Analysis of Decontamination from Concrete by Microwave Power

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ABSTRACT

The paper analyzes a scheme of decontamination of radionuclides from concrete structures, in which rapid microwave heating is used to spall off a thin contaminated surface layer. The analysis is split in two parts: (1) The hygrothermal part of the problem, which consists in calculating the evolution of the temperature and pore pressure fields, and (2) the fracturing part, which consists in predicting the stresses, deformations and fracturing. The rate of the distributed source of heat due to microwaves in concrete is calculated on the basis of the standing wave normally incident to the concrete wall with averaging over both the time period and the wavelength because of the very short time period of microwaves compared to the period of temperature waves and the heterogeneity of concrete. The reinforcing bars parallel to the surface are treated as a smeared steel layer. The microplane model M4 is used as the constitutive model for nonlinear deformation and distributed fracturing of concrete. The aim of this study is to determine the required microwave power and predict whether and when the contaminated surface layer of concrete spalls off. The effects of wall thickness, reinforcing bars, microwave frequencies and power are studied numerically. As a byproduct of this analysis, the mechanism of spalling of rapidly heated concrete is clarified.

1. Introduction

Concrete is ubiquitous in nuclear facilities. As a consequence their longtime operation, various radionuclides, such as Strontium, Cesium, Cobalt, Uranium, etc., have gradually diffused into a surface layer of concrete. Although the radionuclide concentrations are very small, the exposure to radiation over many years could be hazardous to human health. Typically, the contaminated layer is only 1 to 10 mm thick (Fig. 1) and so a demolition of the whole structures is unnecessary. Nevertheless, to guarantee safe long-time work environment, the contaminated layer needs to be removed and properly disposed of as nuclear waste.

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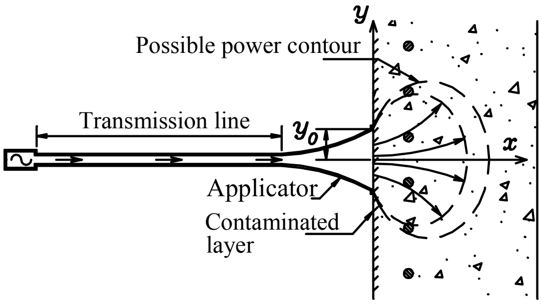


Fig. 1: Sketch of microwave power decontamination system.

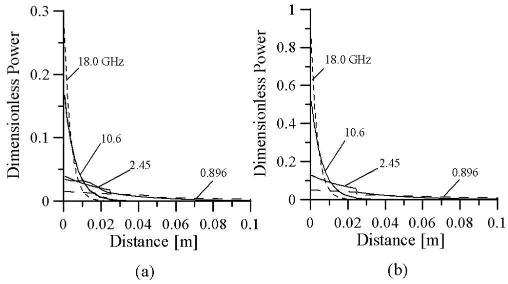


Fig. 2: Examples of volumetric heat generations with (a) the full reflection at the surface of the concrete wall and (b) no reflection. Here, reinforcing bars are located 2.5 cm under the surface to which waves are incident

Although there are several alternatives to decontaminate the concrete walls, this paper deals with the recently developed technique with heating generated by microwaves. This new technique allows a much faster removal of the contaminated layer (within only about 10 sec; [1]). Some studys of the microwave decontamination of concrete have already been undertaken [2,3]. However, they could not study the development of pore pressures because they did not model the moisture transfer coupled to the heat transfer. They assumed the surface layer to spall off when the compressive stress in the direction parallel to surface under a perfect restraint in that direction exhausts the compressive strength of the concrete. They did not take into account the deformation of the body surrounding the heated zone.

2. Heat generation by microwaves

The energy carried by electromagnetic waves through surface S (see the power contour in Fig. 1) is

$$-\int_S \mathbf{P}\cdot d\mathbf{S}=\frac{\partial}{\partial t}\int_V (w_e+w_m)\,dV+\int_V p_\sigma\,dV \tag{1}$$

where $\mathbf{P}$=Poynting vector, characterizing the power density of an electromagnetic wave, w_e=electric energy density, w_m=magnetic energy density, p_σ=Ohmic power dissipation, t=time, S=surface and V=volume. Because the heat generation rate is a function of the electric field strength, one needs to solve the electric field strength vector $\mathbf{E}$ to obtain the heat source. For our purpose, however, an approximate solution can be obtained by using the solution of standing electromagnetic wave, particularly the solution of a transverse electromagnetic waves normally incident to a half space of a dielectric material, the concrete. Two more simplifications can be introduced: (1) Because the wave period is far shorter than the time that the thermal heat front takes to advance through one wavelength of the electromagnetic wave, it is meaningful to average the heat generation rate over the period. (2) Due to the heterogeneity of concrete wall, we may take the spatial average of the heat source over the wave number. For the detailed discussion, see [4-6]. The final form of the heat generation rate in concrete due to its exposition to microwave radiation is given by

$$I_{(h)} = \frac{1}{2}\sigma \| C \|^2 (e^{-2\alpha x} + \| R \|^2 e^{2\alpha x}) \tag{2}$$

where σ = dielectric conductivity, α = attenuation factor, C = transmission factor and R = reflection factor.

3. Coupled heat and moisture transfer

$$\frac{\partial w}{\partial t} + \nabla \cdot \boldsymbol{J} = I_{(w)} \tag{3}$$

$$\frac{\partial}{\partial t}\{(wC_w + \rho C)T\} + \nabla \cdot \boldsymbol{q} = I_{(h)} \tag{4}$$

where T = temperature, ρ = mass of concrete, C = specific heat of concrete, w = water content, C_w = specific heat of water, $\boldsymbol{J}$ = water flux vector, $\boldsymbol{q} = \boldsymbol{q}_{cd} + \boldsymbol{q}_{cv}$ = total heat flux vector, $\boldsymbol{q}_{cd}$ = conductive heat flux, $\boldsymbol{q}_{cv}$ = convective heat flux vector due to moisture transfer, $I_{(w)}$ = source of water due to release of chemically bound water and $\boldsymbol{q}$ = conductive heat flux vector.

The water content w depends on pore pressure p and temperature T. The water flux is given by the Darcy's law since the speed of moisture transfer is very slow; it is in the order of $\approx 10^{-12} m/s$. The permeability of concrete changes abruptly near $T = 100C$. The source of water comes from the hydration and the dehydration of concrete. For the detailed description of the model, refer to [4].

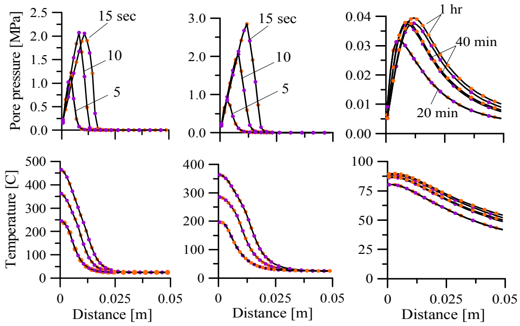
4. Mechanical model to simulte the fracturing process

To determine whether a given microwave source will achieve spalling and predict the depth of spalling and the time at which it occurs, a good constitutive model relating the stress and strain in concrete is needed. For this purpose, version M4 of the microplane model which is a powerful explicit model that yields the best fit a broad range of test data on nonlinear triaxial behavior, has been adopted [7,8].

5. Results of the analysis

5.1 Volumetric heat generation

The heat generations calculated by Eq. (2) for various frequencies are shown in Fig. 2. Electromagnetic waves are reflected in a place where the dielectric properties suddenly change like the surface of the concrete wall. The adjustment of the dielectric properties of the applicator (in Fig. 1) increases the heat generation almost 3 times greater than the case without the adjustment. As the frequency increases, the heat generation tends to concentrate to the concrete near the surface.



(a) (b) (c)

Fig. 3: The effects of frequencies, wall thicknesses and reinforcements: (a) $f = 18$ GHz, (b) 10.6 GHz with $P = 1.1$ MW/m^2, and (c) $f = 18$ GHz, (b) 10.6 GHz with $P = 1.1$ kW/m^2.

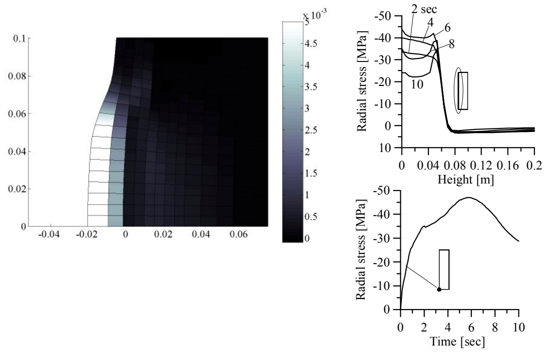


Fig. 4: The strain and stress contour of the concrete wall exposed to 10 sec microwave heating with $f = 18$ GHz and $P_0 = 1.1$ MW/m^2.

5.2 Effect of microwave frequencies and reinforcing Bars on Pore Pressures and Temperatures

To investigate the effect of the reinforcement to the efficiency of the decontamination process, the temperature and pore pressure profiles after 10 seconds of heating obtained in absence of steel bars (Fig. 3a) are compared to the profiles with reinforcing bars (Fig. 3b) for three different microwave frequencies after 10 sec heating. The area fraction of the steel bars (in a projection on the surface of the wall) is considered to be about 19%. The location of the bars is marked by the dashed lines in the figure. The center of the reinforcing bars in concrete structures is located typically in 2.5 to 4 cm below the surface. At that depth, the electromagnetic power is almost exhausted by the dissipation (Fig. 2). Therefore, it appears that the existence of steel bars is not important for the decontamination process. However, note that this argument is not true in general. It holds true only for the high-power decontamination process and the typical reinforced concrete structures. If much lower frequencies were used or conductive materials were located closer to the concrete surface, this effect could get important.

5.3 Stress Fields and the Triggering of Spalling

Fig. 4 depicts the contour plots of the computed strain field after 10 seconds of microwave heating; it shows the mechanical strain, i.e., the total strain minus the hygrothermal strain (strain produced by changes of temperature and water content). It is found that the maximum principal mechanical strain in the surface layer exceeds 0.005 in tension and the strain state is essentially biaxial. This strain value is much higher than the typical strain at peak in uniaxial tension (about 0.0002). So we must conclude that the concrete must suffer disintegration by cracking. The compressive stress induced by the temperature increase is resisted not only by radial compression in the cold concrete mass surrounding the heated zone but also by tensile stress in the circumferential direction of the axisymmetric mesh.

The maximum pore pressure for $f = 18.0$ GHz after 10 seconds of heating is $P_{max,10} = 2.0$ MPa at 7.5 mm below the surface. If this pore pressure acted on an unrestrained element of concrete, it would produce in concrete the tensile volumetric (hydrostatic) stress $\sigma_V \approx 0.1 \times 2.0 = 0.2\ \mathrm{MPa}$ where the value 0.1 is adopted for the typical porosity of concrete. Compared to the tensile strength of ordinary concrete, this stress is only about 5% of the tensile strength. The effect of pore pressure is in fact even weaker since the foregoing estimate is the maximum possible pore pressure if the additional pore space created by the formation of microcracks has been neglected. Taking it into account, a even smaller tensile volumetric stress in an unrestrained element of concrete would be indicated. So, although the effect of pore pressure is not completely negligible, it cannot be the main cause of spalling.

6. Conclusions

(1) The paper presents a mathematical formulation for analyzing a proposed technique of decontamination of concrete walls from radionuclides residing in a thin surface layer, which is to be spalled off by rapid microwave heating. The formulation consists of (1) a model for heat generation in the bulk of concrete by microwave power dissipation, (2) a model for heat and moisture transfer with build-up of pore pressure, and (3) a constitutive model for nonlinear triaxial behavior and fracturing of concrete.

(2) A simple analytical expression for the heat generation rate is developed. The heat generation caused by normally incident TEM waves is averaged both over both the frequency and the wavelength. The resulting formula agrees with the Lambert's law used in food engineering but the microwave power reflection by steel reinforcing bars is taken into account in it.

(3) The computations show that the power and efficiency of the microwave applicator is a key factor for the proposed decontamination process. For the maximum power efficiency considered, the heat generation per unit volume of the wall is almost 3-times greater than it is for zero efficiency.

(4) Calculations show that the thickness of the concrete wall has a negligible effect on the evolution of pore pressure and temperature. The reason is heating durations of the order of 10 seconds. For long heating durations, differences would of course be

obtained, due to microwave reflection and heat loss at the opposite surface.

(5) The electromagnetic power carried by the microwaves is almost exhausted when the waves reach the location of the reinforcing bars in typical concrete structures. Therefore, the same decontamination process can be used for both unreinforced and reinforced concrete walls.

(6) The pore water pressure caused by heating is not a major factor. The main cause of spalling are high compressive stresses along radial lines emanating from the heated zone and high tensile stresses along circumferential lines, produced by thermal expansion of the heated zone.

6. References

[1] T. L. White, D. Jr. Foster, C. T. Wilson, and C. R. Schaich, ORNL Report of contract DE-AC05-84OR21400, (1995).

[2] L. E. Lagos, W. Li, and M. A. Ebadian, Int. J. Heat & Mass Trans. 38 (1995, 887.

[3] W. Li, M. A. Ebadian, T. L. White, and R. G. Grubb, J. Heat Trans., ASME, 115 (1993) 42.

[4] G. Zi, Size effect of quasibrittle materials and simulation of concrete decontamination using microwave heating, Northwestern Univ. (2002).

[5] Z. P. Bazant, and G. Zi, J. Eng. Mech. ASCE. 129 (2003) 777.

[6] G. Zi, and Z. P. Bazant, J. Eng. Mech. ASCE. 129 (2003) 785.

[7] Z. P. Bazant, F. C. Caner, M. D. Adley, and S. A. Akers, J. Engrg Mech., ASCE, 126 (2000), 944

[8] F. C. Caner and Z. P. Bazant, J. Engrg Mech. Div., ASCE, 126 (2000), 954