Microwave-Assisted Ablation of Contaminated Concrete Surfaces – Modeling, Simulation and Experiments

Andreas Melcher[1], Martin Umminger[2], Thorsten Kayser[1], Guido Link[1], Michael Haist[2], Harald S. Müller[2], and John Jelonnek[1]

[1]Institute for Pulsed Power and Microwave Technology, Karlsruhe Institute of Technology, Germany
[2]Institute of Concrete Structures and Building Materials, Karlsruhe Institute of Technology, Germany

***Abstract* –** The paper gives a short review of the activities at KIT related to dismantling nuclear contaminated concrete in power plants by microwaves. The experimental setup of a prototype of spalling concrete due to microwave heating is described, followed by a modeling of the problem by coupling Maxwell's equations with the heat equation for isotropic, homogeneous concrete. Finally, we give some simulation results. An outlook of future work concludes the paper.

Introduction

Since the nuclear accident in Fukushima, Japan, in March 2011, political policies surrounding nuclear power plants in Germany have changed. Decommissioning and dismantling of the remaining nuclear power plants is becoming a first priority. A major difference from the dismantling of other power plants is the presence of radioactive material that requires special precautions to minimize nuclear waste. Massive amounts of concrete from the concrete containment domes that sit over the reactors have to be dismantled. The first few centimeters of concrete below the surface become contaminated by radioactivity, but removal of that contaminated layer by mechanical means will result in cross-contamination. Within the German Federal Ministry of Education and Research (BMBF) project *MACOS* a new technology based on high power microwaves is being developed; that will allow the ablation of that radioactive layer, preventing the production of radioactive dust particles before dismantling the remaining "clean" containment. The first section gives a brief discussion of the experimental setup, followed by modeling and simulation of the coupled problem containing Maxwell's equations and the heat equation in the second section. Finally, a conclusion and outlook of future work is given.

Experimental Setup

In the experimental part of the project, a setup to study the influence of the microwaves to concrete was built. In a WR340 waveguide we excite a TE_{10} mode with a frequency of 2.45 GHz with variable power between 1-10 kW. As test samples, Portland-type concrete with different chemical compositions and different moisture contents was used to represent several stages of concrete aging. The experimental setup can be seen in Figure 1.

Under microwave radiation with different power levels and radiation time, four effects were observed with our experimental setup. For long radiation times $t > 180$ s with microwave power in the range of 1-4 kW, melting of the concrete samples was observed, and with a radiation time of 30-180 s and microwave power between 4-6.5 kW, macroscopic crack formation and propagation occurred. Ablation of concrete is found for microwave power >6.5 kW within a radiation time of 5-15 s. In the case of concrete spalling, the time until ablation was

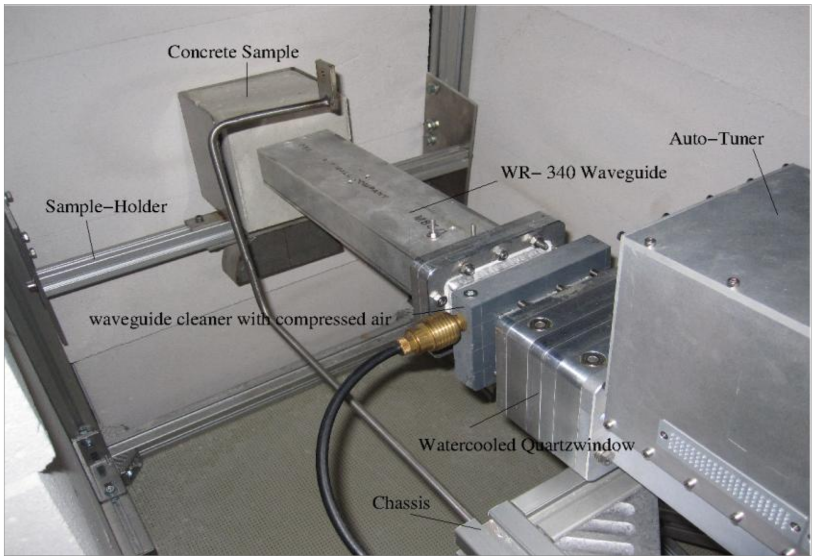


Fig.1: Experimental setup of spalling concrete.

(a) (b)

Fig. 2. Spalling of concrete with the experimental setup – dry (a) and wet (b) concrete.

correlated to the humidity of the concrete for constant microwave power. For a fully saturated concrete sample, the typical ablation time lies between 5-7 s, in contrast to 10-15 s for a complete dry concrete. Furthermore, the spalled volume of the wet concrete is greater than for the dry concrete, as can be seen in Fig. 2.

Modeling and Simulation

In this section, modeling and simulation of the experimental setup is described. We first give a brief description of the concrete structure. Concrete is a compound consisting of cement, water, sand, gravel, and different chemical aggregates. After hydrating, concrete is a porous medium with typical porosity, *i.e.* the ratio between the volume fraction of pores and the total volume, of $p = 0.1$. The solid phase of concrete includes the hydrated cement paste, bonded aggregates, and unhydrated cement, while the liquid phase consists of free water, and the gaseous phase is the air in the pores.

The interaction between microwaves and concrete is dominated by the water content in concrete, because water is a strong dipole at frequency f = 2.45 GHz and therefore can easily be heated by microwaves. Under microwave radiation, if the sum of the rate of evaporation of the free water and rate of the dehydration of chemcal bond water in concrete is higher than the vapor migration rate, pore pressure will increase due to heat and mass transfer [1-3] This effect will be neglected in this study. A more important effect comes from the nonuniform heating of the concrete at high frequency. Microwave radiation generates local hot spots, which lead to thermal expansion in the heated zone. This results in high compressive stress parallel to the surface of the concrete and to spalling of concrete due to thermal gradients [3, 4].

The mathematical and physical model of the problem on a macroscopic scale consists of a coupled system containing Maxwell's equations for electromagnetic contributions, the heat equation describing the heating of the concrete under microwave radiation, and the thermoelastic version of Navier's equation describing the thermoelastic effects on the concrete [1, 4, 5]. At this stage of modeling we assume that the material is isotropic, and that its properties at the macro-scopic scale are homogeneous and independent of temperature. Convection due to heat and mass transfer and thermoelastic effects are neglected in this study. It is a well known fact that Maxwell’s equatrions and the heat equation act on different time scales [6], since the time dynamics of Maxwell’s equations solved for microwave frequencies act on the order ot nanoseconds, in contrast to the time dynamics of the heat equation, which acts on a time scale of seconds or minutes. Since microwave radiation is used as heating source, Maxwell’s equations must be solved to compute the distribution of the electromagnetic field inside the concrete. The heat equation for homogeneous isotropic material is

$$\rho_c c_c \frac{\partial T}{\partial t}(\mathbf{r},t) = K_c \Delta T(\mathbf{r},t) + Q(\mathbf{r},t) \text{ with } Q(\mathbf{r},t) = \frac{1}{2}\omega\epsilon_0\epsilon_r''|\mathbf{E}(\mathbf{r},t)|^2,$$

where T is the temperature field, E the electric field, Q the microwave source, ρ_c the density of concrete, c_c the specific heat and K_c the heat conductivity, ω is the angular frequency, and ε_ρ'' the dielectric loss factor in concrete. The time coordinate is denoted by t, and $\boldsymbol{r}$ represents the spatial coordinate. The microwave heat source Q in the heat equation can be derived from Poynting’s theorem in terms of the electromagnetic power dissipated per unit volume in concrete.

Finally, we have to specify the electromagnetic and thermal boundary condition for the simulation of our experimental setup. For the waveguide, we use the perfect electric conductor (PEC) boundary condition, which means that the tangential component of the electric field on the surface of the waveguide will vanish; for the concrete sample we use the PML (perfect matched layer) boundary condition, which represents an open boundary condition to absorb the outgoing electromagnetic wave from the concrete to avoid reflections. By neglecting thermal radiation over the surface of the concrete, Neumann boundary conditions were used to describe convective and conductive heat flow over the surface of the concrete sample.

The simulations were performed in the 2011 release of *CST Studio Suite*®. The *CST Micrtowave Studio*® module was used to compute the microwave heat source needed for the thermal simulations run in *CST MPHYSICS Studio*®. The evaluation of the data was done with MATLAB® R2011b. The electromagnetic part was performed with the transient solver, a time domain solver based on the finite integration technique [7], while for the thermal simulations the stationary thermal solver was used to get the stationary temperature distribution. For both simulations tools a hexahedral mesh for the spatial discretization with standard settings was used.

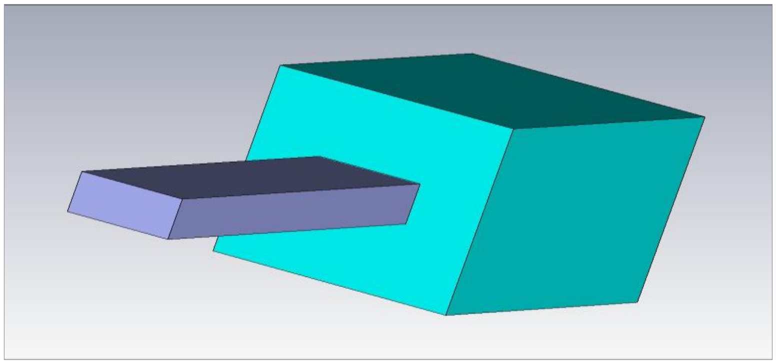


Fig. 3. Simplified experimental setup.

The ratio c between the time step Δt and the spatial resolutions Δx, Δy, and Δz was computed from the well-known Courant-Fredrichs-Lewy condition

$$\Delta t \leq \left(c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}} \right)^{-1}$$

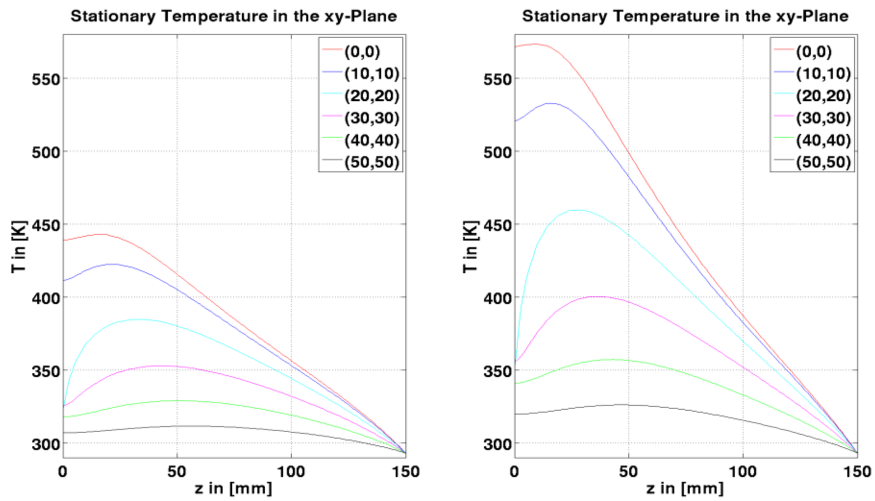
and was chosen as 0.7 for the accuracy of the electromagnetic transiet solver [8]. The accuracy of the stationary thermal solver, which is an iterative solver, was 0.0001.

The coupling between the two modules is considered as one-way coupling. After computing the electromagnetic field with the transient solver, power losses were calculated and then imported into the thermal solver with a pre-processing tool to compute the thermal losses. After this we ran the thermal simulation.

We did the CAD modeling of the problem with the *CST Studio Suite*® under Windows 7 Enterprise running on a virtual machine of VirtualBox 4.0.12 using 12 GB of memory and 6 processors. The real hardware consists of an Intel i7 processor with 6 cores and 24 GB memory, under a Linux OpenSUSE 11.4 environment with kernel 2.6.37.6-0.11. For running the solver modules in CST with the distributed computing option on up to 32 processors, no GPU or MPI computing is used. The distributed computing is performed on a workstation with 48 AMD Opteron processors with 2.2 GHz clock speed with 128 GB memory running under an Ubuntu-Linux 11.10 environment using kernel 3.0.0.15.

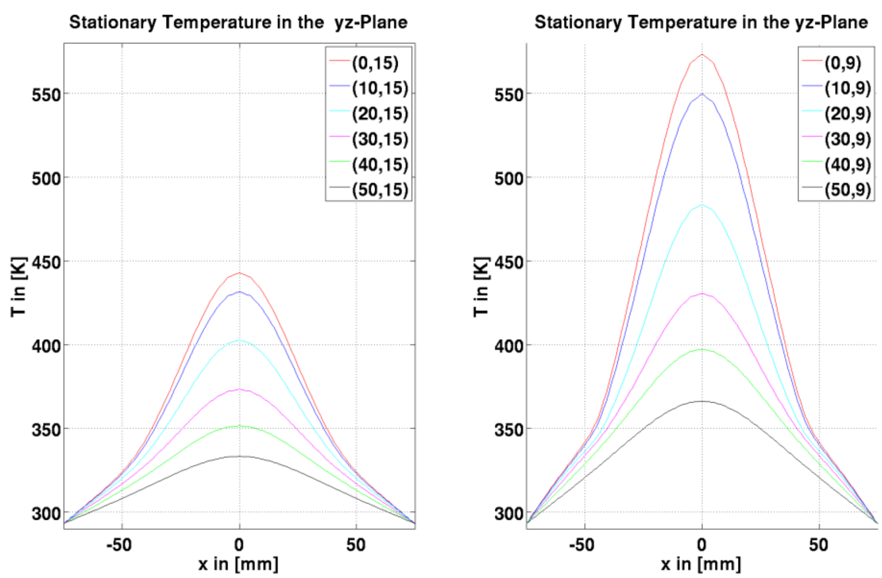
We simulate a simplified version of our experimental setup consisting of a waveguide and a concrete cube, where the edges of the cube have 0.15 m each (Fig. 3). We have chosen two data sets for the concrete from the *CST Microwave Studio* database: one that represents one year old concrete, and another that represents forty year old concrete; the complex permittivity at f = 2.45 GHz are 5.52 – j0.125 and 4.58 – j0.23, respectively. For the volumetric heat source we chose the power magnitude to be 3.2 kW, and the thermal constants as ρ_χ = 2400 kg/m^3 for the mass density of the concrete, c_c = 0.8 kJ/K kg for the specific heat, and K_c = 1.7 W/Km for the thermal conductivity.

In Fig. 4 the evolution and decay of the temperature profile in the z-direction along certain straight lines in the xy-plane is plotted for each specimen with a step size of 10 mm. Due to the higher losses in the forty year old concrete in comparison to the one year old concrete, the maximum temperature is 573.3 K at (x, y, z) = (0, 0, 9) mm, in contrast to 442.8 K at (x, y, z) = (0, 0, 15) mm. This gives maximum temperature increases of 280.15 K and 149.65 K



(a) (b)

Fig. 4. Temperature profile of concrete 1 year (a) and 40 years (b) for different points (x, y).



(a) (b)

Fig. 5. Temperature profile of concrete 1 year (a) and 40 years (b) for different points (y, z).

respectively, if we assume a homogeneous starting temperature of 293.15 K. In Fig. 5 the corresponding temperature profiles in the yz-plane for z = 9 and z =15 mm are plotted for varying x- and y-values. For both concrete samples, we see the formation of hot spots at (x, y, z) = (0, 0, 9) and (0, 0, 15) mm respectively, which both lie in the range we want to spall from the concrete.

Conclusion and Outlook

In this work, the experimental setup for ablation of concrete was considered. Microwave heating is modeled with a coupled model using Maxwell's equations and the heat equation. We present data sets obtained by performing this simulation in the *CST Microwave Studio Suite.* In the future, we will extend our model with contributions from thermoelasticity and perform simulations with datasets corresponding to different stages of aging of the concrete. Due to the growing complexity, an alternative simulation tool like *COMSOL Multiphysics* will be required. Furthermore, we will derive a model of the temperature-dependent permittivity of concrete using electromagnetic mixing formulas to take into account the porous structure of the concrete at the microscopic scale for the simulations on the macroscopic scale.

Acknowledgement

This work was supported by the German Federal Ministry of Education and Research within the project *MACOS* under the grant 02S8709.

References

[1] Z.P. Bazant, F. Asce, and G. Zi, Decontamination of radionuclides from concrete by microwave heating, I: Theory, *J. Eng. Mech.*, vol. 129, no 7, pp. 777-784, 2003.
[2] K.C.G. Ong and R. Prakash, Prediction of moisture migration and pore pressure development in concrete subjected to microwaves, *Proc. 31st Conf. "Our World in Concrete and Structures", Singapore, 2006*, vol. XXV, 100031036.
[3] K.C.G. Ong and A. Akbarnezhad, Thermal stresses in the microwave heating of concrete, *Proc. 31st Conf. "Our World in Concrete and Structures", Singapore, 2006*, vol. XXV, 100031038.
[4] A. Akbarnezhad and K.C.G. Ong, Microwave decantamination of concrete, *Magazine of Concrete Research*, vol. 62, no 12, pp. 879-885, 2010.
[5] K.G. Ayappa, H.T. Davis, G. Crapiste, E.A. Davis, and J. Gordon, Microwave heating: an evaluation of power formulations, *Che. Eng. Sci*., vol. 64, no 4, 1991.
[6] A.C. Metaxas and R.J. Meredith, *Industrial Microwave Heating*, Teter Peregrinus, London, 1983.
[7] T. Weiland, A discretization method for the solution of maxwell's equations for six-component fields, *Electronics and Communications AEUE*, vol. 31, no. 3, pp. 116–120, 1977.
[8] T. Weiland, Time domain electromagnetic field computation with finite difference methods, *Intern. J. Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 9, pp. 259–319, 1996.