N O R T H W E S T E R N

U N I V E R S I T Y

ZDENĚK P. BAŽANT
Ph.D., S.E., Dr.h.c., McCormick School Professor and
W.P. Murphy Professor of Civil Engineering and Materials Science
McCormick School of Engineering & Appl. Science, CEE -Tech A135
2145 Sheridan Road
Evanston, Illinois 60208-3109

Tel.: 847-491-4025
Secretary: 847-491-3351
Dept.: 847-491-3257
Fax: 847-491-4011
E-mail: z-bazant@northwestern.edu
Secr. E-mail: h-bean@northwestern.edu

December 1, 2003

To: Department of Energy, Idaho
Attn: Dr. Roland F. Hirsch and Dr. Ker-Chi Chang

Re: **Final Scientific/Technical Report**
Grant: **DE-FG07-98ER45736**
Grant Title: **Decontamination of Radionuclides from Concrete During and after Thermal Treatment**
Duration: **9/15/98-9/14.2003**
Total funds: $215,720.00

1. Research Objective:

The objective was to clarify from the theoretical viewpoint the mechanical, diffusional, thermodynamic and electromagnetic aspects of the decontaminations problem, by means of developing a powerful computational model to evaluate the effect of a very rapid heating regime on the on the contaminated concrete walls or slabs.

The practical objective was to assess the feasibility of the microwave heating scheme envisaged and determine its suitable parameters such as power and duration.

This objective was complementary to, but separate from, the chemical and nuclear aspects of long-time processes that led to the contamination and various conceivable alternative methods of decontamination which were investigated by *Dr. Brian Spalding* of *Oak Ridge National Laboratory*, with whom the start-up phase of this project was coordinated.

2. Research Results and Implications:

All the investigations initially planned for this grant have been completed (thanks to two no-cost extensions of this grant, necessitated by staffing problems and a medical problem caused by an accident).

The proposed scheme of decontamination of radionuclides from concrete structures, in which rapid microwave heating is used to spall off a thin contaminated surface layer, has been analyzed in great detail. The analysis was split in two parts:

(1) The hygrothermal part of the problem, which consists in calculating the evolution of the temperature and pore pressure fields within the concrete wall under the high-powered microwave applicator, and

(2) The fracture-damage mechanics part of the problem, which consists in predicting the stresses, deformations, cracking damage and fracture with spalling.

The former has been shown to be virtually independent of the latter, but the latter is strongly coupled to the former. The heat and moisture transfer governing the temperature and pore pressure fields induced by the decontamination process is analyzed and numerically simulated using an improved form of the classical Bazant-Thonguthai model for heat and moisture transfer in concrete at high temperatures.

The rate of the distributed source of heat within the mass of concrete, caused byt the interaction of microwaves with the molecules of water contained in concrete (vapor, liquid-capillary, adsorbed, and interlayer water) is calculated on the basis of the standing wave normally incident to the concrete wall. Because the microwave time period is much shorter than the time a heating front takes to propagate over the length of microwave, and because concrete is heterogeneous, the Ohmic power dissipation rate is averaged over both the time period and the wavelength.

The reinforcing bars parallel to the surface are treated as a smeared steel layer. The recently developed microplane model M4 is employed as the constitutive model for nonlinear deformation and distributed fracturing of concrete.

Based on this mathematical model, a numerical analysis of the process of decontamination of radionuclides from concrete by application of rapid microwave heating is conducted. The aim of the analysis is to determine the required microwave power and predict whether and when the contaminated surface layer of concrete spalls off.

The finite element method is used for the stress and fracture analysis. The material parameters used as the input are calibrated on the basis of extensive prior test data.

As a departure from previous studies, the finite volume method is adopted to treat the heat and moisture transfer, in order to prevent spurious numerical oscillations that plagued the finite element response at moving sharp interface between the saturated and unsaturated concrete, and to deal accurately with the jumps in permeability and in sorption isotherm slope across the interface.

The effects of wall thickness, reinforcing bars, microwave frequency and power are studied numerically. As a result of this analysis, the mechanism of spalling of rapidly heated concrete typical of microwave heating is clarified.

The importance of short-time viscoelasticity and its effect on prevention of localization of thermal cracking has also been analyzed. Simulations were conducted to elucidate the role of pressure of the heated pore water on the spalling, and the decay of pressure with time. A minor increase in strength and fracture energy due to high rate of deformation and its effect of spalling has also been determined.

3. Publications:

a) Main Publications:

1. Bazant, Z.P., and Zi, G. (2003). "Decontamination of radionuclides from concrete. I. Theory." ASCE J. of Engrg. Mech., submitted to.

2. Bazant, Z.P., and Zi, G. (2003). "Decontamination of radionuclides from concrete. II. Computations." ASCE J. of Engrg. Mech., submitted to.

3. Bazant, Z.P., and Zi, G. (2001). "Spatial and temporal scaling of concrete response to extreme environments". Concrete Under Severe Conditions (Proc., 3rd Int. Conf., CONSEC'01), N. Banthia, K. Sakai and O.E. Gjorv, eds., University of British Columbia, Vancouver, BC, 3--10.

b) In Preparation:

4. Bazant, Z.P. (2004). "Modeling of concrete fracture and thermal spalling based on fracture and diffusion." Invited Paper in Preparation for Proceedings of 4th International Conference, CONSEC-4, Seoul, June 27-30, 2004.

c) Related Publications and Review Articles:

5. Zi, G., and Bazant, Z.P. (2002). "Continuous relaxation spectrum for concrete creep and its incorporation into microplane model M4." J. of Engrg. Mech. ASCE 128 (12) 1331--1336.

6. Zi, G., and Bazant, Z.P. (2001). "Continuous relaxation spectrum of concrete creep and its incorporation into microplane model M4." Creep, Shrinkage and Durability Mechanics of Concrete and Other Quasi-Brittle Materials. (Proc., 6th Intern. Conf., CONCREEP-6, held at MIT, Cambridge), F.-J. Ulm, Z.P. Bazant and F.H. Wittmann, eds., Elsevier, Amsterdam 2001, 239--243.

7. Bazant, Cedolin, L., and Cusatis, G. (2001). "Temperature effect on concrete creep modeled by microprestress-solidification theory." Creep, Shrinkage and Durability Mechanics of Concrete and Other Quasi-Brittle Materials. (Proc., 6th Intern. Conf., CONCREEP-6, held at MIT, Cambridge), F.-J. Ulm, Z.P. Bazant and F.H. Wittmann, eds., Elsevier, Amsterdam 2001, 197--204.

8. Bazant, Z.P. (2001). "Prediction of concrete creep and shrinkage: Past, present, future." Nuclear Engrg. and Design 203 (1), Jan., 27--38.

9. Bazant, Z.P., and Kaplan, M.F. (2002). Concrete at High Temperatures: Material Properties and Mathematical Models, 2nd edition, Pearson Education, Edinburgh, UK.

10. Carol, I., Jirasek, M., and Bazant, Z.P. (2001). “New thermodynamic framework for microplane model.” Fracture Mechanics of Concrete Structures (Proc., FraMCoS-4 Int. Conf., Paris), R. de Borst, J. Mazars, G. Pijaudier-Cabot and J.G.M. van Mier, eds., Swets & Zeitlinger (A.A. Balkema Publishers), Lisse, 519--524.

11. Cusatis, G., Bazant, Z.P., and Cedolin, L. (2001). “3D lattice model for dynamic simulations of creep, fracturing and rate effect in concrete.” Creep, Shrinkage and Durability Mechanics of Concrete and Other Quasi-Brittle Materials. (Proc., 6th Intern. Conf., CONCREEP-6, held at MIT, Cambridge), F.-J. Ulm, Z.P. Bazant and F.H. Wittmann, eds., Elsevier, Amsterdam 2001, 113--118.

12. Bazant, Z.P., Caner, F.C., Carol, I., Adley, M.D., and Akers, S.A. (2000). “Microplane model M4 for concrete: I. Formulation.” J. of Engrg. Mechanics ASCE 126 (9), 944--953.

13. Caner, F.C., and Bazant, Z.P. (2000). “Microplane model M4 for concrete: II. Algorithm and Calibration.” J. of Engrg. Mechanics ASCE 126 (9), 954--961.

14. Bazant, Z.P., Caner, F.C., Adley, M.D., and Akers, S.A. (2000). “Fracturing rate effect and creep in microplane model.” J. of Engrg. Mechanics ASCE 126 (9), 962--970.