, respectively. E_1^+ and E_1^- are the unknown constants to be determined by the boundary conditions.

2.2 Presence of the Steel Reinforcement

When the infinitely thin reinforcement layer is located between s - and $(s+1)$ -th division, the energy reflection ratio, $|\Gamma_s(z_s)|^2$ has the following relation as, Li et al. (1993b):

$$|\Gamma_s(z_s)|^2 = \left| \frac{Z_s - \eta_s}{Z_s + \eta_s} \right|^2 = \beta + (1-\beta) \left| \frac{Z_s - \eta_s}{Z_s + \eta_s} \right|^2 \quad (6)$$

where

$$\Gamma_s = \frac{E_1^-}{E_1^+} e^{2\gamma_s z_s} \quad \text{and} \quad Z_s(z) = \frac{E_z^i}{H_y^i} = \eta_i \frac{1 + \Gamma_s(z)}{1 - \Gamma_s(z)} \quad (7)$$

All E_1^+ and E_1^- can be solved as $E_0^+=1$ and $E_{N+1}=0$.

2.3 Microwave Power Dissipation

The microwave power dissipation per unit volume is evaluated by:

$$Q_{d,ave}^i = \frac{1}{2} (\omega \epsilon''_{eff}) |E_z^i|^2 \quad (8)$$

It should be noted that the time averaged microwave power dissipation ($Q_{d,ave}^i$) in the i -th subdivision is proportional to the imaginary part of the concrete complex dielectric permittivity (ϵ''_{eff}) and the square of the norm of the complex electric potential (E_z^i), while both are strongly dependent on the temperature.

3. TEMPERATURE AND PRESSURE

Concrete is basically a mixture of cement and aggregate, both of which are porous. In addition, the concrete as a whole contains voids caused by incomplete compaction and cement bleeding. These voids may occupy from a fraction up to 20% of the whole volume of the concrete. According to studies of the properties of concrete, as summarized by Neville (1981), the hydro-permeability of concrete is of the order, 7×10^{-16} m/s, and the total surface area per unit of concrete volume is of the order, 4×10^8 m². In the concrete decontamination and decommissioning process, the concrete spalling-off time is on the order of one minute. Therefore, movement of liquid, vapor, and air through the concrete is very slow. In the meantime, all phases within the concrete have a sufficiently large area to achieve equilibrium. Thus, it is reasonable to assume that the local thermal equilibrium between all phases (liquid, vapor, air, and the solid concrete matrix) is achieved instantaneously.

3.1 Governing Equations

By conservation of mass, momentum, and energy in a porous medium, the governing equations of mass, momentum, and energy for the solid (0), liquid (1), vapor (2), and air (3) phases can be derived by using a volume (local) average technique [cf. Kaviany (1991)]:

Mass Conservation:

$$\phi \frac{\partial}{\partial t} (S_1 \rho_1) + \Delta m = 0 \quad (9)$$

$$\phi \frac{\partial}{\partial t} [(1-S_1) \rho_2] - \Delta m = 0 \quad (10)$$

$$\frac{\partial}{\partial t} [(1-S_1) \rho_3] = 0 \quad (11)$$

Momentum Conservation:

$$V_i = 0, \quad i=1, 2, 3 \quad (12)$$

Energy Conservation:

$$(\rho C_p)_0 \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(k_{eff} \frac{\partial T}{\partial z} \right) \quad (13)$$

$$+ Q_{d,ave}(T, z) - \Delta m \Delta h_v + \frac{\partial P_1}{\partial t},$$

where

$$(\rho C_p)_0 = (1-\phi) \rho_0 C_{p,0} + \phi \sum_{i=1}^3 S_i \rho_i C_{p,i} \quad (14)$$

$$k_{eff} = (1-\phi) k_0 + \phi \sum_{i=1}^3 S_i k_i \quad (15)$$

$$S_2 = S_3 = 1 - S_1 \quad (16)$$

Since $(1-\phi) \rho_0 C_{p,0}$ is dominant in $(\rho C_p)_0$, the variations resulting from the changes of S_1 and ρ_1 are insignificant. Therefore, the initial value of $(\rho C_p)_0$ is used in the calculation. Similar to $(\rho C_p)_0$, the initial value of k_{eff} is also used during the calculation.

Constitutive State Equations:

Without considering the capillary pressure, the pressures have the following relation among three phases within the concrete:

$$P = P_1 = P_2 = P_3 \quad (17)$$

Although the hydro-permeability is very low, it might also be initially assumed that the vapor pressure (P_v) within the concrete is a function

of the relative humidity around the concrete, which has the following relationship:

$$P_2 = \omega P_{sat} \quad (18)$$

where ω is the relative humidity around the concrete. For simplicity, saturated vapor ($\omega = 1$) was used in the analysis. The residual water continuously evaporates in the concrete when subjected to microwave heating. A fraction of the vapor phase is then almost dominant in the air-vapor mixture. Therefore, it is assumed that the vapor pressure equals the saturation pressure of the vapor, i.e., $P_2 = P_{sat}(T)$ throughout the entire process.

Precisely, the governing equations have four differential equations with three state equations and two pressure relations, which are non-linear parabolic partial differential equations. It is estimated that the maximum value of dP_1/dT is only 1.7% of the value of $(\rho C_p)_0$ within the temperature range of 25 to 250°C. Therefore, it is quite reasonable to neglect the term $(\partial P_1/\partial t)$.

3.2 Initial and Boundary Conditions

Knowing the initial condition of all densities (ρ_i), the liquid volume saturation (S_l), and temperature (T) are required to solve the governing equations. The initial conditions are:

$$P_1 = P_{1,0}, P_2 = P_{2,0}, \rho_1 = \rho_{1,0}, S_l = S_{l,0} \quad (19)$$

$$T = T_0 \text{ and } P_1 = P_{1,0} \text{ at } t=0,$$

where $P_{1,0}$ is the atmospheric pressure (101.3 kPa). All initial conditions should also satisfy the state equations.

Assuming constant wall temperatures are specified at both the front and back surfaces of the concrete, one can then clarify the following boundary conditions:

$$T = T_w \text{ at } z=0, L \quad (20)$$

Fig. 2 Variations of temperature distribution within the concrete slab for $\phi=0.1$ and $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$. (a) For $f=0.896 \text{ GHz}$; (b) For $f=2.45 \text{ GHz}$; (c) For $f=10.6 \text{ GHz}$; (d) For $f=18.0 \text{ GHz}$.

4. RESULTS AND DISCUSSION

In this section, the results of variations of the temperature distribution within a 0.6 m thick concrete slab are analyzed. The composition and the thermal properties of the concrete used in the analysis are listed in Table 1. In the present discussion, four commonly used frequencies, 0.896, 2.45, 10.6, and 18.0 GHz are utilized.

TABLE 1
Values of the Ordinary Concrete Properties

$\rho \text{ [kg/m}^3\text{]}$	$C_p \text{ [J/kg.K]}$	$k \text{ [W/m.K]}$	$\sigma_t \text{ [Mpa]}$
2,300	650	0.87	3.5-4.0

4.1 Effect of Frequency (f)

For a certain power intensity ($Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$), temperature and pressure distributions for four microwave frequencies (0.896, 2.45, 10.6 and 18.0 GHz) are plotted in Figs. 2 and 3. Figures 2 (a) and (b) show the temperature distribution and its variation for frequencies of 0.896 GHz and 2.45 GHz. The peaks of the temperature distribution decay slowly along the wave propagation direction (z). As seen in Figs. 2 (c) and (d), only one peak appears on the temperature distribution for the $f=10.6 \text{ GHz}$ or higher. Figure 3 shows the same behavior for the pressure and its variation. Since pore pressure is not a linear function of temperature, the pressure distribution decays more abruptly than the temperature does. It is demonstrated in Fig. 3 that for $f=10.6 \text{ GHz}$ or higher, the pressure at a position deeper than 0.15 m ($z/L=0.2$) does not change too much compared to the initial pressure (0.1013 MPa).

Fig. 3 Variations of pore pressure distribution within the concrete slab for $\phi=0.1$ and $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$. (a) For $f=0.896 \text{ GHz}$; (b) For $f=2.45 \text{ GHz}$; (c) For $f=10.6 \text{ GHz}$; (d) For $f=18.0 \text{ GHz}$.

4.2 Effect of Concrete Porosity (ϕ)

The effects of concrete porosity (ϕ) on the maximum temperature and pressure with different heating times are listed in Table 2. In this table, $\phi=0.0$ refers to the solid concrete conduction model results calculated by Li et al. (1993a). Only the maximum temperature is given in this column since pore pressure is not defined within the solid concrete. It is seen from the table that as porosity increases, the maximum temperature decreases slightly. For a higher porosity value, there is more void space and more liquid phase within the concrete. Generally, during the heating process, more liquid will be evaporated, which requires more energy to raise the temperature of the solid. Table 2 shows that as the concrete porosity varies from 0.0 to 0.3, the maximum temperature and pressure barely change for the same heating time and temperature range of 20 to 250°C, which corresponds to the steam pressure $P_1 \approx \sigma_1$, since only a small amount of microwave power dissipation is used to evaporate the liquid within the concrete.

4.3 Effect of Dielectric Permittivity (ϵ')

The temperature and pore pressure distributions and their variations within the concrete are dependent on the microwave power dissipation. In Figs. 4, Case 1 represents the temperature dependent dielectric permittivity while Case 2 presents the dielectric permittivity, which assumes that the dielectric permittivity equals to the value measured at 25°C.

At low frequencies ($f < 2.45 \text{ GHz}$), as the dielectric permittivity varies with temperature, the temperature distribution due to the variation of ϵ' (Case 1) is significantly higher than that of constant ϵ' (Case 2). The variation of the power dissipation due to the variation of the dielectric permittivity initiates a greater rise in temperature, Fig. 4(a). For the higher microwave frequencies, the microwave penetration becomes smaller regardless of how the dielectric permittivity changes. Except for the energy reflected from

the front surface of the concrete, all microwave energy is absorbed in a distance less than 10 cm from the front surface for $f=10.6 \text{ GHz}$ and less than 5 cm for $f=18.0 \text{ GHz}$, Fig. 4(b). Corresponding to the temperature distributions, the pore pressure distributions for low frequencies ($f \leq 2.45 \text{ GHz}$) ascend to a higher level, Figs. 4(c). When

TABLE 2
Effect of Porosity (ϕ) on T_{max} (°C)
and P_{max} (MPa) at $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$

$f=2.45 \text{ GHz}$				
$t \text{ (s)}$	T_{max} $\phi=0.0$	T_{max}/P_{max} $\phi=0.1$	T_{max}/P_{max} $\phi=0.2$	T_{max}/P_{max} $\phi=0.3$
5.0	45.81	45.81/0.12	45.80/0.12	45.80/0.12
10.0	71.23	71.21/0.16	71.19/0.17	71.15/0.17
15.0	96.35	96.31/0.22	96.27/0.22	96.21/0.22
20.0	121.23	121.18/0.36	121.07/0.36	120.92/0.36
25.0	145.91	145.75/0.59	145.60/0.59	145.45/0.59
30.0	170.42	170.16/0.98	169.90/0.97	169.64/0.97
35.0	194.80	194.37/1.59	193.95/1.57	193.53/1.56
40.0	219.05	218.38/2.48	217.73/2.45	217.09/2.42
45.0	243.18	242.16/3.74	241.17/3.68	240.21/3.62
$f=10.6 \text{ GHz}$				
5.0	117.74	117.67/0.33	117.60/0.33	117.53/0.33
10.0	209.38	208.84/2.08	208.31/2.06	207.80/2.04
15.0	297.50	294.83/8.35	292.42/8.07	290.22/7.83

cf. Li et al. (1993a).

Fig. 4 Effect of temperature-dependent dielectric permittivity (ϵ') on temperature and pressure distributions for $\beta=0.1$ and $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$. (a) Temperature, $f=2.45 \text{ GHz}$; (b) Temperature, $f=10.6 \text{ GHz}$; (c) Pressure, $f=2.45 \text{ GHz}$; (d) Pressure, $f=10.6 \text{ GHz}$.

Fig. 5 Variation of the temperature and pressure distributions with and without the steel reinforcement located at $L_s=0.1 \text{ m}$ for different values of β when $f=2.45 \text{ GHz}$ and $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$. (a) Temperature at $t=45 \text{ sec}$; (b) Pressure distribution at $t=45 \text{ sec}$.

the heating time increases, the pressures for Case 1 become greater than that for Case 2. For higher frequencies ($f \geq 10.6 \text{ GHz}$), the pressure distributions for both cases are almost identical, since the temperatures do not differ significantly, Fig. 4(d).

4.4 Presentation of Steel Reinforcement

The temperature distribution for $f=2.45 \text{ GHz}$, $Q_{0,ave}=2.4 \times 10^6 \text{ W/m}^2$, $L_s=0.1 \text{ m}$ and different values of β at $t=45 \text{ sec}$ is plotted in Fig. 5(a). The corresponding pressure distribution is plotted in Fig. 5(b). Without steel reinforcement ($\beta=0$), the temperature oscillates almost uniformly along the propagation direction. When different reinforcements are presented, the temperature and pressure oscillations become more and more evident as the value of β increases. This indicates that with the presence of the reinforcement, the

spalling-off time (t_s) decreases as the value of β increases. In addition to a rise in the maximum temperature, the locations of this maximum temperature also shift deeper into the concrete. The deeper maximum temperature will cause more concrete to be removed. For $f \geq 2.45 \text{ GHz}$, the temperature and the pressure distributions, with and without steel reinforcements, are almost identical since the microwave penetration distance becomes shorter.

CONCLUDING REMARKS

A one-dimensional heat and mass transfer model coupled with temperature dependent dielectric property is developed in the current analysis. The microwave frequency (f), concrete porosity (ϕ) and

different steel reinforcement are all considered. The following conclusions are made based on the results and discussion.

1. For the microwave frequency lower than 2.45 GHz ($f \leq 2.45$ GHz), the temperature and pore pressure distributions display the wavy behavior. The peak temperature and pressure decay slowly along the wave propagation direction, while for the microwave frequency higher than 10.6 GHz ($f \geq 10.6$ GHz), only one sharp peak of temperature and pressure is formed accordingly during the microwave heating process.
2. The effect of concrete porosity (ϕ) ranging from 0.0 to 0.3 can be neglected for the microwave power intensity from 6.0×10^5 to 6.0×10^6 W/m².
3. As ϵ^* increases with temperature, the temperature and pressure distributions for a low frequency ($f < 2.45$ GHz) change vitally. The effect of the variation of the concrete dielectric properties with temperature should be considered for a low frequency ($f < 2.45$ GHz).
4. When the reinforcement is present, the maximum temperature and pressure ($T_{\max}$ and $P_{\max}$) rise significantly as the value of β increases. The concrete spalling-off time (t_s) steadily decreases as the value of β increases for a microwave frequency of 2.45 GHz. For a microwave frequency of 10.6 GHz or higher, the concrete spalling-off time (t_s) is nearly constant for $L_s = 0.1$ m.

ACKNOWLEDGMENT

The results presented in this paper were obtained in the course of research sponsored by the Department of Energy under Subcontract No. 19X-SK164V

REFERENCES

- Ayappa, K. G., Davis, H. T., Davis, E. A. and Gordon, J., 1990, Analysis of Microwave Heating of Materials With Temperature-Dependent Properties, *AIChE J.*, vol. 37, pp. 313-322.
- Bruce, R. W., 1988, New frontiers in the use of microwave energy: power and metrology, *Microwave Processing of Materials*, Ed., Sutton, W. H., Brooks, M. H. and Chabinsky, I. J., Materials Research Society, Pittsburgh, Pennsylvania.
- Copson, D. A., 1975, *Microwave Heating*, 2nd ed., AVI Publishing, Westport, Connecticut.
- Data, A. K., 1990, Heat and Mass Transfer in Microwave Processing of Food, *Chem. Eng. Prog.*, vol. 6, p.47.
- Ebadian, M. A. and Li, W., 1992, A Theoretical/Experimental Investigation of the Decontamination of a Radioactively Contaminated Concrete Surface Using Microwave Technology, *Final Report*, DOE Project (DE-AC05-84OR2140), 1992.
- Hills, D. L., 1989, The Removal of Concrete Layers from Biological Shields by Microwave, *EUR 12185, Nuclear Science and Technology*, Commission of the European Communities.
- Johnk, C. T. A., 1988, *Engineering Electromagnetic Fields and Waves*, 2nd ed., John Wiley, New York.
- Kaviany, M., 1991, *Principles of Heat Transfer in Porous Media*, Springer-Verlag, New York.
- Li, W., Ebadian, M. A., White, T. L., Grubb, R. G., 1993a, Heat Transfer Within a Radioactive Contaminated Concrete Slab Applying a Microwave Heating Technique, *ASME Transactions, Journal of Heat Transfer*, vol. 115, p.42.
- Li, W., Ebadian, M. A., White, T. L., Grubb, R. G. and Foster, D., 1993b, "Effect of Steel Reinforcement on Heat and Mass Transfer in a Contaminated Porous Concrete," *Heat Transfer in Porous Media*, HTD-Vol. 240, pp. 1-10, 1993 National Heat Transfer Conference.
- Neville, A. M., 1981, *Properties of Concrete*, 3rd ed., Pitman, Massachusetts.

Wei, C. K., Davis, H. T., Davis, E. A., and Gordon, J., 1985, Heat and Mass Transfer in Water-Laden Sandstone: Microwave Heating, *AIChE J.*, vol. 31, 5, p.842.

White, T. L., Grubb, R. G., Pugh, L. P., Foster, D., Jr. and Box, W. D., March 1992, Removal of Contaminated Concrete Surfaces by Microwave Heating - Phase I Results, Presented at the 18th American Nuclear Society Symposium on Waste Management, Waste Management 92, Tucson, Arizona.

Yasunaka, H., Shibamoto, M., and Sukagawa, T., 1987, Microwave Decontaminator for Concrete Surface Decontamination in JPDR, *Proceedings of the Int. Decommissioning Symposium*, p. 109.

NOMENCLATURE

C_p	specific heat of the concrete [J kg ⁻¹ K ⁻¹]
E_0	wave amplitude of the initial electric field [V m ⁻¹]
E_x	electric field [V m ⁻¹]
E^* , E'	complex constants, Eqs. (3) and (4)
f	microwave frequency [s ⁻¹] [Hz]
H_y	magnetic field [A m ⁻¹]
j	imaginary number, $\sqrt{-1}$
k_{eff}	effective thermal conductivity [W K ⁻¹ m ⁻¹]
L	thickness of the concrete [m]
L_s	location of steel reinforcement mesh [m]
N	number of divisions in the numerical calculation
P	pressure [Pa]
Q_d	microwave power dissipation [W m ⁻³]
Q_0	microwave power intensity [W m ⁻²]
r	propagation constant, Eq. (5), [m ⁻¹]
S	volume saturation
T	temperature [°C]
T_{∞}	ambient temperature [°C]
t	time [s]
V	migration velocity vector [m s ⁻¹]
x, y, z	coordinates [m]
Z	field independence, Eq. (5)

Greek Symbols

β	energy reflection due to steel reinforcement
Γ	reflection coefficient, Eq. (7)
Δh_v	water latent heat [J kg ⁻¹]
Δm	evaporation rate [kg s ⁻¹ m ⁻³]
δ	thickness of the steel reinforcement layer [m]
ϵ_{air}	dielectric permittivity of air, 8.86×10^{-12} [F m ⁻¹]
ϵ'	real part of the complex dielectric permittivity, or dielectric constant [F m ⁻¹]
ϵ''_{eff}	effective dielectric loss [F m ⁻¹]
ϵ^*	complex dielectric permittivity, $\epsilon' - j\epsilon''_{\text{eff}}$ [F m ⁻¹]
η	intrinsic impedance, Eq. (5) [ohms]
μ	magnetic permeability [Henries m ⁻¹]
μ_{air}	magnetic permeability of air, $4\pi \times 10^{-7}$ [Henries m ⁻¹]
ρ	density [kg m ⁻³]
σ_c	tensile strength of the concrete [Pa]
ϕ	concrete porosity
ω	angle frequency, $2\pi f$ [rad s ⁻¹]
ω	relative humidity

Subscript

ave	time average
i	value at the i th node
s	spalling off or steel reinforcement condition
0	initial condition at $t=0$, or the solid phase
1	liquid phase
2	vapor phase
3	air phase