REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-99-

0200

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 1998

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL REPORT 1 Nov 97 - 31 Oct 98

4. TITLE AND SUBTITLE
~~INTEGRATED~~ THERMAL-MECHANICAL-CHEMICAL DAMAGE MODELING OF AIRFIELD CONCRETE PAVEMENTS ~~FOR JOINT STRIKE FIGHTERS~~ Under High Temperature Loading

5. FUNDING NUMBERS
F49620-98-1-0110
61102F
2302/CS

6. AUTHOR(S)
J.W JU AND HONGWEI GONG

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF CALIFORNIA-LOS ANGELES
CIVIL & ENVIRONMENTAL ENGINEERING DEPARTMENT
BOX 951593
LOS ANGELES, CA 90095-1593

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
801 N. RANDOLPH STREET, ROOM 732
ARLINGTON, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Ordinary Portland Cement (OPC) is a widely used construction material. In airbase facilities, it is used to construct the runways and parking aprons. During the takeoff and landing of aircrafts, the high temperature exhaust has splashed to the concrete pavement from the modern vectored thrust engines (VTE) or auxiliary Power Unit (APU). The APU is a low-power has turbine that provides compressed air, from a load driven compressor, for starting the main engines and for operating auxiliary systems during ground maintenance. In particular, the exhaust gas temperature of a VTE could rapidly reach over 700 oC, and the corresponding exhaust velocities could go beyond 1800 ft/s. The pavement is subjected to extremely rapid transient high temperature loadings as well as thermal cycles of heating and cooling. Figure 1.1 shows a typical damaged area in an F/A-18 parking apron. The origin of the problem is the F/A-18 auxiliary power unit, which is located at the bottom of the fuselage near the tail section. The exhaust gas temperature isotherms on the pavement top are almost circular and show a decrease along the radios. Chemical degradation of concrete due to hydraulic fluid, lubricating oils also contribute to the damage of concrete pavement. The U.S. Department of Defense has seen an increase in airfield concrete apron distress in the form of surface scaling when the aprons are exposed to cyclic heat, spilled lubricants, and/or hydraulic fluid (McVay, Smithson and Manzione, 1993). Chemical analysis of the damaged concrete reveals that the spilled fluid from the engines are undergoing hydrolysis (breakdown) accompanied by the consumption of calcium hydroxide, plus hydrated silicate and aluminate phases. A thermo-chemical-micromechanical damage model is to be derived as the future

14. SUBJECT TERMS

15. NUMBER OF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

UNIVERSITY OF CALIFORNIA

LOS ANGELES

THERMO-MICROMECHANICAL DAMAGE MODELS OF AIRFIELD CONCRETE PAVEMENT UNDER HIGH TEMPERATURE LOADING

by

J.W. Ju and Hongwei Gong

December 1998

For: AFOSR

Chapter 1

INTRODUCTION

1.1 Introduction

Ordinary Portland Cement (OPC) is a widely used construction material. In airbase facilities, it is used to construct the runways and parking aprons. During the takeoff and landing of aircrafts, the high temperature exhaust gas splashed to the concrete pavement from the modern vectored thrust engines (VTE) or Auxiliary Power Unit (APU). The APU is a low-power gas turbine that provides compressed air, from a load driven compressor, for starting the main engines and for operating auxiliary systems during ground maintenance. In particular, the exhaust gas temperature of a VTE could rapidly reach over 700 °C, and the corresponding exhaust velocities could go beyond 1800 ft/s. The pavement is subjected to extremely rapid transient high temperature loadings as well as thermal cycles of heating and cooling. Figure 1.1 shows a typical damaged area in an F/A-18 parking apron. The origin of the problem is the F/A-18 auxiliary power unit, which is located at the bottom of the fuselage near the tail section. The exhaust gas temperature isotherms on the pavement top are almost circular and show a decrease along the radius.

Internal microcracks nucleate and propagate in concrete due to these severe thermomechanical loadings. The damage significantly affects the residual effective moduli and strength of the pavement concrete. Situations are much worse to airfield concrete pavements for the future vertical take-off/landing (VSTOL) aircraft (i.e. the Joint Strike Fighter) with vectored thrust engines (VTE) [Hooker (1981)]. The damage of airfield concrete pavements caused by the aircraft exhaust is an expensive problem that is expected to get worse. The damage occurs in the upper 1/4 to 1/2 inch of the surface and results in debris that can severely damage the aircraft engines. The loose cement paste and aggregate may be easily ingested.

Damage of airfield concrete pavement could be in the form of thermomechanical **spalling, delamination**, and **splitting**. Spalling refers to small, thin pancake-shaped pieces that explode into the air because of the very large steam pressure in pores, high thermal gradients and large compressive thermal stresses (parallel to the surface in the pavement). Specifically, compressive stresses produce not only concrete crushing, but also a bulging instability (similar to buckling) of the top layer. Under these severe thermomechanical loadings, internal microcracks nucleate and propagate in concrete, leading to progressive delamination at some shallow depth beneath the pavement surface. Figure 1.2 is the explosive spalling occurring in saturated concrete heated to simulate VSTOL jet exhaust (Kodres, 1996). During the heating procedure concrete pavement is under high level compressive thermal stress loading. The microcracks may propagate in the plane parallel to the pavement surface. This mechanism will cause another type of delamination. However, during the cooling procedure, the dry-shrinkage strain can not recover. A high level tensile thermal stress will be generated. In this case, the microcracks will propagate perpendicular to the pavement surface. Finally, the pavement will be splitted. Since concrete is weak under tension, it is important to investigate the behavior of concrete under tensile loadings. If the pavement is delaminated in horizontal plane and splitted in vertical direction relative to the pavement surface, thin plate-like pieces or lamina that flake or peel off from the damaged concrete surfaces. This phenomenon is referred to as scaling. Figure 2.3 is the pavement scaling due to F/A-18 exhaust at the Naval Air Station, North Island, San Deigo (Kodres, 1996).

1.2 Composition of concrete

In its most general definition, concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix material (the cement or binder) that fills the space between the aggregates and binds them together (Mindess and Young, 1981). Concrete is popular because it is economical, and features desirable casting and in-situ forming capabilities. However, hardened concrete is both chemically and mechanically complex. It has been suggested that at least three main structural levels or scales exist for concrete, and that each of these levels exhibits unique characteristics with varying degrees of complexities (Wittmann, 1983)

The structure and characteristics of the hardened cement paste are the main factors considered at the **micro-level**. When mixed with water, the constituent compounds of Portland cement undergo a series of complex chemical reactions (hydration) which lead to the eventual hardening of the concrete. These reactions are always exothermic (i.e., they generate heat). The amount of heat generated during these reactions results in thermal stresses which usually lead to cracking within the matrix. After the primary hydration process is complete, the new solids formed are called the hydration products.

The characteristic features of the heterogeneous structure of the **meso-level** consist of inclusions (hard aggregate), pores, and pre-existing cracks embedded in the hardened cement paste (matrix) (Figure 1.4). In normal weight concrete, randomly dispersed aggregates of varying sizes and shapes are tougher than the cement matrix and, consequently, act as crack arrestors. It is the geometry of the mesostructure (the dispersion and volume fraction of constituent phases, the specific area of weak interfaces, and the size and distribution of pre-existing defects) which affects the overall mechanical response and ultimately determines the rupture strength of the material. A well-documented mesoscale characteristic is that the aggregate-cement paste interface is often the weakest-link in the concrete composite. Therefore, the cracks formed at this interface have the most significant influence on the material behavior. This influence is macroscopically observed as the nonlinearity in the stress-strain curve.

At the **macro-level**, the size of the specimen is considered to be large enough (i.e., possessing a large number of heterogeneities) so that the material can be considered statistically homogeneous; i.e., stress/strain fluctuations are not significant.

1.3 Literature review

An improved understanding of the underlying deformation and damage mechanisms will help the pavement design and prolong the usable life of airfield pavements. Research on micromechanical damage level is needed to better understand the basic physical phenomena responsible for these changes.

High-temperature thermomechanical behavior and properties of concretes have been studied in the past thirty-five years primarily due to the interests in heat resistance of concretes in fire engineering, conventional and nuclear electric power plants. For an extensive literature review on high-temperature behavior of Portland cement and refractory concretes, we refer to Bazant et al. (1982). Some important aspects of temperature-dependent properties of OPC concretes at elevated temperatures discussed by Bazant et al. (1982) include dehydration of cement, increase of porosity, moisture content, thermal expansion and shrinkage, pore steam pressure, loss of strength, thermal cracking due to thermal incompatibility, degradation of elastic moduli, thermal creep, heat capacity, thermal conductivity and thermal diffusivity, and explosive thermal spalling due to excessive pore steam pressure, etc.

The two principal culprits for the damage of concrete pavement are the microcracks and the high pore pressure. Accordingly, there are two types of thermo-micromechanical damage models of concrete. One type of damage model emphasizes the development of the microcracks in the concrete. Krajcinovic and Fanella (1986) proposed a constitutive theory for concrete based on the geometry of its mesostructure and the actual kinetics of the microcrack evolution. Fanella and Krajcinovic (1988) develop a general three-dimensional micromechanical constitutive theory for plain concrete subjected to uniaxial and triaxial compressive loads. Ju and Lee (1991) present three-dimensional micro-mechanical anisotropic damage models for microcrack-weakened brittle solids. Lee and Ju (1991) developed three-dimensional self-consistent damage models for brittle solids under compressive triaxial loadings based on micromechanics and microcrack geometry within a representative volume. Ju and Zhang (1998) proposed a simple one-dimensional thermo-micromechancal constitutive and damage model for airfield concrete pavement under rapid transient high temperature loadings due to vectored thrust. Chandra and Krauthammer (1996) present a micromechanical damage model for a brittle solid capable of taking into account the effect of high loading rate (in the form of stress-rate).

By experimental program, Zoldners (1960, 1971), Zoldners et al. (1963), and Zoldners and Wilson (1973) studied effects of sustained and cyclic high temperatures on concretes containing different aggregates. Khoury, Grainger and Sullivan (1985a, 1985b, 1986) conducted research on transient (free and load-induced) thermal strain of concrete, including first heating to 600 °C and first cooling from 600 °C under load. Dias, Khoury and Sullivan (1990) discussed mechanical properties of hardened cement paste exposed to temperatures up to 700 °C. Moreover, Baluch et al. (1989) studied the degradation (microcracking) of concrete bridge decks in Saudi Arabia due to incompatible coefficients of thermal expansion between aggregates and cement paste. Although the aforementioned studies (on high-temperature behavior of concrete) in the literature are quite useful, they concentrate on relatively slow heating rates (e.g., less than 10 °C/min.) of thermomechanical properties of concretes. By contrast, our objective here is to conduct preliminary investigation of the transient high-temperature (say 700 °C), fast heating rate (say 500 °C/min.) thermomechanical behavior of ordinary Portland cement concrete airfield pavements with various mixtures of cement pastes and aggregates.

Other scholars pay attention to the high-level pore pressure in the concrete pavement. Concrete is a material that contains extremely fine pores with a great amount of water. Therefore, heating of concrete will produce significant pore pressure that may induce transfer of moisture through concrete and eventual drying. The high pore pressure and the migration of moisture and exhaust caused by heating of concrete pavement due to the exhaust gas from the aircraft is of considerable concern for predicting the damage of airfield concrete pavement. There exist some studies on the mass transport and heat transfer within the stagnation zone. For instance, Stevens, Pan and Webb (1992), and Pan, Stevens and Webb (1992) experimentally studied the turbulent flow structure, local heat transfer and effects of nozzle configuration on transport in the stagnation zone of axisymmetric, impinging free-surface liquid jets. In addition, Rish and McVay (1994) investigated the moisture release and migration in concrete due to vectored thrust. Specifically, Rish and McVay (1994) conducted research on mass transport under isothermal conditions, and measured pore pressures during transient heating.

There are several different approaches to this analysis. One approach is to assume the mass flow of the liquid phase is negligible and treat the problem as a flow of gas through a porous concrete. Sahota and Pagni (1979) used this approach to examine the thermodynamics of moisture in the pores of a concrete structure subjected to fire. They solved the conservation equations for energy and species, employing a finite difference scheme. Permeability was used as a parameter. However, they stopped the parametric study when pore pressures reached 10 atm. Pressures above 10 atm "are not expected due to microcracking and cracking". An empirical approach was adopted by Bazant and Thonguthal (1978) to study the heating of concrete. By fitting data, they developed relationships between pore saturation and pore pressure and between permeability and pore pressure. These equations were coupled with conservation of energy and mass, and solved using finite element method. An unsealed concrete slab was modeled (Bazant and Thonguthal, 1979), with surface temperature increasing at the rate of 80 °C/min. At this rate, the surface temperature reached 150 °C in slightly less than 2 minutes, similar to the rate at which an APU heats an airfield pavement. The predicted maximum pore pressure was about 5 atm.

Another approach to calculating moisture migration through high-resistance porous media is to use the methods developed to study the migration of moisture through permeable media such as soil. The flow of both liquid and gaseous phases is accounted for. Applying theoretical correlations between capillary pressure and pore saturation, and relative permeability and pore saturation (Van Genuchten, 1980). Doughty and Pruess (1990) employed this method to determine the feasibility of constructing a geologic repository for high-level nuclear waste. Kodres (1996) used a constitutive relationship to characterize the flow of high-velocity, compressible, heated gasses through a high-resistance porous medium. The resistance to flow was modeled with friction coefficients analogous to the method used for simpler geometries. Pore pressure generated by water and air in the pores of airfield concrete being heated by a jet exhaust was predicted.

Abdel-Rahman and Ahmed (1996) predicted the heat and mass transfer in concrete wall exposed to fire. Dayan and Gluekler (1982) treated the concrete as a porous material containing water, vapor and air. They studied the heat and mass transfer within a surface of heated concrete slab. The most cited experimental study is still the works of England and Ross (1970) and England and Sharp (1971). They heated one end of a 0.6 m cylindrical concrete specimen and measured pressure and, using resistance meters, moisture along its length. The sides of the specimen were insulated to ensure one dimensional heat and mass transfer. The hot end reached 150 °C. Although time and space gradients of temperature were very small, this work is of special interest because it provides, in part, an experimental confirmation of the hypothesis behind the airfield erosion analysis.

Chemical degradation of concrete due to hydraulic fluid, lubricating oils also contribute to the damage of concrete pavement. The U.S. Department of Defense has seen an increase in airfield concrete apron distress in the form of surface scaling when the aprons are exposed to cyclic heat, spilled lubricants, and/or hydraulic fluids (McVay, Smithson and Manzione, 1993). Chemical analysis of the damaged concrete reveals that the spilled fluid from the engines are undergoing hydrolysis (breakdown) accompanied by the consumption of calcium hydroxide, plus hydrated silicate and aluminate phases. A thermo-chemical-micromechanical damage model is to be derived as the future research.

1.4 Scope

In Chapter 2, a thermo-micromechanical damage model is proposed for the airfield concrete pavement under extremely rapid heating and cooling processes due to high temperature exhaust gas from the vectored thrust engines. This is typical of advanced aircraft during their short take-off and vertical landing routines. Since the temperature range in this research is quite large, and thermal properties of concrete are usually varying with the change of temperature, thermal properties are treated as functions of temperatures. The temperature distribution of the airfield concrete pavement is assumed to be independent of the stress field, and is numerically calculated by the explicit finite difference method. We consider the purely elastic strain, the stable crack-induced strain, the unstable crack-induced strain, the void-induced strain, the vapor pressure-induced strain, the thermal expansion strain, and the dry-shrinkage strain. Based on the strain analysis, a three-dimensional constitutive equation is derived for concrete under high temperature loading. In addition to the constitutive relations, three types of failure mechanisms are discussed. The pavement failure mainly consists of three mechanisms: the delamination due to horizontal void-induced cracks; the delamination due to horizontal interfacial cracks; and the splitting due to vertical cracks. This damage occurs in the upper surface and results in debris that can severely damage the aircraft engines. Within the framework of linear thermo-elasticity, the stress distribution as a function of location and time is also calculated by the finite difference method. Furthermore, based on the ASME Steam Tables and the temperature histories, we are capable of predicting the pore pressure fields and histories. For demonstration, a general one-dimensional problem is numerically simulated. Both normal-weight aggregate concrete and light-weight aggregate concrete are considered. The parametric study of the concrete can lead to the optimum design of the pavement.

In Chapter 3, the coupled governing equations of heat and mass transfer in concrete pavement are derived. Concrete is a material that contains extremely fine pores with water. Therefore, heating of concrete will produce significant pore pressure that may induce the transport of moisture through concrete and the eventual drying. Meanwhile, the migration of moisture through concrete may appreciably contribute to the heat transfer and affect the temperature distribution inside the concrete. The pore pressure depends on the pore space available to water, which is known to change in response to heating and other factors. The material properties involved in the diffusion problem of moisture and heat transfer are strongly variable. Therefore, analysis of pore pressure, moisture content and temperature in heated concrete necessitates a numerical approach. The objective of this study is to develop a finite difference program to accomplish this task. For the case of jet exhaust impinging on the concrete pavement, migration of exhaust through the concrete is also involved besides the transfer of heat and moisture. The high pore pressure and the migration of moisture and exhaust caused by heating of concrete pavement due to the exhaust gas from the aircraft is of considerable concern for predicting the damage of airfield concrete pavement. To model the mass (moisture and exhaust) and heat transfer through concrete, coupled partial differential equations concerning the conservation of moisture, exhaust and energy must be solved. The effects of Soret flux to the moisture flux and gas flux are considered. Water vapor pressure and gas pressure are chosen to be the driving forces that govern moisture transfer and gas transfer, in order to eliminate the effects of temperature gradient to the moisture flux and gas flux. Dehydration of water in concrete at high temperature is also considered. Empirical relations among water vapor pressure, temperature and water concentration in the concrete are employed. The moisture and exhaust gas transfer in concrete are also investigated. Semi-implicit finite difference scheme is applied to calculate temperature and pore pressure distributions. The stability criteria of the numerical simulation is also derived.

1.5 References

1. Abdel-Rzhman, A.K. and Ahmed, G.N., 1996. Computational heat and mass transport in concrete walls exposed to fire. Numerical Heat Transfer, Part A, 29, 373-395.

2. Baluch, M.H., Al-Nour, L.A.R., Azad, A.K., Al-Mandil, M.Y., Sharif, A.M., and Pearson-Kirk, D., 1989. Concrete degradation due to thermal incompatibility of its components. Journal of Materials in Civil Engineering, 1 (3), 105-118.

3. Bazant, Z.P., and Thonguthai, W., 1978. Pore pressure and drying of concrete at high temperature. Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, 104 (EM5), 1059-1079.

4. Bazant, Z.P., and Thonguthai, W., 1979. Pore pressure in heated concrete walls: theoretical prediction. Mag. of Concrete Res., 32 (107), 67-76.

5. Chandra, D. and Krauthammer, T., 1996. Rate-sensitive micromechanical damage model for brittle solid. Journal of Engineering Mechanics, Vol. 122, No. 5, May.

6. Dayan, A. and Gluekler, E.L., 1982. Heat and mass transfer within an intensely heated concrete slab. Int. J. Heat Mass Transfer, 25 (10), 1461-1467.

7. Dias, W.P.S., Khoury, G.A., and Sullivan, P.J.E., 1990. Mechanical properties of hardened cement paste exposed to temperatures up to 700 oC. ACI Materials Journal, 87, (2), 160-166.

8. Doughty, C. and Pruess, K., 1990. A similarity for two phase fluid and heat flow near high-level nuclear waste packages emplaced in porous media. Int. J. of Heat and Mass Transfer, 33 (6), 1205-1222.

9. England, G.L., and Ross, A.D., 1970. Shrinkage, moisture, and pore pressure in heated concrete. Concrete for nuclear reactors, Spec. Publ. No. 34, Am. Concrete Inst. Detroit, Mich., 883-907.

10. England, G.L. and Sharp, T.J., 1971. Migration of moisture and pore pressures in heated concrete. Proc., First Int. Conf. on Struct. Mech. in Reactor Technol., Paper No. H2/4, Commission of the European Communities, Berlin, Germany.

11. Fanella, D. and Krajcinovic, D., 1988. A micromechanical model for concrete in compression. Engineering Fracture Mechanics, Vol. 29, No. 1, pp. 49-66.

12. Hooker, S., 1981. History of the pegasus vectored thrust engine. J. Aircraft, 18, (5), 332-326.

13. Ju, J.W. and Lee, X., 1991. Micromechanical damage models for brittle solids. I: tensile loadings. Journal of Engineering Mechanics, Vol. 117, No. 7, July.

14. Ju, J.W. and Zhang. Y., 1998. A thermomechanical model for airfield concrete pavement under transient high temperature loadings. Int. J. Damage Mechanics, 7, 24-46.

15. Khoury, G.A., Grainger. B.N., and Sullivan, P.J.E., 1985a. Transient thermal strain of concrete: literature review. conditions within specimen, and behavior of individual constituents. Magazine of Concrete Research, 37 (132), 131-144.

16. Khoury, G.A., Grainger, B.N., and Sullivan, P.J.E., 1985b. Strain of concrete during first heating to 600 °C under load. Magazine of Concrete Research, 37 (133), 195-215.

17. Khoury, G.A., Grainger, B.N., and Sullivan, P.J.E., 1986. Strain of concrete during first cooling from 600 °C under load. Magazine of Concrete Research, 38 (134), 3-12.

18. Kodres, C.A., 1996. Moisture-Induced pressures in concrete airfield pavement. Journal of Materials in Civil Engineering, Vol. 8, No. 1, February.

19. Krajcinovic, D. and Fanella, D., 1986. A micromechanical damage model for concrete. Engineering Fracture Mechanics, Vol. 25, Nos 5/6, pp. 585-596.

20. Lee, X. and Ju, J.W., 1991. Micromechancial damage models for brittle solids. II: Compressive loadings. Journal of Engineering Mechanics, Vol. 117, No. 7, July.

21. McVay, M.C., Smithson, L.D., and Manzione, C., 1993. Chemical damage to airfield concrete aprons from heat and oils. ACI Materials Journal, May-June.

22. Mindness, S. and Young, J., 1981. Concrete. Prentice-Hall, Inc., Englewood Cliffs, N.J..

23. Pan, Y., Stevens, J., and Webb, B.W., 1992. Effect of nozzle configuration on transport in the stagnation zone of axisymmetric, impinging free-surface liquid jets: Part 2 – Local heat transfer. J. of Heat Transfer, ASME, 114, 880-886.

24. Rish, J.W., III, and McVay, M.C., 1994. Moisture release and migration in concrete due to vectored thrust. Annual Task Report for AFOSR Contract No. 93WL004.

25. Sahota, M.S. and Pagni, P.J., 1979. Heat and mass transfer in porous media subject to fires. Int. J. Heat and Mass Transfer, 22 (7), 1069-1081.

26. Stevens, J., Pan, Y., and Webb, B.W., 1992. Effect of nozzle configuration on transport in the stagnation zone of axisymmetric, impinging free-surface liquid jets: Part 1 – Turbulent flow structure. J. of Heat Transfer, ASME, 114, 874-879.

27. Van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. of Am. J., 44, 892-898.

28. Wittmann, F.H., 1983. Structure of concrete with respect to crack formation. In Fracture Mechanics of Concrete. Ed. F.H. Wittmann, Elsevier Publishing Company, The Netherlands, pp. 43-74.

29. Zoldners, N.G., 1960. Effect of high temperatures on concretes incorporating different aggregates. Proceedings ASTM, 60, 1087-1108.

30. Zoldners, N.G., 1971. Thermal properties of concrete under sustained elevated temperatures. Temperature and Concrete, ACI Publication SP-25, 1-31, Detroit.

31. Zoldners, N.G., Malhotra, V.M., and Wilson, H.S., 1963. High temperature behavior of aluminous cement concretes containing different aggregates. Proc. Am. Soc. of Testing Mater., 63, p. 966.

32. Zoldners, N.G., and Wilson, H.S., 1973. Effect of sustained and cyclic temperature exposures on lightweight concrete. Behavior of Concrete under Temperature Extremes, ACI Publication SP-39, 149-178.