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International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

Long T. Phan, Nicholas J. Carino, Dat Duthinh, and Edward Garboczi

COVER

Fire-induced spalling of concrete and buckling of reinforcement
in the Channel Tunnel due to fire on November 18, 1996
(photo by Paul Acker - Laboratoire Central des Ponts et Chaussees, France)

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International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

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EXECUTIVE SUMMARY

A workshop on the fire performance of high-strength concrete (HSC) was sponsored by the Building and Fire Research Laboratory (BFRL), National Institute of Standards and Technology (NIST), on February 13-14, 1997 at NIST facilities in Gaithersburg, Maryland. The organizing committee included Dr. George C. Hoff of Mobil Technology Company, Mr. Michael P. Gillen of Dupont Engineering, Dr. S.K. Ghosh of the Portland Cement Association, and Drs. Nicholas J. Carino, H.S. Lew, and Long T. Phan of NIST. The objective of the workshop was to identify research areas to address issues concerning the fire performance of HSC: namely, (1) the high rate of compressive strength loss of HSC when exposed to high temperature; (2) the high susceptibility of HSC to explosive spalling; and (3) the current inadequacy of code provisions for design of HSC structures exposed to fire. The workshop participants included leading researchers, representatives of trade organizations, government regulators from nine different countries, including Canada, Finland, France, Germany, Norway, Sweden, Taiwan, United Kingdom, and the United States of America.

Following the welcoming remarks by Dr. Jack Snell, Deputy Director of BFRL, the workshop commenced with 13 technical presentations by various researchers. These presentations were followed by four concurrent working group sessions whose objectives were to develop lists of research needs in the topic areas of **material testing**, **element testing**, **analytical studies**, and **codes and standards**. The workshop concluded with a plenary session where recommended research needs were summarized by the four working group Chairmen. The following are summaries of the recommended research needs identified by the four working groups:

Material Tests

(1) *Develop an understanding of the spalling mechanism(s) and establish a predictive parameter and standard test method(s) to measure it.* A parameter that includes concrete properties such as permeability, tensile strength, porosity, and moisture content has been found to be useful in predicting susceptibility to spalling of refractory concrete during the de-watering process prior to exposure to refractory temperatures. A similar parameter is desirable and needs to be developed for use in evaluating spalling potential of fire-exposed HSC. Factors that contribute to the occurrence of spalling need to be understood so that methods to mitigate spalling tendency can be developed.

(2) Measurement of properties of HSC as a function of temperature. Material properties of HSC need to be measured as functions of temperature to provide input data for numerical models. These include mechanical properties (compressive strength, elastic modulus, tensile strength, time-dependent behavior, and fracture mechanics parameters), transport properties (permeability, diffussivity, etc.), thermal properties (thermal conductivity, heat capacity, etc.), sorption isotherms, and water release during dehydration.

(3) Methods for evaluating aggregates for optimizing fire resistance of concrete. Practical methods, based on aggregate characteristics such as coefficient of thermal expansion and physico-chemical reactions leading to volume changes, are needed to evaluate different aggregate sources so that those that can be expected to result in poor performance during fire can be eliminated during the selection of materials for HSC mixtures to be used in critical structural elements.

(4) Methods for evaluation of fire damage. The applicability of advanced techniques based on stress-wave propagation (e.g., acoustic tomography and spectral analysis of surface waves), microwave radiation, and scanning electron microscope (micrographic and chemical analysis) to evaluate the extent of damage after a fire needs to be studied and standards for their used developed.

Element tests

(1) Spalling Mechanisms and Methods to Prevent or Control Spalling. Explosive spalling occurs inconsistently in fire-exposed HSC test specimens and is not completely understood. It is safe to conclude that material tests alone will not suffice in predicting spalling in reinforced structural elements, and element tests will be needed so as to be able to include the effects of reinforcement, cover depth, element size and shape in studying the spalling mechanisms and methods to prevent or control spalling.

(2) Application of Laboratory Test Results to Actual Structures. For normal strength concrete (NSC), laboratory fire tests have been successfully extrapolated to actual structures. However, because the fire performance of HSC is not completely understood and predictable, this cannot yet be done for HSC. Tests, which include scaling laws to account for size effects, are needed to translate reduced scale laboratory tests to full scale prototypes.

(3) Tests of Connections. Individual members are fire tested much more often than entire frames or joints between members, because of the size and cost associated with the latter. However, these tests are necessary for understanding and predicting the behavior of critical areas in HSC structures under fire. This is particularly important in the case of connections between columns of HSC and slabs of NSC.

(4) Determination of Residual Strength. Most structures damaged by fire do not collapse. However, they may have to be demolished because of uncertainty about their residual strength. This is true of NSC and HSC. Much can be learned from post-fire evaluations of residual structural capacity. The effectiveness of repair methods should also be evaluated.

Analytical Studies

(1) Transport Phenomena: (a) Coupled heat and mass transfer leading to pore pressure prediction. The relationships of pore pressure buildup and thermal stresses to the initiation of spalling of HSC need to be studied. The observed success of polypropylene fibers in reducing spalling suggest that pore pressure buildup is a significant factor in the spalling phenomenon. Modeling the heat and mass transfer in HSC should be done to gain an understanding of the spalling process and how fiber can be used to reduce this tendency.

(2) Transport Phenomena: (b) Investigation of new numerical methods to handle the saturated-unsaturated interface zone. The success of different numerical techniques in handling numerical modeling difficulties that occur at the sharp liquid-vapor interface (saturated-unsaturated) zone in concrete when heat is applied needs to be studied.

(3) Thermal stress analysis with inclusion of fracture mechanics. Analysis of internal stresses in HSC elements, caused either by thermal stresses or pore pressure buildup, with consideration of other factors such as creep and shrinkage, must be made in order to determine the relative importance of thermal stresses and pore pressure on the tendency for spalling. A fracture mechanic approach may be needed.

(4) Coupling of pore pressure and fracture process. Accurately measuring and predicting pore pressure buildup during a fire situation is not enough. Experimental data showing that pore pressure does not drop to zero when a crack forms led to a new approach in analyzing the initiation of spalling. Thus modeling to predict spalling should include the effect of cracking and interaction between the pore pressure and the crack.

Codes and Standards

(1) Standard Test Protocols for Engineering Properties of Fire-Exposed HSC. Internationally accepted protocols for fire testing of HSC, which include guidelines for data collection and reporting, need to be developed to ensure compatibility of results from different test programs.

(2) Mechanical Properties-Temperature Design Curves for HSC. Existing design curves for estimating mechanical properties of fire-exposed concrete have been developed based on experimental data of NSC. These design curves have been shown to be unconservative when applied to HSC. Thus, mechanical properties-temperature design curves for HSC at high temperature need to be developed and incorporated into building codes to ensure safety in HSC structures in the event of a fire. Such design curves would also be helpful for assessing the residual strength of HSC structures after a fire.

(3) Guidelines for Interpretation of HSC Material Tests and Standard Fire Tests. Engineering properties of HSC at elevated temperature are obtained by testing HSC cylinders or prisms. The measured properties are typically related to the temperature measured at the center of the specimens and are dependent on, among other things, heating rate. Whereas the current standard fire tests, such as ASTM E 119 and ASTM E 1529, prescribe procedures for testing structural assemblies by subjecting them to standard ambient temperature-time histories. These standards characterize the temperature history and duration of exposure inside the test chamber, but not necessarily the temperature and the rate of temperature development within the assemblies. Thus the results of material and standard tests are not directly compatible. Guidelines should be developed to relate the results of these tests.

(4) Guidelines for Selecting Realistic Design Fire Exposures. Current standard fire exposures, prescribed by ASTM E 119 and E 1529, ISO 834, and JIS A 1304, do not represent likely temperature histories of real fires. As a result, the exposure conditions specified in these standard fire test methods are not necessarily representative of the conditions that may exist in real fire scenarios. With the current tendency of moving towards performance-based standards, it is necessary to provide guidance for the selection of realistic design fire exposures which are particularly suitable for the specific HSC structure being evaluated.

(5) Guidelines for Fire Design of HSC Structural Elements. Guidelines for the fire design of HSC structural elements, which allow the calculation or assessment of the fire resistance period and load carrying capacity of structural elements, are not available in U.S. codes and standards. Such guidelines are desirable and should incorporate the different responses due to differences in structural element types (beam, column, wall, or slab), HSC engineering properties, applied loads, and HSC spalling characteristics.

(6) Design Guidelines to Mitigate Spalling in Fire-Exposed HSC. The risk of explosive spalling in HSC elements may be reduced by using appropriate design detailing , such as optimal sizes and spacing of transverse reinforcement, concrete cover, etc., and additions such as steel and polypropylene fibers. The effects of these design details and mixture additions should be studied, and results should be incorporated into design guidelines to reduce the risk of explosive spalling in HSC structures during a fire.

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1. INTRODUCTION

With the recent increase in use of high-strength concrete (HSC) for building and other structural applications, a considerable number of studies, which focus on the material properties as well as the design, manufacturing, and curing aspects of HSC, have been initiated and conducted at various laboratories worldwide. These studies aim to provide technical data for the full exploitation of HSC as a superior construction material compared with the conventional normal strength concrete (NSC). Included in these HSC studies are a limited number of studies on the effect of elevated temperatures on the thermal and mechanical properties of HSC. A subset of the elevated temperature studies includes those where HSC specimens were exposed to increasing temperature and properties were measured as a function of the temperature. These studies, which used a typical heating rate of about 1 °C/min and a maximum temperature of about 800 °C, were designed to provide an understanding of the behavior of HSC when exposed to fire conditions. The results of this group of studies have design implications and were reviewed and reported in NIST publications on the state-of-the-art on the fire performance of HSC [Phan, 1996; Phan and Carino, 1997]. These publications are part of the overall research effort on high performance concrete (HPC) at the National Institute of Standards and Technology (NIST). The NIST publications compiled and compared test data as well as experimental observations reported by various investigators. Specifically, the NIST publications outlined and discussed issues concerning the fundamental differences in material properties between HSC and NSC at elevated temperatures, the increased susceptibility of HSC to explosive spalling when subjected to rapid heating, and the applicability of existing code provisions to fire design of concrete structures made of HSC. Three major findings were identified as a result of this data synthesis:

1. HSC has a higher rate of compressive strength loss at high temperatures compared with NSC. The range of temperatures where this difference is most pronounced is between 100 °C and 400 °C.
2. HSC is susceptible to explosive spalling when exposed to temperatures above 300 °C.
3. Current code provisions for concrete properties at elevated temperatures are unconservative when applied to HSC.

Besides these findings, the NIST publications also identified a shortage of data on a number of issues that are essential for a complete understanding of how HSC would behave at elevated temperatures. The missing data include experimental measurements of tensile strength, pore pressure buildup, and permeability of HSC at high temperatures. Also lacking are data on thermal and mechanical properties of HSC under *stressed test* conditions (the specimens carry load prior to heating, similar to the case of HSC columns in a building during a fire). This shortage of data inhibits effective validation of existing analytical models and limits the development of new ones.

Thus, following the publication of the reports on the state-of-the-art, it was decided to organize a workshop on the fire performance of HSC. Workshop participants were to include researchers and members of academia who have been involved in studies of fire-exposed concrete, as well as practitioners, regulators, and representatives of professional trade organizations who have an understanding of the technical needs concerning the use of HSC. The focus of the workshop would be on research needs to address the technical deficiences associated with fire-exposed HSC. As a result, the Building and Fire Research Laboratory (BFRL) at NIST, in collaboration with industry representatives, which included Dr. S.K. Ghosh of Portland Cement Association, Mr. Michael P. Gillen of Dupont Engineering, and Dr. George C. Hoff of Mobil Technology Company, convened an International Workshop on Fire Performance of HSC in Gaithersburg, Maryland on February 13 and 14, 1997. The workshop participants were comprised of a select group of individuals from nine different countries, including Canada, Finland, France, Germany, Norway, Sweden, Taiwan, United Kingdom, and United States. A list of the workshop participants is provided in Appendix A.2.

In the chapters to follow, the workshop objectives and format are explained and technical presentations made at the workshop are summarized (Chapter 2); the research needs to address the current knowledge gaps concerning fire performance of HSC are described (Chapter 3); and information on worldwide research activities related to the subject of fire performance of HSC are provided (Chapter 4). Finally, papers which accompanied technical presentations made at the workshop are included in Appendix B.

2. NIST WORKSHOP ON FIRE PERFORMANCE OF HSC

2.1 Workshop Objectives and Format

The workshop was intended to provide an open forum where researchers, practitioners, and regulators could exchange expert opinions on current knowledge, technical problems, and design needs concerning the fire performance of HSC. The objective was to identify research areas which would address the unresolved issues concerning the fire performance of HSC as outlined in the NIST report [Phan, 1996]. Fire tests are expensive, and it is not possible for any one agency to perform all of the needed research. Thus a secondary objective of the workshop was to foster a collaborative spirit for potential joint research activities between different agencies, universities, and laboratories. It is hoped that these workshop proceedings will serve as a catalyst for such integrated international research efforts.

The workshop format included: (1) *technical presentations*, (2) *working group sessions*, and (3) a final *plenary session*. Thirteen *technical presentations* were given on the first day of the two-day workshop. The topics included experimental and analytical studies as well as proposed code applications in various countries. This activity was followed by *working group sessions*, which continued to the second day of the workshop. The workshop concluded with a *plenary session* where summaries of the findings were presented by the working group Chairmen. These findings form the basis for these workshop proceedings.

Four working groups were organized based on four research topics: *Material Tests* (Working Group A-1), *Element Tests* (Working Group A-2), *Analytical Studies* (Working Group B), and *Codes and Standards* (Working Group C). Each working group had a Chair and co-Chair to facilitate discussion. NIST staff attended each working group session to serve as a liaison and help record the discussion. The membership of each working group was selected in advance by individual participants based on their interests in the working group topics. The agenda for the workshop is listed in Appendix A.1, and a list of workshop participants by working group is given in Appendix A.3.

Section 2.2 summarizes the technical presentations and includes brief biographies of the presenters. Of the thirteen authors who made technical presentations at the workshop, nine followed up with papers. These papers are included with minimal editorial changes in Appendix B of these proceedings. In addition, a summary of the research efforts at Milan University of Technology, which was submitted by Drs. R. Felicetti and P. Gambarova who were invited but were not able to attend the workshop, is also included in Appendix B. Workshop findings are presented in Chapter 3.

2.2 Workshop Presentations

2.2.1 High-Strength Concrete in Germany - Utilization, Research and Standardization Presenter: Ulrich Diederichs, Amtliche Materialprüfanstalt für das Bauwesen, Germany.

About the presenter:

Dr. Ulrich Diederichs is a physicist at Amtliche Materialprüfanstalt für das Bauwesen of the Institut für Baustoffe, Massivbau und Brandschutz (IBMB/MPA). IBMB/MPA is the largest building materials testing and research institute in Northern Germany and is a non-profit institute of the Technical University of Braunschweig, operating under the auspices of the Lower Saxony State Ministry of Economics and Trade and the Ministry of Science and Culture. His main fields of research included: behavior of concrete at high temperatures, microstructure of building materials, building materials physics, fire resistance of HSC structures, and behavior of concrete for prestressed nuclear reactor vessels under accidental and service conditions. He was a member of RILEM TC PHT-44 "Properties of Materials at High Temperatures," RILEM TC FMC-50 "Fracture Mechanics of Concrete," and RILEM TC MHT-129 "Test Methods of Mechanical Properties of Concrete at High Temperatures."

Summary of presentation:

A summary of Germany's effort in utilization, research, and standardization of HSC was presented. Due to environmental demands for high durability and structural demands for higher compressive strength in new building constructions, HSC is being used more and more in Germany. The German Standard DIN 1045 defines HSC as concrete with average cube compressive strength exceeding 55 MPa (strength class B 55). To meet classification, reinforced HSC structural elements and plain concrete cylinders had to pass fire resistance tests performed by specialists. Many of the fire tests were performed at the Technical University of Braunschweig. Some of the specimens were pre-dried for 6 to 8 weeks at 60 °C, and all were exposed to the ISO 834 standard fire curve. Despite this treatment, severe spalling occurred. Explosive spalling was also observed in many small, 80mm dia. x 700mm, cylinders, made with and without silica fume, after the temperature within the specimens reached 350 °C. In structural element tests, anti-spalling mesh and steel fibers were also used as protection against spalling. The anti-spalling mesh is currently required by DIN 4102, Part 4/03.94 for fire safety on the exposed sides of structural elements. This anti-spalling mesh must be installed with a nominal concrete cover of at least 15 mm if the elements are in normal environments. For elements in moist and/or chemically agressive environments, this nominal concrete cover is to be increased by 5 mm. These spalling mitigation techniques, however, were observed in experiments at the Technical University of Braunschweig to be ineffective.

The results of fire tests on structural elements were incorporated into a set of guidelines of the Deutscher Ausschuss für Stahlbeton, which is a supplementary standard for the German DIN 1045 (*DAfStb-Richtlimie für hochfesten Beton - Ergänzung zu DIN 1045/07.88 für die Festigkeitsklassen B 65 bis B 115*). The current version of these guidelines (August 1995) provides design information, such as fire endurance and load carrying capacity of columns, beams, and walls, made of HSC of strength classes up to B 95. For HSC with compressive strength exceeding 95 MPa, additional tests and requirements must be met prior to use. According to the guidelines, spalling tendency must be counteracted by an antispalling mesh or other means (e.g., addition of polypropylene fibers). At present, the Technical University of Braunschweig is conducting fire tests on concrete tunnel linings made with HSC.

2.2.2 Fire Test of Normal-Weight/High Performance Concrete in Taiwan
Presenter: T.D. Lin, Architecture and Building Research Institute, Taiwan

About the presenter:

Dr. T.D. Lin is currently the president of Lintek International Inc. and a consultant to the Architecture and Building Research Institute in Taiwan. He was formerly with the Portland Cement Association (PCA) and is a pioneer in lunar concrete research. He was a select member of the U.S. delegation to the 1980 U.S.-Soviet Joint Seminar on "Mathematical Computations of Heat Flow." His recent work includes a new method for producing concrete using steam to cause hydration of a dry cement mixture, which results in concrete with twice the compressive strength in 18 hours than that of companion concrete made with the conventional wet procedure. Dr. Lin was the chairman of the ACI Lunar Concrete Committee (ACI 125) and is a member of the Fire Resistance and Fire Protection of Structures Committee (ACI-TMS 216) and ASCE's Fire Safety Committee. He is the recipient of many awards and honors for his research in concrete technology.

Summary of presentation:

The text of Dr. Lin's presentation is printed in Appendix B, Section B.1.

2.2.3 Fire Resistance and Residual Strength of HSC Exposed to Hydrocarbon Fire
Presenter: Jens Jacob Jensen, SINTEF, Norway.

About the presenter:

Dr. Jensen is a senior research engineer at SINTEF Civil and Environmental Engineering, Cement and Concrete Division in Trondheim; Norway. SINTEF is a research organization with about 2000 employees and closely connected to the University of Trondheim. Dr. Jensen's main areas of emphasis are structural mechanics, structural dynamics, reinforced concrete design, high strength concrete, tension structures, protective structures, bridges, and offshore structures. He has conducted a number of projects concerning the fire resistance of high strength concrete structures.

Summary of presentation:

The text of Dr. Jensen's presentation is printed in Appendix B, Section B.2.

2.2.4 Spalling Phenomena of HPC and OC
Presenter: Yngve Anderberg, Fire Safety Design (FSD), Sweden

About the presenter:

Dr. Anderberg is presently the managing director of Fire Safety Design (FSD) in Sweden and director of FSD in the U.K., a practice he founded in 1977. He is a frequent speaker at international conferences, has published numerous papers on fire safety engineering and is a member, secretary, and chairman of several European committees and working groups, including the Swedish Concrete Association, RILEM, CIB W14, the Swedish Fire Protection Association, the Society of Fire Protection Engineers (USA), the Institute of Fire Safety (UK), and Firepro Institute Ltd., which engaged in the advancement of fire protection techniques. He is the Swedish specialist on fire engineering design for concrete and steel constructions within CEN and has been responsible for building fire safety solutions for more than 1000 projects in Sweden as well as in Europe since 1977. Dr. Anderberg has been responsible for and actively involved in the assessment of fire safety of 10 offshore platforms, including the Hibernia, Ekofisk, Njord, and Visund.

Summary of presentation:

Dr. Anderberg's presentation is printed in Appendix B, Section B.3.

2.2.5 Fire Damage in the Eurotunnel
Presenter: Franz-Josef Ulm, Laboratoire Central des Ponts et Chaussees (LCPC), France.

About the presenter:

Dr. Ulm is a research engineer in the concrete department at the Laboratoire Central des Ponts et Chaussees (LCPC), Paris, of the French Ministry of Public Works. He lectures on continuum mechanics, structural dynamics and materials science at Ecole Normale Superieure de Cachan, Ecole Centrale de Paris, Technische Universitat Muenchen (FRG), and is Professor at the Federal University of Rio de Janeiro (COPPE/UFRJ, Brazil).

Summary of presentation:

A brief summary was presented of fire damage to a section of the 52-km long Channel Tunnel connecting Britain and France, caused by a fire on November 18, 1996, and LCPC's repair work.

The incident occurred when a fire broke out on a shuttle train carrying freight trucks that was en route from France to England through one of the Channel Tunnel's two transport tubes. The fire was reported to have lasted for about 10 hours, and the temperature of the fire was estimated to have reached between 1000 °C to 1200 °C. The flames and intense heat severely damaged both the concrete and reinforcing mesh of a portion of one of the two transport tubes. The damaged portion of the 450 mm thick tunnel ring was about 40 m in length. The concrete used did not contain silica fume and was designed to have compressive strength of about 50 MPa. However, post-fire testing on the undamaged concrete indicated actual compressive strength of about 100 MPa. Fortunately, the damaged section was surrounded by solid bedrock, which prevented water from entering the tunnel at places where full-depth spalling occurred.

For most of the damaged section, fire induced spalling, up to a depth of 150 mm to 200 mm, was observed with an estimated spalling rate of 1mm/minute. Local buckling due to exposure to fire after the concrete spalled off was observed for some sections of the reinforcing grid, and a loss of about 40% of the reinforcement's yield strength was observed for other sections. The reinforcing grid was found to provide some restraint for the concrete even though it was not actually designed as anti-spalling mesh. The repair involved the use of fiber reinforced shotcrete. The tunnel was closed for 6 months, at an estimated revenue loss of about $1.5 million a day.

2.2.6 Research Activities in Finland on Fire Resistance of HSC
Presenter: Ulla-Maija Jumppanen, VTT Building Technology, Finland

About the presenter:

Ms. Jumppanen is a senior research scientist at the Fire Technology Laboratory of the Valtion Teknillinen Tutkimuskeskus (VTT, Technical Research Center of Finland). She has conducted research and written extensively on the subject of properties of fire exposed concrete. A detailed biography of Ms. Jumppanen is not available at this writing.

Summary of presentation:

A brief summary was presented of research activities in Finland on the fire resistance of HSC and ultra HSC (UHPC, concrete with compressive strength exceeding 150 MPa). These research activities are in support of research activities of the European BRITE EURAM program (HITECO), which was created in 1996 to promote the understanding and industrial applications of high performance concretes in high temperature environments, and in which VTT is a partner. The following aspects of HSC are investigated in this program:

- Concrete strength: HSC (C60 - 100) and UHPC
- Thermal stability of materials:
  - Thermal expansion
  - Porosity
  - Acoustic emission analysis
- Mechanical behavior:
  - Stress-strain relationships
  - Total deformation
  - Effect of restraint forces
- Spalling
  - Small specimen
  - Column tests
- Tests on short columns
- Tests on structural members
- Material model for fire exposed HSC

Other partners of the BRITE EURAM program include Bouygues (France), ENEA (Italy), Aalborg (Denmark), Imperial College (England), PARTEK (Finland), CSIC (Spain), and PADOVA (Italy).

Program duration is 3 years (1996-1998). Program deliverables include software, studies of spalling and mechanical behavior, and prenormative recommendations. The National Building Code of Finland for Concrete Structures (Rak MK B4) is one of only a few building codes at present that prescribes a strength reduction curve as a function of temperature specifically for HSC (concrete strength classes of K70 to K100), and a compressive capacity curve for HSC columns as a function of fire duration (applicable up to 120 minutes of fire exposure).

2.2.7 Studies on the Fire Resistance of HPC at the National Research Council/Canada
Presenter: Venkatesh Kumar R. Kodur, National Research Council-Canada (NRCC), Canada

About the presenter:

Dr. Kodur is a research associate at the National Fire Laboratory of the National Research Council in Canada. His expertise is in the areas of laboratory testing and numerical analysis for the evaluation of fire resistance of structural members, and non-linear design and analysis of concrete and steel structures. He is a member of many professional committees, including the ASCE's Fire Protection Technical committee, the Underwriter Laboratories of Canada Task Group on Fire Endurance Tests, and the Canadian Standards Association Technical Committee on FRP Structural Components for Buildings. Dr. Kodur has written or co-authored many articles on the fire resistance of structural members.

Summary of presentation:

Dr. Kodur's presentation is printed in Appendix B, Section B.4.

2.2.8 Spalling of High-Strength LWA Concrete - Cause and Cure
Presenter: M.P. Gillen, Dupont Engineering, U.S.A.

About the presenter:

Mr. Gillen is a Consultant (Engineer) at DuPont Engineering in the Civil Engineering Systems group, with responsibility for providing technical support on concrete design, construction, and repair for DuPont and Conoco facilities. Prior to this position, he was Project Engineer - Concrete on Conoco's Heidrun Tension Leg Platform project in Norway (1992-1994). His past work experience includes ten years as engineer in the Portland Cement Association Fire Research Section, 3 years with Rockwell as concrete/geomechanics laboratory manager at DoE's Hanford facility, and 4 years as research engineer for Conoco's Production R&D Division. He is presently a member of ACI committees on Fire, Corrosion, Nuclear and Hazardous Waste, Offshore Structures (former Chair), and Lunar Concrete.

Summary of presentation:

The Heidrun offshore tension leg platform in Norway is a unique floating platform made with lightweight concrete. The concrete was designed with a design life of 50 years in the North Sea, contained 3% to 4% of silica fume, and had a design compressive strength of 60 MPa. High water pressure exposure tests, done at SINTEF in Norway, showed that the Heidrun platform concrete has extremely low permeability. In fact, after 144 days of exposure to high water pressure, only one aggregate diameter of penetration by the water was observed compared with complete saturation of a 83 MPa normal density concrete after the same exposure. Unfortunately, the unintended effect of low permeability is high vulnerability to fire damage. Upon exposure to a simulated hydrocarbon fire, the Heidrun platform concrete disintegrated due to spalling.

To remedy the increased spalling vulnerability of the Heidrun platform concrete, Conoco initiated a project to study the effects of different variables such as moisture content, curing regimes, and inclusion of steel or polypropylene fibers. The test program consisted of 12 concrete prisms, 300 mm x 300mm x 1500 mm in size. Some specimens were dried at approximately 60 °C for a month prior to exposure to hydrocarbon fire. One specimen was dried at 105 °C until free moisture was completely eliminated. Other specimens included either steel or polypropylene fibers at 0.1% to 0.2% by volume. The lengths of polypropylene fibers varied from 12 mm to 20 mm.

The test results indicated the important role of moisture in the spalling phenomenon. Explosive spalling was observed in specimens pre-dried at 60 °C (moisture was not completely eliminated), and in moist specimens with steel fibers (steel fibers increased the tensile strength of the concrete but resulted in spalling of larger pieces of concrete). However, no spalling was observed in the specimen that was completely predried at 105 °C and in moist specimens that contained polypropylene fibers. Polypropylene fibers with lengths between 150 mm to 200 mm were found to be most effective for the Heidrun concrete. The study concluded that:

- The primary culprit for spalling is moisture.
- Stress and restraint has an influence on the spalling behavior.
- Polymeric fiber addition reduces spalling and offers a tremendous financial advantage over fire protection by passive coatings or other means.

2.2.9 Limitations of Current U.S. Standards and Challenges of Proposed Performance-Based Standards

Presenter: J.A. Milke, Department of Fire Protection Engineering, University of Maryland

About the presenter:

Dr. Milke is an Assistant Professor in the Department of Fire Protection Engineering at the University of Maryland. He has a Ph.D. in Aerospace Engineering and M.S. in Mechanical Engineering, both from the University of Maryland and B.S. degrees in Physics from Ursinus College and Fire Protection Engineering from the University of Maryland. Recently, his research activities have included a description of the sensing mechanisms for a smart fire detector, analysis of water mist fire suppression systems, smoke management and structural fire protection. He is active in several professional societies, including the National Fire Protection Association, Society of Fire Protection Engineers, International Association of Fire Safety Science and American Society of Civil Engineers. Dr. Milke has numerous publications in the fire protection field, principally in the areas of structural fire protection and smoke management.

Summary of presentation:

The text of Prof. Milke's presentation is printed in Appendix B, Section B.5.

2.2.10 Computational Modeling of Temperature, Pore Pressure, and Moisture Content in Concrete Exposed to Fire

Presenter: G. Ahmed, Portland Cement Association (PCA)

About the presenter:

Dr. Ahmed is a Fire Research Engineer at Portland Cement Association in Skokie, Illinois. His primary research activity is in developing heat/mass transfer models for applications to concrete exposed to elevated temperatures. A detailed biography of Dr. Ahmed is not available at the time of this writing.

Summary of presentation:

The text of Dr. Ahmed's presentation is printed in Appendix B, Section B.6.

2.2.11 Analysis of Pore Pressure, Thermal Stress, and Fracture of Concrete in Rapidly Heated Concrete

Presenter: Z.P. Bazănt, Department of Civil Engineering, Northwestern University.

About the presenter:

Born and educated in Prague, Dr. Zdeněk P. Bažant became a professor at Norwestern University in 1973, was named in 1990 to the distinguished W.P. Murphy Chair, and served during 1981-87 as Director (founding) of the Center for Concrete and Geomaterials (a predecessor to the current Advanced Cement Based Material Center). He has authored numerous journal articles and books on stability of structures (1991), concrete at high temperatures (1996), and creep of concrete (1996). He served as Editor (in Chief) of the ASCE Journal of Engineering Mechanics (1988-1994) and is Regional Editor of the International Journal of Fracture. He was founding president of IA-FraMCos, and president of the Society of Engineering Science. He has chaired many technical committees in ASCE, RILEM, and ACI, and is the recipient of numerous awards. He is a Fellow of the American Academy of Mechanics, ASME, ASCE, and ACI, and in 1996 was elected to of the National Academy of Engineering.

Summary of presentation:

Dr. Bazănt's presentation is presented in Appendix B, Section B.10.

2.2.12 Fire Tests on Normal and High-Strength Reinforced Concrete Columns

Presenter: Corina-Maria Aldea, Northwestern University

About the presenter:

Dr. Aldea is a post-doctoral research fellow at Northwestern University, National Science Foundation Center for Science and Technology of Advanced Cement Based Materials, where she was a Fulbright visiting research fellow in 1995-1996. She was a senior assistant professor and head of the French Division of the Department of Engineering Sciences of the Technical University of Civil Engineering in Bucharest, Romania. Her current research areas focus on cement based materials. Most recently she has been involved in studying transport properties in order to quantify concrete durability.

Summary of presentation:
Dr. Aldea's presentation is printed in Appendix B, Section B.7.

2.2.13 Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperatures
Presenter: Gary Consolazio, Rutgers University.

About the presenter:
Dr. Consolazio is a professor in the Department of Civil and Environmental Engineering at Rutgers University, and is an active participant in the Center for Advanced Infrastructure Technology located at Rutgers. His current research areas focus on modeling and measurement of heat and mass flow through concrete at elevated temperatures and pressures, and on the application of finite element analysis techniques to vehicle impact simulation. Most recently he has been involved in the measurement and numerical prediction of pore pressures and temperatures in moist cement mortar specimens subjected to high temperature radiant heating.

Summary of presentation:
The text of Dr. Consolazio's presentation is printed in Appendix B, Section B.8.

3. RESEARCH NEEDS IDENTIFIED BY WORKING GROUPS

The working groups were tasked with identifying research needs within the working group topics that would lead to a better understanding of the fire performance of HSC. Each of the working groups was free to select its own discussion format. In general, the working groups started with free discussion to arrive at a consensus on knowledge gaps relevant to the topics of the working groups and, towards the end of the working group sessions, used the identified knowledge gaps to formulate lists of research needs. The following sections list the research needs that were developed by the four working groups. Even though some similarities exist between lists, the NIST editors decided not to consolidate research needs into a single list, since these similarities reflect the importance of some research needs to more than one working group.

3.1 Working Group A-1: Material Tests

3.1.1 Introduction

This working group addressed research needs related to understanding the effects of short-term elevated temperatures on the mechanical, thermal, and mass transport properties of HSC. The working group was composed of the following individuals:

Y. Anderberg (Chair)	Fire Safety Design	Sweden
L. Bell	FiberMesh	USA
A. Bilodeau	CANMET	Canada
N.J. Carino (Recorder)	NIST	USA
J.R. Clifton	NIST	USA
M. Gillen	DuPont Engineering	USA
U-M. Jumppanen	VTT	Finland
R.E. Moore	Univ of Missouri-Rolla	USA
T. Sander	Univ of Missouri-Rolla	USA

First, the group identified those areas in which there is a serious lack of knowledge related to the materials performance of HSC when exposed to high temperatures. Input from workshop invitees, that were provided prior to the workshop, were reviewed. Based on that information and the personal knowledge of working group members, the following were found to be the areas where there are significant knowledge gaps:

(1) Spalling mechanism and methods to prevent or control spalling

This is by far the most important knowledge gap in the fire performance of HSC. As reviewed in the NIST state-of-the-art report [Phan 1996], spalling has been observed in some but not all high-temperature tests of HSC. It is generally believed that spalling results from the buildup of internal pressure due to the transformation of water to vapor. The pressure buildup is believed to result from the extremely low permeabilities of concretes with low water-binder ratios. However, thermal gradients may also play a role in the development of internal stresses that contribute to the spalling phenomenon. While progress has been made in modeling heat conduction and mass transport in concrete subjected to high external temperature, additional work is needed to link these calculations to the buildup of internal stresses and to verify the accuracy of model predictions. When a verified model has been developed, it can be used in parametric studies to determine the effects of different conditions on the internal state of stress (or strain) during fire exposure. A useful outcome of the parametric study would be to identify those conditions that minimize the possibility of spalling during a fire, including an explanation of why the addition of polymeric fibers has been found to reduce the severity of spalling.

(2) Properties of HSC as a function of temperature

In order to be able to predict the performance of a reinforced concrete structure during a fire, it is necessary to know how the properties of concrete are affected by temperature. These properties include the "constitutive properties" such as ultimate strength and stress-strain behavior, and other "material properties," such as thermal and mass transport properties. The latter properties are essential for developing a material model to predict the buildup of internal stress (or strain) during heating.

(3) Effects of composition and processing variables on the performance of HSC at elevated temperature

To produce concrete that is least susceptible to damage during fire, it is necessary to understand how changes in composition and processing affect performance. Since there are numerous possible combinations of materials, proportions, and processing conditions (curing methods, maturity at time of fire exposure, etc.), a model to predict performance for a given set of parameters would be an efficient means for identifying those conditions that would result in the best performance. Limited testing could be used to verify model predictions.

(4) International standard test methods

A major problem in comparing data on fire performance from different laboratories is the lack of common test methods. RILEM Committee 129-MHT on Test Methods for Mechanical Properties of Concrete at High Temperatures is in the process of developing a set of recommendations that may provide the basis for future international standards.

In experimental assessments of the performance of concrete exposed to elevated temperature, several key features of the test methods need to be considered in order to interpret and compare results [Phan 1996; Anderberg 1983]. These include:

- temperature distribution in the test specimen during the measurement of material properties,

- relationships between temperature and load histories, and
- type of loading.

The nature of the temperature distributions during testing can be characterized by considering two groups of tests:

- *Steady-state test*—The specimen is heated slowly to a target temperature; the external temperature is held constant to allow the internal specimen temperature to reach a uniform value; the properties are measured after a uniform internal temperature is reached.
- *Transient test*—The specimen is exposed to an ambient temperature that increases at a relatively fast rate so that temperature gradients exist in the specimen during the test. During the heating, the specimen could be subjected to a constant load or a constant deformation (restraint provided).

Steady-state tests are better suited for measuring the effects of temperature on material properties, and transient tests are better suited for investigating behavior under conditions that may be encountered during an actual fire. Thus transient tests are usually used for tests of structural elements.

In addition to the temperature distribution during testing, another important feature of elevated temperature tests is the relationship between temperature and loading histories. For steady-state tests, three types of tests are commonly used to characterize the effects of temperature on material properties:

- *Unstressed test*—The specimen is heated to the target temperature in the absence of stress, and the specimen is loaded after a steady-state condition has been reached.
- *Stressed test*—The specimen is loaded at room temperature to a fraction of its room temperature strength; the specimen is heated to a target temperature; and, after a steady-state condition is reached, the specimen is tested.
- *Residual property test*—The specimen is heated to a target temperature and maintained until a steady-state condition is reached, then it is cooled to room temperature, and tested at room temperature.

These three types of steady-state tests are illustrated in Fig. 3.1, in which the upper graphs are schematics to show the temperature histories and the lower graphs show the loading histories.

Finally, different methods of loading are possible to measure mechanical properties. These include:

- *Stress-rate control*—The stress is increased at a constant rate.
- *Strain-rate control*—The strain is increased at a constant rate.
- *Constant stress (creep)*—Stress is maintained constant and deformation is measured as a function of time.
- *Constant strain (relaxation)*—Strain is maintained constant and stress is measured as a function of time.

The first two of these are commonly used to develop the stress-strain relationship of the concrete. However, the most common loading method is using strain (or deformation) control, because of the instability that occurs in stress-rate controlled tests as ultimate capacity is approached. The latter two types of loading are used to measure time-dependent response, and these may be of limited importance considering the relatively short duration of a fire.

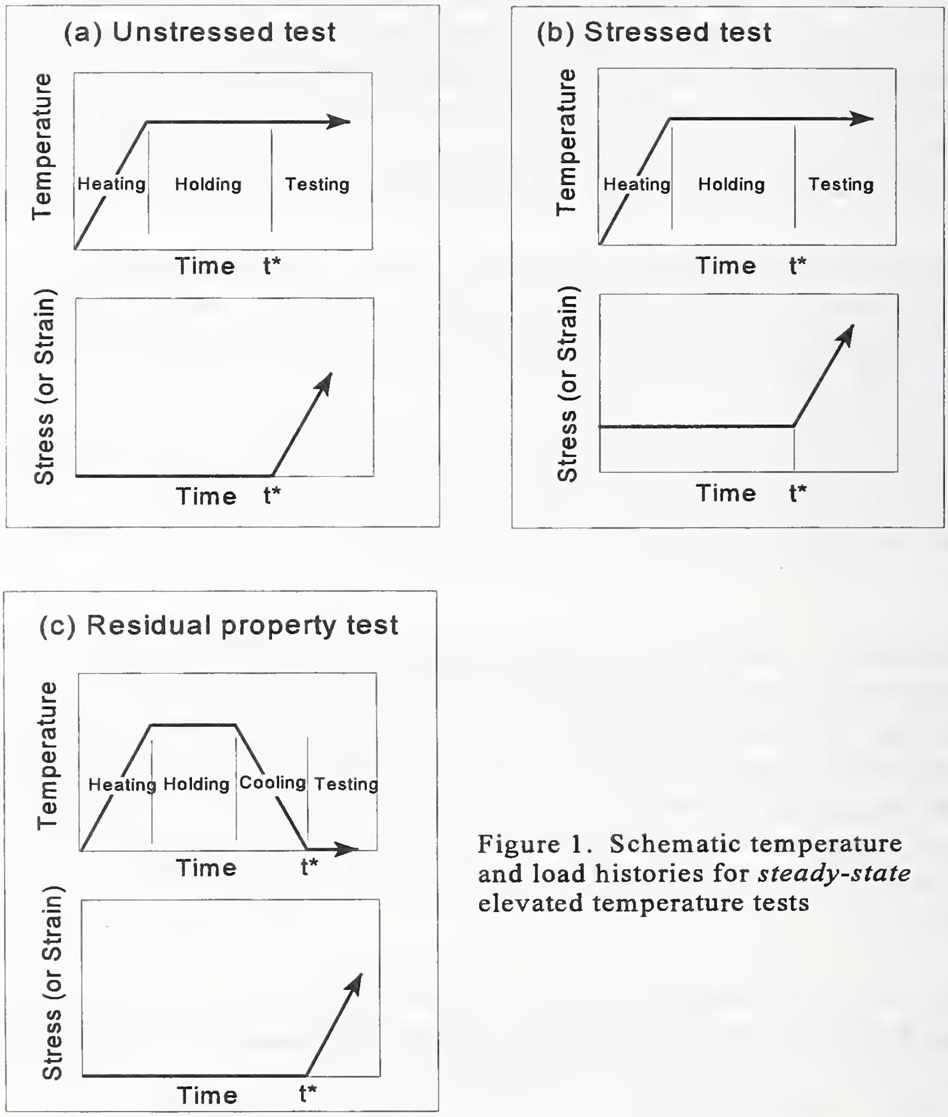

Figure 1. Schematic temperature and load histories for *steady-state* elevated temperature tests

(5) Methods for evaluating performance of local aggregates

Aggregate properties are known to have a strong influence on the performance of concrete during a fire. However, there are no standard procedures for the selection of the suitable aggregate for improved fire performance. Simple tests or selection criteria would be helpful in evaluating the suitability of a particular aggregate.

(6) Guidelines for evaluation of fire-damaged structures

While not restricted to HSC, there is a need for standard practices to permit economical and reliable evaluation of the extent of damage due to fire. Such information is vital for evaluating the safety of a structure exposed to a fire and for delineating the extent of damage in order to develop a repair strategy. The working group felt that this topic could also fall under the domain of the "element tests" group.

3.1.2 Research Needs

The following research areas were discussed in relation to the above-mentioned knowledge gaps. Each research area is followed by a brief discussion of the scope of required work.

(1) Develop an understanding of the spalling mechanism(s) and establish a predictive parameter and standard test method(s) to measure it

Discussion: It would be desirable to develop a parameter that could be used to evaluate the spalling potential of HSC when exposed to fire. In the area of refractory concretes, it has been found that a parameter that includes permeability, tensile strength, porosity, and moisture content has been found to be useful in predicting susceptibility to spalling during the de-watering process prior to exposure to refractory temperatures. A combination of experimental and analytical studies will likely be needed to gain the understanding to develop this parameter.

In order to validate the results of analytical predictions of stresses leading to spalling, experimental data are needed. Such data might include measurement of internal pore pressures and moisture distributions during heating of a test specimen.

A major component of the research will involve studies of the effects of compositional and processing factors (curing methods, maturity, self-desiccation) on spalling tendency. In addition the effects of other factors, such as magnitude of thermal gradients, reinforcement location, geometrical constraints, size, and presence of stress on spalling tendency should be considered. Also, the effects of thermal exposure conditions (rate of temperature rise, maximum temperature, direct exposure to flames, and uniformity of exposure conditions) should be examined. The results of this work should allow understanding of why spalling has not always been observed in tests of HSC.

When the factors that contribute to occurrence of spalling are understood, it should be possible to develop methods to mitigate spalling tendency. Included among potential methods would be the use of "sacrificial" synthetic fibers and "reinforcing" steel fibers. The long-term product would be the development of recommended guidelines or practices for producing HSC that will resist spalling when exposed to fire.

(2) Measurement of properties of HSC as a function of temperature

Discussion: Knowledge of HSC properties ("intrinsic") at high temperatures forms the foundation for evaluating the performance of fire-exposed reinforced concrete elements. In order to permit the comparison of data from different research programs, it will be necessary to establish a suite of standard test methods. In developing these methods, distinctions will need to be made between transient and steady-state tests. Also, distinctions are needed between properties measured at high temperatures versus those measured at room-temperature after heating (residual properties). Guidelines will need to be developed on which types of tests should be used for different purposes. Factors such as maturity and conditioning prior to testing need to be studied and standardized.

Past studies have focused on the effects of temperature on compressive strength and elastic modulus. However, the scope of future studies should be expanded to include other mechanical properties such as tensile strength, time-dependent behavior, and fracture mechanics parameters. Splitting tensile tests have been found to be useful in studies of refractory concretes and should be applied to HSC.

Methods should be established for determining relationships between mechanical properties and microstructural changes (porosity, pore structure, nature of interfacial zone, and microcracking). The effects of specimen shape and size and of previous load histories on measured properties should also be understood.

In addition, other material characteristics need to be measured as functions of temperature to provide input data for numerical models. These other characteristics include transport properties (permeability, diffussivity, etc.), thermal properties (thermal conductivity, heat capacity, etc.), sorption isotherms, and water release during dehydration.

(3) Methods for evaluating local and manufactured aggregates for optimizing fire resistance of concrete

Discussion: Practical methods are needed to evaluate different aggregate sources so that those that can be expected to result in poor performance during fire can be eliminated during the selection of materials for HSC mixtures to be used in critical structural elements. Characteristics such as coefficient of thermal expansion and physico-chemical reactions leading to volume changes need to be understood. In addition, methods are needed to identify aggregates with bound water that can be released during fire exposure and contribute to the development of internal pressure.

(4) Methods for evaluation of fire damage

Discussion: There have been advances in nondestructive testing methods to evaluate concrete. There should be investigations of the applicability of advanced techniques based on stress-wave propagation (e.g., acoustic tomography and spectral analysis of surface waves) and microwave radiation to evaluate the extent of damage after a fire. Other techniques based on the scanning electron microscope (micrographic and chemical analysis) should be developed for more in-depth analysis of microstructural damage or changes of samples taken from the affected structure.

3.2 Working Group A-2: Element Tests

3.2.1 Introduction

The working group addressed research needs related to the effects of short term, high temperatures on the behavior, load bearing capacity and structural integrity of various structural elements, such as columns, beams, slabs, wall panels, etc., made of high strength concrete. The working group was composed of the following individuals:

C.-M. Aldea	Northwestern University	U.S.A.
L. W. Bell	Fibermesh	U.S.A.
R. G. Burg (co-Chair)	Construction Technology Lab.	U.S.A.
U. Diederichs (Chair)	IBMB / MPA Braunschweig	Germany
D. Duthinh (recorder)	NIST	U.S.A.
W. L. Gamble	Univ. Of Illinois, Urbana-Champaign	U.S.A.
G. C. Hoff	Mobil Technology	U.S.A.
J. J. Jensen	SINTEF	Norway
U. M. Jumppanen	VTT Building Technology	Finland
V. Karthigeyan	HSB-OSD (Health and Safety)	U.K.
V. Kodur	National Research Council	Canada
T. D. Lin	Fire Laboratory	Taiwan

First, the group attempted to establish a definition of high strength concrete which, up to now, varies from country to country. In general, as the concrete compressive strength increases, fire tests are fewer, and less is known about concrete fire performance. Most fire test data are for normal strength concrete, with compressive strength less than 50 MPa. On the other hand, some codes define HSC as concrete exceeding a certain compressive strength (40 MPa for ACI, 55 MPa cube strength for the German Code). Since the water-to-binder ratio[1] can be used to predict the difference in the spalling behavior of NSC and HSC under fire (with $w/b \approx 0.4$ being the transition), it was suggested that the w/b ratio could serve to define HSC for the purpose of fire testing.

3.2.2 Research Needs

(1) Spalling Mechanisms and Methods to Prevent or Control Spalling

Discussion: Explosive spalling has been observed in tests of elements of reinforced HSC and also in cylinder or cube tests (material tests). The phenomenon is not completely understood, and spalling behavior occurs inconsistently, sometimes with two identical specimens heated identically behaving quite differently. Although spalling is undesirable, it is not necessarily catastrophic. It was

[1] Water-binder ratio is widely used in Europe, while in North America the term commonly used is water-cementitious material ratio.

reported that, in a recent panel test, the cover concrete spalled off, but the concrete inside the reinforcement was relatively undamaged. When polypropylene fibers were added to the concrete, their effect was to delay the onset of spalling, which involved larger chunks of concrete when it finally occurred.

Although existing analytical models are not adequate due to the complexity of the phenomenon, it is safe to predict that material tests alone will not suffice in predicting spalling behavior, as the effects of reinforcement and cover depth have shown. Element size and shape are also likely to be important. Element tests are therefore needed to study spalling mechanisms and methods to prevent or control spalling in actual structures.

(2) Application of Laboratory Test Results to Actual Structures

Discussion: For NSC, laboratory fire tests have been successfully extrapolated to actual structures. However, because the fire resistance behavior of HSC is not completely understood and predictable, this cannot yet be done for HSC. As the specimen size, material properties (compressive strength, *w/b* ratio, concrete moisture content) and the reinforcement design change, the behavior also changes.

Clearly, a behavioral model is needed. Also needed is a number of tests to verify and calibrate the model, which should also include scaling laws, i.e., account for size effects in order to translate reduced scale laboratory tests to full scale prototypes.

(3) Development of Test Protocols

Discussion: There is a need to develop international test protocols for fire testing of HSC members. Current standards were developed for NSC and may not be appropriate for HSC. For example, it does not make sense to pre-dry HSC specimen to 75 % relative humidity as is recommended for NSC because this could have a direct effect on the test results.

Guidelines for data collection and reporting should also be established. For example, reinforcement details are important in understanding spalling behavior, and yet are often unreported. Guidelines on measurement of deflections, visual recording of overall behavior, weighing of spalled pieces, etc. would also be most useful. It was suggested that a standards organization, such as NIST, is ideally suited for such a task.

(4) Tests of Connections

Discussion: Individual members, cylinders and cubes are fire tested much more often than entire frames or joints between members, because of the size and cost associated with the latter. However, these tests are necessary for understanding and predicting the behavior of structures under fire. This is particularly important in the case of connections between columns of HSC and slabs of NSC.

(5) Determination of Residual Strength

Discussion: Most structures damaged by fire do not collapse. However, they may have to be demolished because of uncertainty about their residual strength. This is true of NSC and HSC. Much can, and should be learned from post-fire evaluations of residual structural capacity. The effectiveness of repair methods should also be evaluated.

(6) Effects of Fire Extinguishing

Discussion: An example was cited about a building on fire that collapsed when a critical HSC column was doused with cold water and suffered terminal thermal shock. It is a rare fire laboratory that allows investigation of the effect of fire extinguishing measures, because of possible damage to equipment and instrumentation. However, the need is there, to ensure that the remedy is not worse than the disease.

(7) Prioritization of Element Tests

Discussion: HSC is being increasingly used in structural applications. To balance the need for fire safety and the limited resources and cost involved in research, element tests should be prioritized in terms of urgency. Since the most widely used HSC elements are columns, they should be high on the priority list. Questions arise as to the loading (centric or eccentric), fire exposure (symmetrical or asymmetrical), concrete strength, column size and shape, reinforcement design, presence or absence of fibers in the concrete, etc. Doubts were expressed that a sufficient data base exists on the the behavior of HSC (unlike NSC) columns under normal service temperatures. HSC, sometimes with lightweight aggregate, is also increasingly used in precast, prestressed elements and hollow core slabs. Also, there have been more recorded fires in buildings under construction (due to welding, cold weather curing of concrete, etc.), than in completed buildings. So, the fire tests of elements made of young or lightweight, high strength concrete are called for.

It was suggested that NIST, after having reviewed existing data, is in an excellent position to propose such prioritization. In this context, NIST should also review the capability of existing fire laboratories worldwide and compile a detailed description of known future test programs.

3.3 Working Group B: Analytical Studies

3.3.1 Introduction

A comprehensive theoretical understanding of how high temperatures during a fire cause spalling of concrete is not yet known. In general, this knowledge gap is accompanied by the lack of established practical models that can take into account the material properties of concrete and how these properties affect fire performance. Computer models that have some of these capabilities need further development. The charge of this working group was to: identify knowledge gaps for HSC pertinent to its fire performance; and identify research needs for purposes of filling knowledge gaps and complementing the recommended analytical work. Transport phenomena (leading to pore pressure) buildup and thermal stresses are focal points as primary contributing factors of high-temperature induced spalling. Further investigation is needed to determine the relative impact that each of these has on the spalling condition such that a design solution may be developed to reduce or eliminate this event. Members comprising the working group included the following:

J.P. Hurst (Chair)	Portland Cement Association	U.S.A.
E. Garboczi (Recorder)	NIST	U.S.A.
G. Ahmed	Portland Cement Association	U.S.A.
Z.P. Bažănt	Northwestern University	U.S.A.
G.R. Consolazio	Rutgers University	U.S.A.
L. Cooper	NIST	U.S.A.
N. Martys	NIST	U.S.A.
F-J. Ulm	LCPC	France

3.3.2 Research Needs

(1) Transport Phenomena

(a) Coupled heat and mass transfer leading to pore pressure prediction

Discussion: There was a lengthy discussion on whether pore pressure buildup or thermal stresses had a greater impact on the initiation of spalling. After much debate, it remained undetermined, with both requiring further investigation. One of the compelling arguments for pore pressure as a significant contributor to spalling included measured results showing that pore pressure does not immediately dissipate to zero at a crack or gap in the concrete. Instead, pore pressure bridges the gap by experiencing a slight decrease, and then continues to build up again. Additional support came from laboratory results accentuating the success of reduced, or no spalling when polypropylene fibers are added to HSC mixtures. Since the introduction of fibers would not have been expected to relieve thermal stresses, it follows that the relief of pore pressure must have been paramount in the improved spalling behavior. This behavior needs to be further investigated to better understand the process of how and why fibers are effective in this capacity. It was agreed that subsequent modeling of HSC for heat and mass transfer should be done in consideration of the cases with and without polymeric fibers.

(b) Investigation of new numerical methods to handle the saturated-unsaturated interface zone

Discussion: The success in handling numerical modeling difficulties that occur at the sharp liquid-vapor interface (saturated-unsaturated) zone in concrete when heat is applied varies with different numerical techniques used. Philosophical differences expressed in the workshop on how to adequately handle this zone from a numerical standpoint indicated the need for detailed examination of existing numerical methods such as the ones successfully used in Ahmed's model [Ahmed, 1995] and, perhaps, their modification or the development of new methods.

(2) Thermal stress analysis with inclusion of fracture mechanics

Discussion: At present, a consensus with regard to what is the principal cause, between thermal stresses and pore pressure effects, for the spalling of fire-exposed HSC has not been reached. Analysis of internal stresses in HSC elements, caused either by thermal stresses or pore pressure buildup, with consideration of other factors such as creep and shrinkage must be made in order to determine the relative importance of thermal stresses and pore pressure, on the tendency for spalling in fire-exposed HSC. Fracture mechanics principles may be necessary to predict cracking.

(3) Coupling of pore pressure and fracture process

Discussion: Accurately measuring and predicting pore pressure buildup during a fire situation is not enough. Pore pressures must be quantitatively linked to spalling of concrete. Experimental data showing that pore pressure does not drop to zero when a crack forms led to a new approach in analyzing the initiation of spalling. Thus modeling to predict spalling should include the effect of cracking and interaction between the pore pressure and the crack.

(4) Coordination with other groups regarding material and element testing

Discussion: In order to be able to predict pore pressures and thermal stresses at fire temperatures, and link these to a methodology for determining concrete damage, various material properties must be known. Measurements that must be made include material strengths at elevated temperatures, specific heat and thermal conductivity, density, initial moisture content, porosity and permeability, sorption isotherms, mass loss with temperature along with the effect of heating rate, validation tests of fracture including size effect, moisture migration measurements, pore pressure measurements, effect of fibers on porosity and permeability (polypropylene and other polymeric fibers), fracture properties at high temperature and different amounts of saturation, plasticity of concrete-filled steel tube columns at elevated temperatures, and data bases for tests of fracture and other size effects. This list of activities needs to be cross-referenced with those of the other working groups for inclusion of additional tests.

3.4 Working Group C: Codes and Standards

3.4.1 Introduction:

Research needs on fire performance of HSC that are in the domain of codes and standards were identified by this working group, and are described and discussed in this section. Working group C: *Codes and Standards* was composed of the following members:

J.A. Milke (Chair)	University of Maryland	U.S.A.
L.T. Phan (Recorder)	NIST	U.S.A.
W. Jones	NIST	U.S.A.
J. Messersmith	Portland Cement Association	U.S.A.
V. Karthigeyan	HSB-OSD (Health and Safety)	U.K.
L.W. Bell	Fibermesh	U.S.A.

3.4.2 Research Needs:

(1) Standard Test Protocols for Determining Engineering Properties of Fire-Exposed HSC

Discussion: Most current engineering properties data at elevated temperature were obtained by testing HSC specimens using different heating rates, specimen sizes and shapes, and loading histories. These differences may result in incompatible test results, especially for HSC since the rate of pore pressure buildup and the moisture escape path affect the performance of the test specimen. In order to permit the comparison of data from different laboratories, it will be necessary to establish a suite of standard test methods. These test methods will consider the differences between transient and steady-state tests, and between properties measured at elevated temperatures versus those measured at room-temperature after heating (residual properties). Guidelines will need to be developed on which types of tests should be used for different purposes.

(2) Mechanical Properties-Temperature Design Curves for HSC

Discussion: At present, the most used concrete strength and modulus of elasticity-temperature relationships are those prescribed by the Eurocodes [CEN ENV 1994-1-2] and recommended by RILEM Committee 44-PHT [CEB Bulletin D'Information N° 208]. These design curves were based mostly on experimental data of normal strength concrete and are useful for estimating mechanical properties of NSC exposed to high temperature. However, these design curves have been shown to be unconservative when applied to HSC [Phan, 1996]. On the other hand, the Finnish Code [High Strength Concrete, *Supplemental Rules* and Fire Design *RakMK B4*] prescribes a strength-temperature design curve specifically for HSC with compressive strength in the range of 70 MPa to 100 MPa. This design curve is applicable for both *stressed* (preload of up to 30% of room temperature compressvie strength) and *unstressed* test conditions. A comparison with existing test data shows that, while the Finnish strength-temperature curve is more applicable to HSC than those prescribed by the Eurocodes, it is still slightly unconservative in the temperature range of 200 °C to

400 °C, especially for the case of *unstressed* test of HSC with lightweight aggregate. Mechanical properties-temperature design curves, similar to those prescribed by the Finnish and Eurocodes, should be incorporated into U.S. codes to aid in fire design of HSC structures. These curves might include modification factors to account for variations such as different aggregate types used in the United States. Such design curves are also helpful for assessing the residual strength of HSC after a fire. Additional data are required to develop reliable design curves.

(3) Guidelines for Interpretation of HSC Material Tests and Standard Fire Tests

Discussion: Engineering properties of HSC at elevated temperature are obtained by testing HSC cylinders or prisms. The measured properties are typically related to the temperature measured at the center of the specimens and are dependent on, among other things, heating rate. Whereas the current standard fire tests, such as ASTM E 119 and ASTM E 1529, prescribe procedures for fire testing of structural assemblies by subjecting the assemblies to standard temperature histories. These standard temperature histories characterize the ambient environment inside the test chamber, but not necessarily the temperature and the rate of temperature development within the test assemblies. Thus the results of these two types of tests are not directly comparable. Guidelines should be developed to permit the comparison of the results of these tests so that the measured engineering properties, obtained from cylinder or prism tests, can be used to explain the fundamental behavior of the structural assemblies when tested in accordance with these ASTM standard fire tests.

(4) Guidelines for Selecting Realistic Design Fire Exposures

Discussion: At present, ASTM E 119 and E 1529, ISO 834, and JIS A 1304 prescribe fire testing of structural assemblies using standard temperature histories that are characterized by a controlled heating rate. These standard fire exposures do not represent likely temperature histories of real fires. As a result, the fire exposure conditions specified in these standard test methods are not necessarily representative of the conditions that may exist in real fires. With the current tendency of moving towards performance-based standards, it is necessary to provide guidance for the selection of realistic design fire exposures which are particularly suitable for the specific HSC structure being evaluated.

(5) Guidelines for Fire Design of HSC Structural Elements

Discussion: Guidelines for the fire design of HSC structural elements, which allow the calculation or assessment of the fire resistance period and load carrying capacity of structural elements, are not available in U.S. codes and standards. Such guidelines are needed for fire design of HSC structures and should incorporate the different responses due to differences in structural element types (beam, column, wall, or slab), HSC engineering properties, applied loads, and HSC spalling characteristics.

(6) Design Guidelines to Mitigate Spalling in Fire-Exposed HSC

Discussion: Limited experimental studies have shown that the risk of explosive spalling in fire exposed HSC can be reduced by using appropriate design detailing, such as optimal sizes and spacing of transverse reinforcement, concrete cover, etc., and additions to the concrete such as steel and polypropylene fibers. The effects of these design details and mixture additions should be studied and results should be incorporated into design guidelines to reduce the risk of explosive spalling in HSC structures during a fire.

4. RELEVANT RESEARCH PROGRAMS WORLDWIDE

4.1 Introduction

Prior to the workshop in February, NIST staff contacted researchers from various laboratories worldwide to request information on research activities relevant to the subject of performance of HSC at elevated temperatures. The feedback came from researchers, many of whom were able to attend the workshop, in laboratories of 11 countries, including Sweden, Italy, Germany, France, Canada, Taiwan, United Kingdom, Norway, Finland, Australia, and the United States. This chapter provides general information on these research programs as well as points of contact from whom additional information on the respective research programs may be obtained. Both recently completed and on-going projects within each research program are listed.

4.2 Organizations Performing Research and Descriptions of Research Programs

4.2.1 Fire Safety Design (FSD), Lund, Sweden

Program Description

As part of the Swedish national project on High Performance Concrete (HPC), FSD has been working on Fire Performance of HPC since 1992 and is now finishing the work by developing fire design methods for HPC beams, slabs, and columns. In the project numerous fire tests have been performed on small HPC specimens and structural elements. The objectives are to investigate, assess, or develop:

- The risk and tendency of spalling of HPC specimens at different heating rates and load levels for various concrete mixtures.
- The influence of polypropylene fibers on spalling tendency.
- Thermal properties as a function of temperature for the development of analytical expressions.
- Material properties and constitutive laws.
- Analytical simulations of small HPC test specimens.
- Analytical simulations of fire tested HPC columns.
- Fire design methods for HPC beams, slabs, and columns.

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4.2.2 Milan University of Technology, Milan, Italy

Program Description:

As part of a joint Research Project financed by the European Communities and a number of industrial partners and research institutions (the Italian National Agency for Energy, New Technologies and Environment - ENEA), a multi-faceted research program is in progress in Milan to study the fire performance of siliceous HSC (f_c = 72 MPa to 95 MPa) and special microconcretes (Reactive Powder Concretes and Compact Reinforced Concretes, f_c = 170MPa to 200 MPa). The objectives are to (1) measure the complete stress-strain curves, in compression and in tension, of HSC at room and elevated temperatures (up to 500 °C); and (2) evaluate HSC fracture parameters (fracture energy, characteristic length, toughness index) as a function of temperature. Both the material and the structural behavior are investigated, since the thermally-induced softening of concrete favors stress redistribution in a structure, making the overall structural behavior less sensitive to high temperature than the material itself. The project consists of four phases:

(1) Compression and tension behavior of flint-based HSC: residual properties after a cycle at 105°C, 250°C, 400°C and 500°C (heating and cooling in quasi-steady conditions, with 12 hours at the maximum temperature), notched (tension) and unnotched (compression) cylinders (f_c = 72 MPa and 95 MPa).
(2) Deep beams subjected to 3-point bending and circular slabs subjected to punching (both reinforced and unreinforced): residual capacity (load-displacement behavior included) after a thermal cycle at 105°C, 250°C and 400°C (flint-based concrete with f_c = 72 MPa).
(3) Fracture behavior of flint based HSC (f_c = 72 MPa and 95 MPa): evaluation of the fracture energy per unit volume in the case of multiple or distributed cracking (pied prisms, for evaluating the damage density in tension and the characteristic length) after a cycle at high-temperature (T = 105 °C-400 °C).
(4) Tension behavior of one high-strength calcareous concrete (f_c = 95 MPa) and of two very high-strength fiber-reinforced microconcretes: the stress-strain and stress-crack opening curves will be determined at high temperature (T = 105 °C-400 °C). Special dumbbell-shaped and notched specimens have been cast in order to make it possible to extract the measures from the specimens loaded inside the furnace; the specimens are provided with special threaded ends that permit their attachment to the testing machine platens; the tests will be displacement-controlled, as in all previous cases. This phase of the project is being carried out in close collaboration with Prof. Gabriel A. Khoury at the Department of Civil Engineering of Imperial College in London. Further tests regarding the residual behavior after the thermal cycle will be carried out in Milan, as well as most of the data processing.

Phases 1 and 2 are completed, Phase 3 is well advanced, and Phase 4 is in the initial stage.

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4.2.3 Institut für Baustoffe, Massivbau und Brandschutz (IBMB), Braunschweig, Germany

Program Description:

- Joint project BRITE EURAM program (HITECO), funded by the European Community to develop *"understanding and industrial applications of high performance concretes in high temperature environments."* Industrial and research institute partners include: Bouygues (France), ENEA (Italy), Aalborg Portland Cement (Denmark), VTT (Finland), Imperial College (England), PARTEK (Finland), CSIC (Spain), and Padova Ricerche (Italy). Program duration is three years, from 1996 to 1998. Materials studied include 90 MPa -100 MPa HPC and ultra high performance concrete (UHPC) with strength of at least 150 MPa. Program deliverables include: Software, spalling indicators, description of mechanical behavior, and prenormative recommendations.

- Completed project concerning fire behavior of HSC elements under Compression - Elaboration of Calculation Bases for the Load Bearing and Deformation Behavior. This project was funded by the German Industry Research and Development Foundation (AiF) and the Federal Ministry of Economics. The result is proprietary and reported in German.

- Completed investigations of thermal and mechanical characteristics of HSC exposed to fire (Diploma work by Carsten Schwarz, IBMB/MPA Braunschweig, in German).

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4.2.4 Portland Cement Association, U.S.A

Program Description:

- The project High-Temperature Properties of High-Performance Concrete was being conducted by Construction Technology Laboratories (CTL) and was scheduled to be completed by early 1997. In this project, 76 mm x 150 mm cylinders, of representative HPC mixtures, 69 MPa to 148 MPa, were to be cast and such parameters as permeability, rate of drying, moisture content, and strength development were to be measured. These samples were to be subjected to a number of different high-temperature exposures. Factors such as strength degradation, stiffness changes, spalling potential, and moisture movement were to be measured on specimens that are restrained and unrestrained during heating. Measurements were to be taken at elevated temperatures as well as on specimens allowed to return to ambient temperatures. These data will allow for the development of models of high-temperature material behavior of HPC.

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Program Description:

- A Full-scale HSC column fire test program is to be conducted by PCA. The concrete will include carbonate and siliceous aggregates. Six columns have been tested with at least three more planned. There is a possibility of a fourth column being tested containing polypropylene fibers. Test results are scheduled to become available at the end of 1997.

- A project was completed in 1996 on the thermal properties of carbonate aggregate HSC at elevated temperatures. PCA R&D Serial No. 2031 was published to summarize the project. The report includes results of measurements of thermal conductivity, thermal diffusivity, and mass loss at elevated temperatures.

- PCA Publication RD104T (1994), "Engineering Properties of Commercially Available High-Strength Concretes (Including Three-Year Data)" summarizes the results of a non-fire related test program.

- Fire endurance of carbonate aggregate HSC slabs: A paper was published in the ACI Materials Journal (March-April 1988). It compares the fire resistance of HSC slabs with those of normal strength concretes. The fire resistance is based on the heat transmission criteria in ASTM E119.

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4.2.5 Laboratoire Central des Ponts et Chaussees (LCPC), France

Program Description:

- French National Research Project "BHP 2000" ("HPC 2000"), Work-Group 2: "Tenue Au Feu (Fire Resistance)". Project in progress:

  - Comportement des Beton Haute Performance vis-a-vis de L'eclatement - Modelisation (Spalling Behavior of HPC - Modelling), by C. Casselman and O. Corydon, I.P.S.N.
  - Proprietes des BHP a Hautes Temperatures - Etude Bibliographique (Properties of HPC at High Temperatures - Literature Survey), by P. Pimienta and A. Leduff, CSTB.
  - Modelisation du Comportement des BHP vis-vis-vis de L'eclatement - Etudes en Laboratoire et Determination des Caracteristiques Necessaires au Modele, Rapport D'etape (Modelling Spalling Behavior of HPC - Experimental Study and Determination of Modelling Characteristics, Progress Report), by P. Kalifa, CSTB.

- Assessment and repair of damage due to fire in the Channel Tunnel in 1996. Project in progress. States of the materials before and after the fire are examined.

- Physical mechanisms and modeling of the behavior of concrete at high temperature. Project being planned.

- European Research Program on Nuclear Fission Safety: "Containment Evaluation Under Severe Accident."

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4.2.6 Rutgers University, U.S.A.

Program Description:

An experimental laboratory facility is being set up in the Department of Civil and Environmental Engineering at Rutgers University for the purpose of measuring pore pressures and temperatures in moist high- strength concrete exposed to elevated temperatures. This laboratory is scheduled to become operational in the summer of 1997 and will provide experimental data needed to refine numerical analyses. At present, numerical simulations are being conducted to study several key aspects of the performance of high-strength concrete in fires.

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4.2.7 University of Missouri-Rolla, U.S.A.

Program Description:

Under the auspices of the American Iron and Steel Institute (AISI), three projects are ongoing at the University of Missouri-Rolla:

- The simulation of explosive spalling of refractory concrete (calcium aluminate based).
- The measurement of air permeability of refractory concretes using a vacuum decay method. Permeability changes are being measured as a function of:

  a) thermal treatment
  b) concrete composition (original mixture)
  c) additives including chemicals and polymeric fibers

- "Postmortems" of large specimens exposed to one-sided heating involving measurement of key properties along the thermal gradient and explaining the relationships between thermal gradient and texture/property gradients.

AISI quarterly reports are confidential but a recent summary has been published. Comparable work on refractory concretes is unknown at this time.

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4.2.8 National Research Council-Canada (NRCC)

Program Description:

- An experimental and analytical project, which aims to develop design guidelines for fire design of HSC columns for incorporation into the National Building Code of Canada, is being undertaken by the NRCC in collaboration with industry (PCA, CPCA), research organizations such as Concrete Canada (a Center of Excellence of the Canadian government) and the National Chiao Tung University (NCTU) in Taiwan. As part of this project, 48 reinforced HSC columns are being fabricated and tested. These include 20 plain HSC columns and 28 fiber reinforced HSC columns. Both steel and polypropylene fibers are being considered (8 columns include steel fibers and 20 columns include polypropylene fibers). The 28-day compressive strength is about 90 MPa. Both silicious and carbonate aggregates concrete are used. The full-scale columns will be subjected to the standard time-temperature curve given by ASTM E119. Variables to be studied include section sizes, shapes (circular and square), spacing of the ties, load intensities, as well as the end support conditions.

- Fire tests were conducted on HSC-filled steel columns. This project was conducted to quantify the effect of the type of concrete on the fire resistance of concrete filled steel columns. Three types of columns were studied: (1) filled with plain concrete; (2) filled with concrete reinforced with traditional bars; and (3) filled with steel fiber reinforced concrete (1.75% fibers by mass). Both normal strength (40 MPa) and HSC (80 Mpa to 90 MPa) were used in the experimental as well as numerical studies. Circular and square cross sections were considered. Upon completion of the tests on the normal strength concrete filled columns and numerical studies, design guidelines will be incorporated into the Canadian building code.

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4.2.9 Fire Laboratory of Architecture and Building Research Institute (ABRI), Taiwan

Program Description:

A National Research Council-Canada/National Chiao Tung University (NRCC/NCTU) joint test program on fire performance of HPC is being conducted. The current project is for 3 years (1996-1999). The collaboration calls for the NRCC to provide about 300 HSC cylinders (100 mm by 200 mm, minimum strength of 70 MPa) for high temperature stress-strain tests at the NCTU in Taiwan. The NCTU is to fabricate 15 full-scale HSC columns and to ship the columns to the NRCC for load and fire resistance tests in Canada.

The NRCC cylinders are made of siliceous aggregate, siliceous aggregate plus steel fibers, carbonate aggregate, and carbonate aggregate plus steel fiber. The NCTU columns have square cross sections (305 mm x 305 mm x 3810 mm) and concrete strength exceeding 70 MPa. The concretes include siliceous aggregates, carbonate aggregates, steel fibers, glass fibers, and polypropylene fibers in various combinations.

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4.2.10 City University, London, U.K.

Program Description:

A three year national research program on explosive spalling of high strength concrete at fire temperatures using different types of aggregates, curing regimes, strengths and restraint conditions is being conducted at the City University in London. Fire testing is being carried out in conjunction with the U.K.'s Building Research Establishment (BRE).

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4.2.11 SINTEF, Norway

Program Description:

Completed and on-going research activities on fire-exposed HSC by SINTEF include:

- Offshore concrete exposed to hydrocarbon fire (1985-1987)
- Explosion and fire protection (1984-1988)
- High-Strength Concrete. Phase 3: Fire resistance (1986-1993)
- LWA Concrete for floating platforms (1990-1992)
- Fire research on high-strength LWA concrete, and RC structures with nonmetallic reinforcement (in progress)

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4.2.12 VTT, Finland

Program Description:

Under the auspices of the joint European BRITE EURAM project (HITECO, see also section 4.2.3), Finland is presently (1996-1998) investigating the fire performance of HSC (60 MPa to 100 MPa) and ultra high strength concrete (UHPC, exceeding 150 MPa). Thermal and mechanical properties, as well as spalling characteristics of small specimens are being studied for material models development. Fire tests on short columns and other structural members are also planned.

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4.2.13 Monash University, Australia

Program Description:

- *Experimental study to evaluate a mathematical model for the behavior of reinforced concrete walls in fire.* The increasing use of concrete walls as load carrying structural members, mainly in the form of tiltup and precast walls, is allowing structural engineers to design increasingly efficient and economical structures for buildings. The fire resistance requirements for structural adequacy embodied in the Australian concrete structures design code (AS3600-1994) are based partly on results generated by a computer-based mathematical model and partly from experience. There have been no experimental studies to substantiate either the mathematical model or the current design guidelines. Moreover, through discussions with consulting engineers, precast concrete manufacturers and concrete associations, it is apparent that the design guidelines for structural adequacy are restrictive. This project aims to experimentally study the performance of slender, reinforced concrete walls under standard fire conditions. It is anticipated that the experimental tests will be completed by the end of 1997.

  An agreement has been reached with BEP Melbourne Research Laboratories (BHP-MRL) that will allow researchers to use the BHP-MRL fire testing facilities to perform the experimental tests. The gas-fired furnace to be used is 5.1 m long, 2.5 m wide and 2 m tall. A total of eight fire tests are to be conducted in the current testing program.

  Each wall thickness (75 mm, 100 mm and 150 mm) will be tested with a central layer of 0.25% total reinforcement, while the 150 mm wall will be tested with two layers of reinforcement at a total reinforcement content of 0.25%. Each set of four walls will be tested using 40 MPa concrete (normal strength) and 100 MPa concrete (high strength). A special purpose test-rig has been constructed that will apply eccentric compression to the horizontally mounted test specimens. Thus lateral load effects are also being studied. The test specimens will be subject to the ISO834 standard fire environment on one side only, which is representative of a compartment fire within a building. One-way bending action of the test specimens is being studied.

  During the fire tests of loaded specimens, an investigation of several parameters likely to influence spalling of high strength concrete will be conducted. In addition to the loaded test specimens, unloaded spalling test specimens will be fire tested. Reinforcement contents of the spalling test specimens will be identical to the reinforcement contents of the loaded test specimens. The moisture content of representative samples of concrete will be assessed prior to testing the specimens. The parameters to be initially studied in the spalling investigation include:

  - total slab thickness: 75 mm, 100 mm and 150 mm
  - cover to reinforcement: 25 mm, 38 mm, 50 mm and 75 mm.
  - concrete strength: 40 MPa and 100 MPa

The results of the experimental study will be used to develop an appropriate mathematical model to numerically simulate the structural response of concrete walls in fires. Following extensive parametric studies, this mathematical model will be used in the development of more rationally based guidelines for the design of reinforced concrete walls in fire.

A second key component of the current research program is a detailed study of heat and mass transfer characteristics of concrete slabs in fires. It is envisaged to verify experimentally measured pore pressures and temperatures in heated HSC slabs with those predicted by computer-based heat and mass transfer models.

- *Evaluation of the high temperature mechanical properties of high strength concrete.* The conclusions drawn from the recent workshop on the fire performance of high strength concrete (HSC) suggest that there is insufficient experimental data on fire exposed HSC. Furthermore, the increased usage of HSC in structural applications must recognize the fundamental behavioral differences of HSC compared with normal strength concrete.

  To address the deficiency of experimental data on fire exposed HSC, a major research effort is being planned at Monash University, Australia. This research program aims to develop a better understanding of the behavior of fire exposed HSC and to develop suitable constitutive relationships for calculating the structural strength of fire exposed HSC members. The Department of Civil Engineering at Monash University will shortly take delivery of a new electrically powered furnace. The furnace will enable heating rates up to 40 °C/min to be attained (approaching those of standard temperature-time curves). The configuration of the furnace will allow researchers to study both cylinders (100 mm diameter by 200 mm long) and beams (100 mm x 100 mm x 450 mm long). External load is applied via high temperature and stress resistant advanced structural ceramic rams connected to either a 5000 kN Amsler compression testing machine or a 500 kN Baldwin testing machine. With this configuration, three types of high temperature tests can be conducted, i.e., unstressed, stressed or unstressed residual, thus allowing a complete study of fire exposed HSC at all stages of structural life.

  At present, the research program is in its initial stages. A number of tests are planned for late 1997 to assess the capabilities of the furnace. The initial tests planned include:

  - unstressed tests on HSC cylinders to establish variations in compressive strength with temperature.
  - unstressed residual strength tests on model size reinforced concrete beams to establish the criteria for bond induced failure or flexure induced failure in fire damaged concrete beams. Also, suitable design equations to predict the failure load of beams will be developed.

  Additional funding is currently being sought through local sources to equip the furnace with high temperature strain measurement equipment to enable concrete deformation to be recorded during the tests. Such data are fundamental to the development of suitable constitutive relationships for fire-exposed HSC.

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5. ACKNOWLEDGMENTS

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APPENDIX A. Workshop Agenda/List of Participants/Lists of Working Group Members

A.1 Workshop Agenda

Agenda

NIST Workshop on Fire Performance of High-Strength Concrete

National Institute of Standards and Technology

Building and Fire Research Laboratory

Thursday, February 13, 1997

7:45 am - 8:15 am	**Registration (NIST, Lecture Room E)**
8:15 am - 2:30 am	**Introduction and Technical Presentations (NIST, Lecture Room E)**
Welcome	Dr. Jack Snell, Deputy Director, Building and Fire Research Laboratory, NIST
Goal of Workshop	Dr. Nicholas J. Carino, Leader, Structural Evaluation Group, BFRL, NIST
Presentations	Dr. Long T. Phan, BFRL, NIST, Session Chairman
8:30 - 8:50	"*High-Strength Concrete in Germany. Utilization, Research and Standardization*" U. Diederichs, Technische Universität Braunschweig, Germany.
8:50 - 9:10	"*Fire Test of Normal-Weight/High Performance Concrete in Taiwan*" T.D. Lin, Fire Laboratory, ABRI, Taiwan.
9:10 - 9:30	"*Fire Resistance and Residual Strength of High-Strength Concrete Exposed to Hydrocarbon Fire*" J.J. Jensen, SINTEF, Norway.
9:30 - 9:50	"*Spalling Phenomena of HPC*" Y. Anderberg, Sweden.
9:50 - 10:00	*"Fire Damage in the Channel Tunnel"* Franz-Josef Ulm, LCPC, France.
10:00 - 10:30	**Coffee Break**

10:30 - 10:50	"*Research Activities in Finland on Fire Resistance of HSC*" U.-M. Jumppanen, VTT, Finland
10:50 - 11:10	"*Studies on the Fire Resistance of HPC at the National Research Council/Canada*" V. Kodur, NRC/Canada
11:10 - 11:30	"*Spalling of High-Strength LWA Concrete - Cause and Cure*" M.P. Gillen, Dupont Engineering
11:30 - 11:50	"*Limitations of Current U.S. Standards and Challenges for Proposed Performance-Based Standards*" J.A. Milke, University of Maryland
12:00 pm - 1:00 pm	**Lunch**
1:00 pm - 1:20 pm	"*Computational Modeling of Temperature, Pore Pressure, and Moisture Content in Concrete Exposed to Fire*" G. Ahmed, PCA
1:20 pm - 1:40 pm	"*Analysis of Pore Pressure, Thermal Stress, and Fracture of Concrete in Rapidly Heated Concrete*" Z.P. Bazănt, Northwestern University.
1:40 pm - 2:00 pm	"*Fire Tests on Normal and High-Strength Reinforced Concrete Columns*" C.-M. Aldea, Northwestern University.
2:00 pm - 2:20 pm	"*Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperature*" G. Consolazio, Rutgers University.
2:30 pm - 3:00 pm	**Coffee Break**
3:00 pm - 5:30 pm	**Concurrent Working Group Meetings**

	WG: A-1 Material Tests	**WG: A-2 Element Tests**	**WG: B Analytical Studies**	**WG: C Codes & Standards**
Chair:	Y. Anderberg	U. Diederichs	J.P. Hurst	A. Milke
Co-Chair:	M.P. Gillen	R.G. Burg		
Recorder:	N.J. Carino	D. Duthinh	E. Garboczi	L.T. Phan

Friday, February 14, 1997

8:30 am - 12:00 pm **Concurrent Working Group Meeting**

	WG: A-1 Material Tests	WG: A-2 Element Tests	WG: B Analytical Studies	WG: C Codes & Standards
Chair:	Y. Anderberg	U. Diederichs	J.P. Hurst	J.A. Milke
Co-Chair:	M.P. Gillen	R.G. Burg		
Recorder:	N.J. Carino	D. Duthinh	E. Garboczi	L.T. Phan

8:30 - 10:00 Working Group Discussions

10:00 - 10:15 **Coffee Break**

10:15 - 12:00 Working Group Discussions

12:00 pm - 1:00 pm **Lunch**

1:00 pm - 3:00 pm **Plenary Session (Lecture Room E)**
Summary of Working Group Recommendations
Concluding Remarks

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NIST Workshop on Fire Performance of High-Strength Concrete
February 13-14, 1997
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A.3 List of Participants by Working Groups

NIST Workshop on Fire Performance of High-Strength Concrete
List of Participants by Working Groups

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George C. Hoff
H.S. Lew
S.K. Ghosh
Michael P. Gillen
Long T. Phan

Working Groups	A-1: Material Tests	A-2: Element Tests	B: Analytical Studies	C: Codes & Standards
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Meeting Rooms	*Lecture Room E*	*Lecture Room F*	*Bldg. 225, Room B111*	*Bldg. 226, Room B317*
Participants	Y. Anderberg M.P. Gillen N.J. Carino Alain Bilodeau James Clifton U-M Jumppanen Robert E. Moore Todd Sander	U. Diederichs R.G. Burg George C. Hoff Dat Duthinh C-M Aldea W.L. Gamble Jens J. Jensen V. Karthigeyan** V. Kodur T.D. Lin L.W. Bell**	J.P. Hurst Ed Garboczi G. Ahmed Z.P. Bazant G.R. Consolazio L. Cooper N. Martys Franz-Josef Ulm	Walter Jones J.A. Milke L.T. Phan J. Messersmith V. Karthigeyan** L.W. Bell**

** participated in two Working Groups

APPENDIX B. Workshop Papers

B.1 Concrete Fire Test Programs in Taiwan

T. D. Lin* and Sam Chou**

Introduction

Small-scale fire test programs involving wooden and plastic materials might have started within universities in Taiwan in the 1960s or earlier, but fire tests of concrete did not begin until late in the 1980s. In 1988, the National Science Council of Taiwan funded National Taiwan Institute of Technology a sizable fire test program to determine the behavior of concrete slabs in fire and the mechanical properties of fire-exposed concrete. Subsequently, several concrete fire test programs were carried out, some projects are still in progress.

Here is the reason why concrete, a non-combustible material, suddenly became a hot topic for fire research in this island nation. The healthy economic growth in the last 20 years has led to enormous volumes of concrete construction. Because of expensive land cost in Taiwan, commercial and residential buildings of 30, 40, and 50 stories have become attractive commodities in the real estate market in cities, suburbs, and even in rural areas as well.

The densely populated living condition facilitated with large quantities of electric and gas lines provide high living standards, but at the same time it poses vulnerable fire hazards to occupants and properties. KTV and MTV entertainment vendors, a recently developed oriental culture, coupled with the enforcement of building fire insurance have propelled the rise of fire occurrences to an alarming stage in recent years.

In responding to this social problem, the Ministry of Interior established a fire research laboratory under the auspices of Architecture and Building Research Institute (ABRI) in 1989 to coordinate fire research programs and conduct fire safety verification tests on commercial building materials. The laboratory has also conducted a wide range of in-house fire test programs covering wood, metal, aluminum, ceramic, glass, plastic, gypsum board, and concrete. Interestingly, concrete fire research has been considered as one of the top priority programs, because it is virtually the most widely used construction material in Taiwan.

Fire Research on Normal Weight Concrete

In addition to the in-house research programs, the fire laboratory provides funding to support 10 to 15 fire related research projects carried out by universities and research institutes each year. Among them, about 10 to 15 % were earmarked for fire research related to concrete. The followings are few sample projects supported by the National Science Council and ABRI, during the period of 1991 to 1996:

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* President, Lintek International, Inc., Illinois

** Director, Fire Laboratory, Architecture and Building Research Institute, Taiwan

- Experimental studies on thermal properties of normal weight concrete at elevated temperatures.
- Experimental studies on mechanical properties of normal weight and lightweight concrete at elevated temperatures
- Development of post-fire investigation methodologies using the Loss-on-Ignition procedure
- Fire tests of normal weight concrete slabs (1 m wide, 4.5 m long, and 100 to 150 mm thick)
- Fire tests of lightweight concrete slabs (1 m wide, 4.5 m long, and 100 to 150 mm thick)
- Fire tests of concrete-filled steel columns without applied loads

Results of these tests have been published in Chinese technical journals and are available by request.

Fire Research on High Strength and High Performance Concrete

High strength concrete (HSC) and high performance concrete (HPC) have gained substantial attention worldwide in the last 10 years. Without exception, the concrete industry in Taiwan through the domestic R/D and technology transfer has successfully introduced HSC to its domestic construction industry. The use of HSC in the construction of the 85 Story T&C Tower in Kao-Hsiung, the 2nd largest city in Taiwan, is a good example.

Nonetheless, the use of HSC in building construction requires careful studies for it may spall violently in fire. Unfortunately, only limited studies on the related subject have been carried out so far and knowledge gaps in this area are wide open. The fire laboratory of ABRI was aware of the problem and funded a test program to investigate the spalling behavior of HSC/HPC at high temperatures. The test variables included effects of moisture and chemical admixtures on spalling and mechanical properties at high temperatures.

At least two hundred 100 mm diameter by 200 mm high cylinders made with approximately 70 MPa HSC were tested in an electric furnace. The concrete cylinders were divided into groups in accordance with amounts of superplasticizer used to study the effect of the admixture on spalling. The test results verified the explosive behavior of HSC and revealed that the effect of chemical admixtures on the spalling is minimal, but the effect of moisture is obviously severe. In addition, reductions of strength and modulus of elasticity with respect to temperature rise were also studied.

In fact, the behavior of HSC in fire is extremely complicated. Small cylinder tests can only give quantitative answers, not realistic solutions. Full-scale fire tests of structural elements are definitely desirable. For this reason, the fire laboratory of ABRI funded the National Chiao Tung University (NCTU) to collaborate with the fire laboratory of the National Research Council of Canada on a fire test program involving 15 full-sized columns (305 mm x 305 mm x 3810 mm) made with HSC having strength greater than 70 MPa. Various mixtures incorporating siliceous aggregate, siliceous aggregate + steel fibers, carbonate aggregate, carbonate aggregate + steel fibers were used to manufacture these column specimens.

In return, NCTU will test approximately three hundred 100 mm by 200 mm cylinders made with HSC having similar compositions as those of the column specimens to determine their stress-strain relationships at various elevated temperatures.

The collaboration is based on work exchange without monetary transaction between both parties. The agreement for the joint research program was signed for 3 years (Mid 1996- Mid 1999) and can be extended under a mutual agreement. The obtained test data will be shared by both parties and published jointly.

Near-Term Programs

The fire laboratory of ABRI considers concrete fire research an important technical contribution to the concrete industry. It has decided to proceed with its second 5-year research program (1997-2002) in which projects related to concrete and steel are listed below:

1. Fire resistance of HSC/HPC structural elements
2. Fire resistance of normal weight concrete structural elements
3. Fire resistance of steel structural elements
4. Fire resistance of steel/concrete composite structural elements
5. Post fire evaluations

The selection of these subjects is based on the domestic construction needs.

Long Term Programs

The fire laboratory of ABRI anticipates to continue its commitment to concrete fire research. Depending on budget allocated and domestic needs, future research topics will be selected from the followings areas:

1. *Materials for HSC*
   a) Effects of cements such as ordinary portland cement, alumina cement, and refractory cement on the fire performance.
   b) Effects of aggregates (carbonate, siliceous, and lightweight) on fire endurance.
   c) Effects of chemical admixtures (sulphonated naphthalene, formaldehyde condensates, sulphonates melamine formaldehyde condensates, modified lignosulphates, and others) on the fire performance.
   d) Effects of mineral admixtures such as fly ash, silica fume, slag cement.
   e) Effects of rebars (plain, deformed, epoxy/zinc coated) and fibers (steel, glass, carbon, polypropylene) on the fire performance.

2. *Physical and Thermal Properties of HSC*
   a) Paste: Drying shrinkage often results in micro-cracks in paste. These micro-cracks extend to form larger cracks attributed to vapor pressure/thermal stresses during fire.

b) Aggregate: Volume stability and physiochemical reactivities of different aggregates at elevated temperatures deserve in-depth studies.

c) Concrete: Thermal expansion, conductivity, specific heat, vapor pressure, and physiochemical stability affect the fire performance.

3. *Mechanical Properties of HSC*

Modulus of elasticity, strengths (compressive, tensile, bond, and shear), and stress-strain relationships are important variables in predicting the fire resistance of HSC structures.

4. *Small-scale and Full-Scale Fire Tests*

Preparation of cylinders including high temperature resistant capping, positioning of unbonded pads, ground/lapped end-surfaces are essential factors for viable test data. Well thought-out test procedures are extremely important. Full-scale fire tests are very expensive and require sophisticated test equipment and facilities. A good test plan and a careful execution of the plan is absolutely necessary. In full-scale fire tests, furnace temperatures must be regulated to closely follow the standard time-temperature curve specified. Temperature measurements for the test specimen must be accurately taken. Selection of test loads must meet the code requirements and closely simulate the actual loads in the building during fire.

5. *Mathematical models*

Finite element and finite difference methods are generally used to develop computational models to predict the structural behavior of HSC in fire. The development of these models requires data obtained in items 1 to 3 of this section. General engineering theories and rational design methods can be applied in these studies. Design details such as bar sizes and spacing, development length, and concrete covers all have noticeable effects on the fire performance of reinforced concrete.

6. *New Design Concept*

Performance-based design is a new concept and may offer a better engineering solution for fire resistance than the prescriptive design procedure.

7. *Interaction and public awareness*

It is important to provide ACI committee 318 and major foreign design code committees with the research results obtained from the envisioned HSC fire test programs. We hope the major building codes may include provisions related to HSC in the near future.

Conclusion

High strength/high performance concrete has commercial and engineering potentials. It has already changed concrete construction procedures for non-fire hazardous infrastructures. However, use of HSC in building construction faces serious safety problems because of the building official's concern over the explosive spalling behavior in fire. International collaborative efforts are required to undertake this expensive fire test endeavor. Realizing the importance of HSC fire research, the fire laboratory of ABRI envisions the need to make contributions toward this specific research area.

B.2 Fire Resistance and Residual Strength of HSC Exposed to Hydrocarbon Fire

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ABSTRACT:

This paper deals with the evaluation of the residual strength of high-strength concrete (HSC) structural elements exposed to accidental loading as fire. The question is whether a structure retains enough residual strength for continued unaltered or limited use. The after-accident serviceability, residual strength, cost of repair and second-order consequences are all of vital irnportance for industrial production systems such as the petroleum industry, offshore installations, power plants and transportation systems. This study discusses in particular the fire resistance and residual strength of HSC-reinforced beams exposed to hydrocarbon fire. Research needs are also discussed.

1. INTRODUCTION

Concrete structures for special industrial production systems such as the petroleum industry, offshore installations, power plants and those for transport systems and fortifications, are of particular concern regarding extreme loadings such as hydrocarbon fires and explosions. Accidental situations such as fire and explosions are often linked together. Structural damage, degradation of materials, large permanent deflections and plastic behavior may be accepted to a certain extent by accidental loading. However, the acceptance criteria have to be defined on the basis of safety requirements with respect to hazard protection, after-accident serviceability, residual strength, cost of repair and second-order consequences.

2. RESIDUAL STRENGTH OF HSC BEAMS EXPOSED TO HYDROCARBON FIRE

2.1 Background

The reduction in the compressive concrete strength at high temperatures has been taken into consideration in most existing design codes; however, regulations are in general based on experimental evidence obtained by testing low- and medium-strength concretes under normal fire conditions. More rapid reductions of the compressive strength of high-strength concrete than of low-strength concrete has been observed at relatively low temperatures [9]. The same tendency was observed in both normal-density and lightweight concretes, in tests in which concrete was exposed to temperatures between 20 and 600°C [1] See Figure 1.

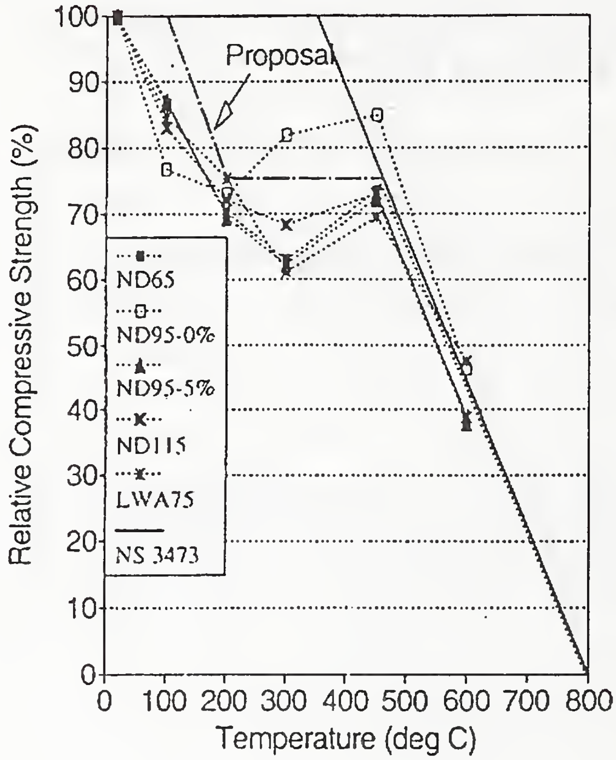

Figure 1. Relative compressive strength vs target temperature of specimens during testing.

The spalling is highly dependent on moisture content. A significant reduction in spalling can be obtained by the addition of polypropylene (PP) fibers to the concrete [2]. This has also been confirmed in structural beam tests [3].

Hydrocarbon fires which are characterized by high temperatures and very rapid temperature rises may cause serious damage to concrete structures. Loss of strength caused by elevated temperatures and spalling damage reduce the load bearing capacity of structural elements. The question which arises after such fires is whether the structure has sufficient residual strength for continued unaltered or limited use.

2.2 Fire Resistance Tests

Fire resistance tests were performed on concrete beams with the dimensions 150 x 200 x 800 mm. A total of 14 beams (11 reinforced and 3 prestressed) of four different concrete types were examined. [3]. Typical reinforcement was as shown in Figure 2. Three of the beams were protected with passive fire protection.

The types of concrete used have the following designations: ND95, LWA75, LWAF75, LWAF75P, LWA50. Where ND=normal density concrete; 95, 75, and 50 refer to the design cube compressive strengths (95, 75, and 50 MPa); LWA=Lighteeight Aggregate concrete, (LWA75: Liapor aggregate, LWA50: Leca aggregate), F= fiber added in concrete mix (Polypropylene, Fibrin type 1825), P=Beam protected with passive fire protection (LightCem LC5).

The different types of concrete and the beam numbers were as follows:

ND95: (61^4, 62^4, 12^3)
LWA75: (21, 22^3)
LWAF75: (31, 32^1, 33^3, 35^2),(30, 34^3)*
LWAF75P: (*41*, 42^1, 43^2)
LWA50: (51^1, 52)

Legend:
[1]Beam tested with vertical load
[2]Beams without shear reinforcement (Longitudinal reinforcement 3-ϕ20 mm).
[3]Prestressed beams. (Dywidag ϕ26, center)
[4]Longitudinal reinforcement 2ϕ32mm
*Reference beams, not exposed to fire

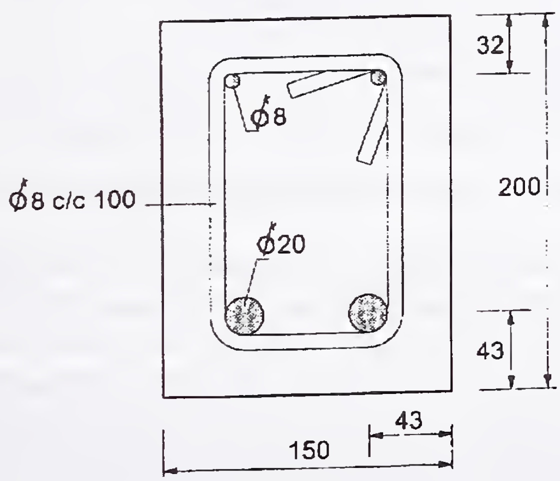

Figure 2. Cross section of typical test beam (21,31,32,41,42,51,52)

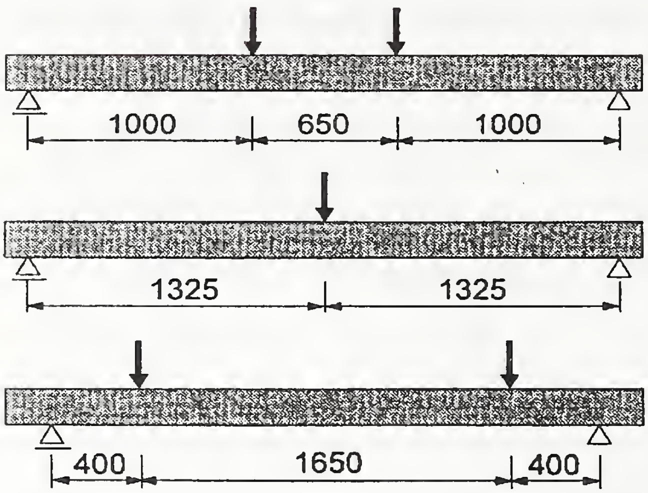

Figure 3. Experimental set-up for testing of residual strength of beams
(a) Nos 30,33,34,52,62 (flexure)
(b) Nos 31,41, and 42 (flexure)
(c) No 43 (shear)

The damage after fire exposure was observed visually. The results may be summarized as follows:

The test results confirmed earlier findings as reported in [5] that severe spalling (exposed reinforcement) occurred on reinforced and prestressed LWA beams. Reduced spalling (spalling, but no exposed reinforcement) of the ND75 concrete beams and normal strength LWA (LWAC50) concrete beams was observed. One of the ND concrete beams collapsed during testing. Reduced or no spalling was observed in the LWAF75 beams. This means that significant improvements in spalling resistance were attained by adding polypropylene fibers to the LWA concrete mix. No spalling was observed on the test specimens with passive fire protection (LWAF75P) [4].

2.3 Residual Strength of Fire-Tested Beams

The residual ultimate strength of seven of the fire tested beams was studied by the structural test arrangement as shown in Figure 3 [41]. None of the LWA75 beams was tested for residual strength because the damage caused by the fire exposure was considered to be too extensive to permit further investigations. Fire testing was conducted on beams 62 (ND95), 31 (LWAW5), 41,42 and 43 (LWAFP75) and 52 (LWA50). In addition the reference beams 30 and 34, which had not been exposed to fire, were tested.

Table I. Failure types and observed and calculated capacities.

Beam No	Failure type	Capacities [KN]		Ratio P_{ex}/P_{th}
	ex/th	P_{ex}	P_{th}	
31	FC/FT	34.3	66.7	0.51
41	FT/FT	68.7	66.7	1.03
42	FT/FT	67.7	66.7	1.01
33	SH/SH	58.9	53.0	1.11
30*	FT/FT	44.1	45.3	0.97
33	FT/FT	13.7	31.6	0.43
34*	FT/FT	43.2	31.6	1.37
52	FC/FC	14.2	38.1	0.37
62	FC/FC	24.0	62.7	0.38

* Reference beams

Types of failure:
FC = Flexure compression
FT = Flexure tension
SH = Shear failure

The test results (ex=experimental) are compared with the calculated (th=theoretical) values for unexposed beams in Table I. The theoretical capacities were calculated according to NS3473 [10], using a characteristic strength, $f_{cn} = 0.56*f_{c28} + 2.8$ MPa. [16].

The results are also presented in Figure 4 in which the residual strength in terms of the moment capacity of fire exposed reinforced LWAF beams (with fibers) are compared with reference beams not exposed to fire.

It may be concluded that even if the structural elements show only minor spalling after exposure, the reduction in concrete strength and thus in the load-bearing capacity may be severe. The beams with passive fire protection had no visual damage after fire exposure and this is consistent with the measured residual strength of the beams. The positive effect of using passive fire protection to prevent spalling and to reduce temperature rise is obvious, and should therefore be considered in design evaluations.

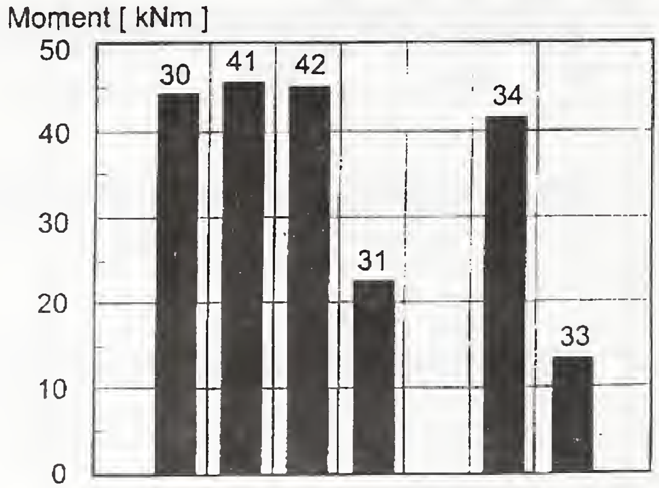

Figure 4. Comparison of residual strength (moment capacity) of fire-exposed reinforced and prestressed LWAF beams (with PP fiber). Beams nos 30 and 34 are reference beams not exposed to fire. Beams nos 41 and 42 have passive fire protection.

3. RECOMMENDATIONS AND RESEARCH NEEDS

3.1 Recommendations

No special recommendations are given for high-strength concrete fire design in Eurocode 2 [14,15]. In the current Norwegian code, NS 3473 [10], special provisions on thermal effects are suggested if the concrete grades are higher than C55. For such grades, it may be assumed, when more precise values are not known, that compressive strength falls linearly from its full value at 100°C to 75% of the full value at 200°C and is constant for higher temperatures until the reduction is as specified for normal strength concrete. See also the proposed recommendation in Figure 1. Similar specifications exist in the Finnish code RakMK B4 [11].

Evaluations of the fire resistance of HSC structures and of the residual strength of structures exposed to fire can be dealt with by means of design methods (material design, adding polypropylene fibers, analysis of temperature development, taking the material properties according to temperature development into account, the use of passive fire protection, structural strength and safety evaluation according to current design methods).

3.2 Research Needs

In spite of the comprehensive investigations carried out, further studies on fire resistance of concrete structures are needed. Special attention has to be paid to the material properties for analysis and evaluation of the **residual strength** of structural elements exposed to accidental loading and fire. The residual strength for continued unaltered or limited use are of importance.

The considerable reduction in compressive strength and E-modulus of HSC at relatively low temperatures (100-300°C) may also cause decreased residual strength of concrete exposed to elevated temperatures in the same range. Further examinations are needed in order to document material properties for design purposes and for evaluation of residual strength of structural elements exposed to fire.

The improvements in spalling resistance by adding polypropylene fibers to the concrete mixture were obvious for LWA concrete. These improvements should be further investigated. By the investigations reported in [2] one special type of passive fire protection was used. Other types of passive fire protection, well suited for concrete structures, have to be examined, eventually refined and/or developed.

The tests performed [2,3]* were carried out under hydrocarbon fire test conditions with temperatures up to 1100°C. Recently higher temperature requirements have been set with temperature rises up to 1300°C. In order to document the fire resistance of concrete and the effectiveness of passive fire protection for the new temperature requirements, additional tests are recommended for documentation purposes.

Accidental situations such as fires and explosions are often linked together. The residual strength of structures damaged by explosion and fire are essential. Accepted methods and criteria for the evaluation of residual strength of concrete structures damaged by explosions and fire are still lacking. Therefore examinations based on the experience obtained through previous research as [17] [Explosion and fire protection (1989)] are recommended.

Research needs: Materials:

- Extend the existing knowledge of temperature dependency of the basic, mechanical properties of HSC (compressive and tensile strength, elastic modulus, stress-strain relationships, residual strengths and elastic properties). Tests have to be performed with different types of aggregates (different lightweight aggregates included) and different types of fibers.
- Optimize concrete mix design in order to prevent spalling (aggregate, additives, fibres).
- Document material properties for analytical approach to the spalling phenomena.
- Update design curves for mechanical properties.

Research needs: Structural elements and structures

- Extension/Revision of existing Codes and Design Standards. HSC has to be included.
- Examination of the fire resistance of structural elements exposed to extreme temperatures (temperatures exceeding the ISO 834 HSC curve).
- Examination of the residual strength of HSC structural elements. Design recommendations for structural evaluation and repair.
- Analytical approach to fire response.

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B.3 Spalling Phenomena of HPC and OC

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1. Swedish Research Project on HPC

In 1992, the Swedish research project on High Performance Concrete (HPC) started. It was financed jointly by government and industry. The research on fire performance of HPC is a part of that project and has been carried out by Fire Safety Design during a period of 5 years. The scope of work includes investigation concerning:

- tendencies to spall
- thermal properties
- mechanical properties

and developing:

- analytical behavior models
- structural models for mechanical behavior
- structural design models for practical use

2. Background

Fire-exposed HPC has a different tendency and feature of spalling compared with ordinary concrete (OC). Due to the compact structure of HPC, which makes it more difficult to transport vapour and moisture, very high vapour-pressure may occur close to the surface. This means that there is a greater risk that HPC spalls compared with ordinary concrete (OC).

In OC, the vapour can be transported much more easily to the surface and, likewise, the moisture towards the inner part. However the moisture concentration can at last be too large and explosive spalling of 20-40 mm concrete cover can occur.

Consequently it is of great importance to find different ways of decreasing the risk and tendency of spalling for HPC. One measure is to choose a concrete mix with various additives to improve the permeability and the pore structure. Another step is to ensure a sufficiently small relative humidity of the HPC in case of fire by allowing a continous hydration and self desiccation process to take place where the free water is transferred to chemically bound water with a volume decrease of 25%. Because spalling tendency is such an important property of HPC under fire the phenomenon must be understood properly.

2. Spalling as Phenomenon

When surface spalling of fire-exposed concrete structures occurs, smaller or greater parts disappear and the reinforcement cover might be gone, which leads to direct heating of the reinforcement and a rapid decrease of load-bearing capacity. Sometimes the spalling can be very comprehensive and cause an immediate failure of the structure. The spalling can be explosive or can be a calmer process.

The tendency for surface spalling is increased by:

- High moisture content
- Dense concrete (HPC)
- Compressive stress from external load and prestress
- Rapid temperature rise
- Considerable unsymmetrical temperature distribution
- Cross-section with thin sections
- High reinforcement concentration

Increase of air in OC is positive as far as spalling is concerned, but for HPC this is of no interest because it influences the strength negatively.

Three primary mechanisms can be identified which separately or in combination can cause surface spalling

- Vapour pressure
- Thermal stresses
- Structural transformation of aggregate

In most cases the vapour pressure is the most important primary mechanism. This is valid especially when the spalling is vast and occurs explosively. The third mechanism is limited to coarse aggregate only.

By heating moist concrete above the boiling point the free water of the material transforms into vapour as the temperature increases. If the material has small diffusivity, the transport of vapour is hindered and an over-pressure is attained. The size of this over-pressure is governed by the balance between the transportation and production of vapour. Spalling takes place if the vapour pressure - possibly in combination with thermal and statical stresses - causes tensile failure in the material.

By heating concrete, a simultaneous process of heat and moisture transport is initiated. The moisture is transported both in vapour and water phase. In the following, a qualitative description of the process is presented. The description is based on a pure one-dimensional case for HPC and OC, i.e., a concrete wall exposed uniformly to fire from one side.

The water is vapourized at the hot surface first, when the temperature reaches 100 °C. As the temperature rises, the vapour zone moves towards the inner part. In Fig 1 the situation is illustrated after a certain time for HPC as well as OC. Nearest the hot surface there is a dry zone, whose thickness increases faster for OC than for HPC. After that follows a narrow zone which is thinner for HPC where vapourization takes place, and inside is a zone where the moiture exists as free water. The vapour, which is created in the vapour zone is transported towards the hot surface but also in the opposite direction where it is cooled down and condenses to water. This means an increased moisture content just inside the vapour zone. The transport of vapour is mainly driven by over-pressure which is maximum at the front of vapourization.

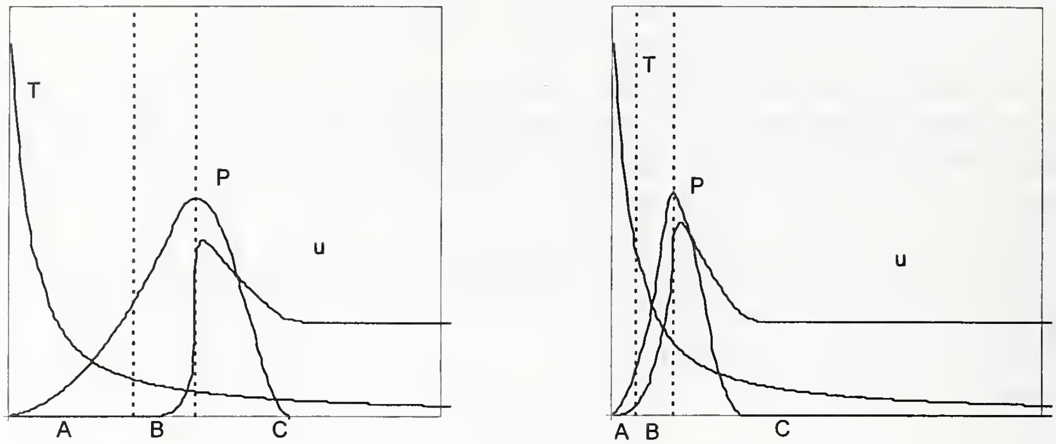
As the vapour front moves inwards, the distance to the hot surface increases, and a higher pressure is needed to lead the vapour away. At the same time the moisture content increases in the domain inside the vapour zone, which causes less vapour transport towards the cold side. Therefore the vapour pressure tends to increase at the vapour front as it moves inwards. However, the intensity of the heat flow decreases with increasing distance to the hot surface, which gives less vapour production. Furthermore, it can be assumed that the hydrodynamic resistance of the outer dry zone does not increase in proportion to its thickness. The temperature rises rapidly in this zone and the gas diffusivity of concrete increases strongly with the temperature. When the distance to the cold surface decreases, the water flow is facilitated in that direction.

When the vapour zone moves to a certain distance from the hot surface, a maximum vapour pressure is created, and at greater distances the pressure decreases again. This critical distance is much less for HPC, about 5-10 mm than for OC, about 20-40 mm. Whether the vapour pressure developed is sufficient to cause spalling depends not only on the amount of moisture, but also on rate of heating, permeability, porosity and pore distribution.

It has been observed from fire tests that spalling of HPC is characterized by a layer of about 5 mm of concrete falling off and after that a new vapour front buildup, which can create a new spalling of 5 mm, and in the end the total spalling can reach considerable depths.

This summary description is only valid for heated, moist concrete in idealized conditions. In practise these conditions can change. Creation of cracks in concrete will facilitate the vapour and moisture transport and reduce the tendency of spalling.

If the concrete wall is exposed to fire on both sides, the inner part of the section will contain further free water if the diffusivity is large enough (OC). This may cause a total collapse of OC. This phenomenon is not probable for HPC.

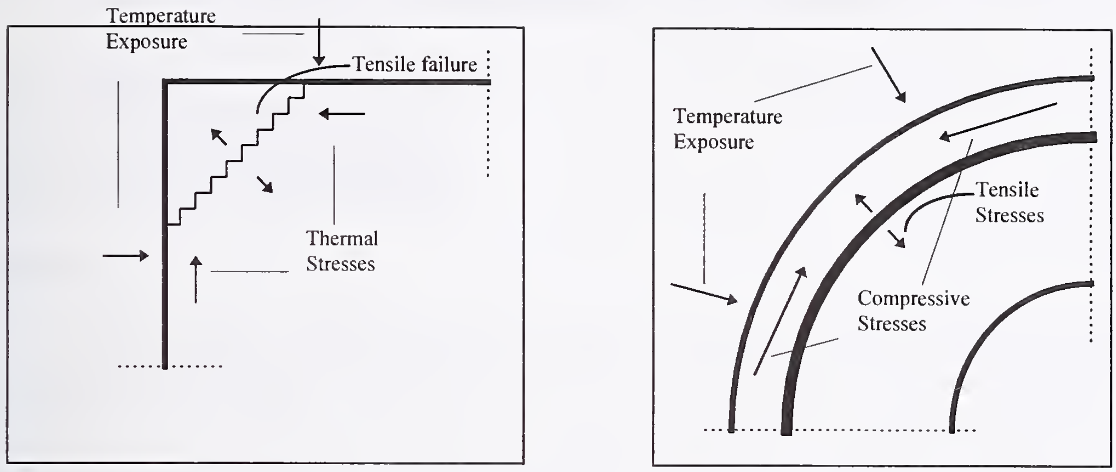


a) OC *b) HPC*

Fig 1. Schematic illustration of temperature- and moisture conditions at one-dimensional heating of moist OC and HPC
A: Dry concrete, B: Vapour zone, C: Moist concrete.
T: Temperature, P: Vapour pressure, u: Moisture content

4. Influence of Thermal Stresses on Spalling

Heating of concrete is characterized by a steep thermal gradient when exposed to fire due to low conductivity and high heat capacity. This produces thermal stresses, which generally are two- or three- dimensional. Consequently tensile stressses arise which can reach the tensile strength. These tensile stresses can sometimes alone or in superposition with pore pressure in one direction, cause spalling. In Fig 2 two different examples are shown where the thermal stresses alone may cause spalling. When the thermal compressive stresses in the hot outer layer are developed and meet each other in a corner, tensile stresses appear. If this tensile stress reaches the tensile strength, the triangular corner piece can spall off as indicated in Fig 2. The same problem occurs for a heated convex surface where radial tensile stresses develop.



a) b)

Fig 2. Thermal stresses at a
a) corner
b) convex surface

5. Conclusions

If HPC, without any additives like polypropylene fibers and with a water binder ratio (w/b) less than about 0.28, is exposed to the standard fire exposure, ISO 834, it is characterized by a successive spalling of 5 - 10 mm thickness, and the longer the fire duration, the deeper the concrete spalls. Therefore the total spalling may lead to a disaster. External loading increases the risk of spalling. If the heating rate is less, the risk of spalling decreases. At the heating rate of 5 °C/min, the spalling tendency is very small.

The relative humidity (RH) as function of time decreases much faster for HPC than for OC. After 3 months of curing, the RH of HPC can be as low as 60%. Due to the continous hydration of the cement, the self desiccation effect seems to be advantageous.

In the Swedish investigation on HPC, it is found that the risk of spalling is low if w/b is greater than 0.32 and the RH is less than 75-80 %. At lower w/b values, polypropylene fibers (or similar) must always be added, but the relative humidity must, nevertheless, not exceed 80 %. The results are limited to one type of concrete mixture with granite aggregate. The limited number of tests means that the conclusion is not generally applicable to different kinds of HPC.

Current code requirements of minimal thickness of concrete slabs and walls made of OC are not valid for HPC.

B.4 STUDIES ON THE FIRE RESISTANCE OF HIGH-STRENGTH CONCRETE AT THE NATIONAL RESEARCH COUNCIL OF CANADA

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ABSTRACT

High-strength concrete has been utilized in many high-rise buildings and its major application is in columns. With the increased use of high-strength concrete in columns, concern has developed regarding its behaviour in fire, in particular, the occurrence of spalling at elevated temperatures. Studies are in progress at the National Research Council of Canada to develop fire resistance design guidelines for high-strength concrete for incorporation in codes and standards. The studies are focussed on conducting full scale fire tests on structural members, establishing material properties at high temperatures, and in developing numerical models to evaluate the performance of HSC structural members. An overview of the current research studies on high-strength concrete columns is outlined in this paper.

Keywords: high-strength concrete, fire resistance design, high temperature behaviour, concrete-filled steel columns, reinforced columns, spalling, material properties

1. INTRODUCTION

In recent years, the construction industry has shown significant interest in the use of high-strength concrete (HSC). This is due to the improvements in structural performance, such as high-strength and durability, that it can provide compared with traditional concrete. In Canada, high-strength concrete is being used in many applications such as bridges, offshore structures and infrastructure projects. In recent years, its use has been extended to high rise buildings as well. One of the major uses of HSC in buildings is in columns.

In Canada, the specifications for fire resistance requirements for structural members are contained in the National Building Code of Canada (NBCC) (1). Concrete structures in Canada are to be designed in accordance with the CSA A23.3-M94 standard (2). The most recent edition of this standard contains detailed specifications on the design of HSC structural members, however, there are no guidelines on the fire resistance design of HSC structural members either in CSA A23.3-M94 or in the NBCC.

The results of fire tests in a number of laboratories (3, 4) have shown that there are well-defined differences between the properties of HSC and normal strength concrete at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire (3, 5).

Studies are in progress at the National Research Council of Canada (NRC) to develop fire resistance design guidelines for the use of high-strength concrete for possible incorporation in codes and standards. The main objective of this research, being undertaken in partnership with industry, is to study the behaviour of HSC at elevated temperatures and to develop solutions to minimize spalling and to enhance its fire resistance. In this paper, an overview of the current research program being undertaken at NRC is outlined.

2. FIRE RESISTANCE OF HIGH-STRENGTH CONCRETE

In buildings, HSC structural members are to be designed to satisfy the requirements of serviceability and safety limit states. One of the major safety requirements in building design is the provision of appropriate fire safety measures for structural members. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defence.

The fire safety measures for structural members are measured by means of fire resistance. Fire resistance is defined as the ability of a structural element to maintain its load-bearing function under fire conditions. It is the time during which a structural member exhibits resistance with respect to structural integrity, stability and temperature transmission. Fire resistance of a structural member is dependent on the geometry, the materials used in construction, the load intensity and the fire characteristics.

In the case of HSC, the spalling of concrete under fire conditions is one of the major concerns due to the low water-cement ratio in HSC. The spalling of concrete exposed to fire has been observed in concrete structural members under laboratory and real fire conditions (5, 6). Spalling, which results in the loss of concrete during a fire, has the effect of exposing deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the structure, including to the reinforcement.

Spalling is theorized to be caused by the build up of pore pressure during heating (3, 7). HSC is believed to be more susceptible to this pressure build up because of its low permeability compared to normal strength concrete. The extremely high water vapour pressure, generated during exposure to fire, cannot escape due to the high density of high-strength concrete and this pressure often reaches the saturation vapour pressure. At 300°C, the pressure reaches about 8 MPa. Such internal pressures are too high to be resisted by the HSC mix having a tensile strength of about 5 MPa (5).

Data from various studies (3, 4, 5) show that spalling of HSC is affected by the following factors:

- original compressive strength
- moisture content of concrete
- concrete density
- heating rate
- specimen dimensions and shapes
- loading conditions

Preliminary studies indicated that the addition of polymeric fibre reinforcement to concrete reduces spalling (3, 6, 8). Experimental studies on high-strength reinforced concrete columns showed deep spalling and rupture after fire tests, however, only slight or no spalling was observed in fire tests on the same HSC columns reinforced with polypropylene fibres (6). The occurrence of spalling, as well as the extent of spalling, varied from one study to the other thus presenting a confusing picture on the behaviour of HSC at elevated temperatures (5).

3. STUDIES AT NRC

Studies are in progress at NRC to develop fire resistance design guidelines for HSC for possible incorporation in codes and standards. The main objective of this research, being undertaken together with the Portland Cement Association, Canadian Portland Cement Association, Concrete Canada, and National Chiao Tung University (NCTU), Taiwan, is to study the behaviour of HSC at elevated temperatures and to develop solutions to minimize spalling. Both experimental and theoretical studies are being carried out to study the behaviour of HSC structural elements and to establish the material properties of HSC at elevated temperatures.

3.1 Element Tests

The experimental studies are focussed on two types of structural elements; namely HSC-filled steel columns and HSC columns.

3.1.1 HSC-Filled Steel Columns

Steel hollow structural section (HSS) columns are very efficient structurally in resisting compression loads and are widely used in the construction of framed structures in industrial buildings. HSS columns, on their own, have a fire resistance of 20 to 30 minutes and need to be provided with additional measures to obtain the required fire resistance, as specified in building codes.

HSS columns are often filled with concrete in order to achieve increased load-bearing capacity. Concrete filling of HSS sections increases fire resistance. In order to quantify the fire resistance from concrete filling, studies were undertaken on three types of concrete-filled HSS columns; namely plain concrete, reinforced concrete and steel fibre-reinforced concrete. Both normal strength concrete (NSC) and HSC were considered. Detailed results on NSC-filled HSS columns are given in Reference (9) while the results of HSC-filled columns are discussed in Reference (4). In this paper, only the comparative performance of HSC-filled and NSC-filled HSS columns are discussed by considering four HSS columns; namely, two columns filled with NSC (NSC1 and NSC2), a column filled with HSC (HSC1) and a column filled with fibre-reinforced high-strength concrete (HFC1).

Figure 1 shows elevation and cross-sectional details for the four HSS columns used in the experimental studies. All columns were 3810 mm long and were of circular cross section. The 28-day compressive strength of concrete for NSC was approximately 40 Mpa, while for HSC it was approximately 90 MPa.

The comparative performance of NSC- and HSC-filled HSS columns under fire conditions is illustrated in Figure 2. The variation of the axial deformation with time is compared for the NSC- and HSC-filling (Columns NSC2 and HSC1). These two columns had similar characteristics and were subjected to similar load levels (4). As expected, the columns expanded in the initial stages, and most of the load was supported by the steel section, then contracted leading to failure. In the range where the steel section was carrying the load, the behaviour of the two columns was similar.

At increased temperatures, the steel section gradually yielded because of decreasing strength, and the column contracted. At this stage, the infilled concrete started to take over the load and carried a progressively increasing portion of the load with increasing temperature. The strength of the concrete also decreased with time and, ultimately, when the column could no longer support the load, failure occurred. In this region, the behaviour was dependent on the type of concrete filling. The failure of the HSC-filled HSS column occurs by sudden contraction, while the failure of the NSC-filled HSS column occurs by gradual contraction. In these tests, the time to reach failure is defined as fire resistance. For the NSC-filled HSS column, the fire resistance was approximately 150 minutes while, for the HSC-filled HSS column, it was only approximately 45 minutes.

The comparative performance of HSS columns filled with NSC (NSC1) and HFC (HFC1) under fire conditions is shown in Figure 3. The variation of the axial deformation with time is compared for the two columns. These two columns had similar characteristics and were subjected to similar load levels (4). The deformation behaviour of the fiber-reinforced high-strength concrete-filled steel column, HFC1, was similar, during the early stages of the test, to that of the normal strength concrete-filled steel Column NSC1. After approximately 40 minutes, Column HFC1 performed better than Column NSC1 since the presence of steel fibres enhanced ductility. While the lower load intensity on Column HFC1 contributed to an increased fire resistance to some extent, much of the contribution is from the presence of steel fibres and the high-strength concrete.

This can be attributed to the superior mechanical properties of steel fibre-reinforced concrete. There is very little information on the properties of steel fibre-reinforced high-strength concrete, however, studies on steel fibre-reinforced normal strength concrete (8, 9) have shown that the compressive strength increases with temperature up to about 400°C.

3.1.2 Reinforced Concrete Columns

As part of an experimental study, forty-eight full-scale reinforced concrete columns are being tested by exposing the columns to fire under structural loads. These columns are made with two types of HSC, namely plain-HSC and fibre-reinforced-HSC. Both polypropylene and steel fibres are being considered in the study. Twenty columns with plain-HSC, eight columns with steel fibre-reinforced-HSC and twenty columns with polypropylene fibre-reinforced-HSC are being fabricated.

All columns are 3810 mm long and are of either square or rectangular cross section. Two sizes of square columns, 306 mm and 406 mm, are being considered in the study. The rectangular columns are 306 x 456 mm and 203 x 916 mm. The test variables are column section dimensions, tie spacing, load intensity, end conditions, concrete strength, aggregate type and reinforcement. Figure 4 shows elevation and cross-sectional details for a typical column considered in the study. Further details on the columns are given by Kodur (8).

The construction of the columns with plain-HSC and with steel fibre-reinforced-HSC is complete. The polypropylene fibre-reinforced concrete columns are expected to be constructed shortly. Two types of coarse aggregate, namely, siliceous aggregate and carbonate aggregate, are being used in the concrete mix to study the influence of aggregate on the fire performance of HSC. The compressive strengths of the concretes are in the range of 80-90 MPa.

The tests will be carried out by exposing the HSC columns to heat in a furnace specially built for testing loaded columns. The test furnace, shown in Figure 5, is designed to produce conditions such as temperature, structural loads and heat transfer, to which a member might be exposed during a fire. It consists of a steel framework with the furnace chamber inside it. The furnace facility includes a hydraulic loading system with a capacity of 1,000 t.

The columns will be tested under the maximum allowable load according to North American Building Codes for concrete structures (2, 10). Most of the HSC columns will be subjected to constant concentric loads during testing. However, some columns will be tested under eccentric loads to study the influence of eccentricity on the performance of columns at high temperatures.

During the test, the column will be exposed, under a load, to heating controlled in such a way that the average temperature in the furnace follows, as closely as possible, the ASTM E119-88 (11) standard temperature-time curve. The furnace, concrete and steel temperatures, as well as the axial deformations and rotations, will be recorded until failure of the column.

3.2 Material Properties

Results from the fire tests will be used to develop computer models for predicting the behaviour of HSC columns exposed to fire. For use in these computer programs, the thermal, mechanical and deformation properties of HSC at elevated temperatures are needed. To establish these properties, a study is being carried out as part of a joint research project involving NRC and NCTU.

The thermal properties that are being studied are thermal conductivity, specific heat and the mass loss of the concretes. The mechanical properties that are being investigated are the compressive strength, tensile strength, modulus of elasticity and ultimate strain. The deformation properties being studied are the thermal expansion and creep.

HSC, with and without fibres, is being considered in this study. Experimental studies on thermal and deformation properties are being carried out at NRC while tests on mechanical properties are being carried out at NCTU. Two types of concrete specimens will be investigated in the study. The first one is plain concrete and the second one is steel fibre-reinforced concrete. Both concrete types will be made with siliceous and carbonate aggregates. The 28-day compressive strength of concrete will be about 90 MPa.

The data obtained from the studies will be used to develop thermal and mechanical relationships, as a function of temperature, for HSC. These relationships can be used as input in computer programs to determine the behaviour of HSC structural members at high temperatures (12).

3.3 Numerical Studies

The development of computer programs for predicting the fire behaviour of HSC columns is currently in progress at NRC (13). The steps, associated with the development of the models, involve the calculation of the fire temperatures, the cross-sectional temperatures, and the evaluation of the deformations and strength of an HSC column. The effect of spalling will be accounted for through pore pressure computations. The validity of the computer programs will be established by comparing the predictions from the computer programs to test data.

The computer programs will then be used to carry out detailed parametric studies of the influences of the various parameters, such as concrete strength and load intensity on the fire resistance of HSC columns. Data from the parametric studies will be used to develop design guidelines to overcome the problem of spalling in HSC columns and for predicting the fire resistance of HSC columns.

4. SUMMARY

An overview of the current research program on high-strength concrete columns is outlined in this paper. Based on the studies completed so far, it was found that:

- The behaviour of HSC-filled steel columns at high temperatures is significantly different from that of NSC-filled HSS columns.
- The fire resistance rating of HSC-filled HSS columns can be significantly improved by adding steel fibre reinforcement to concrete.

The studies, currently in progress at NRC, will generate data on the fire resistance of HSC columns and contribute to identifying the conditions under which these columns can be safely used.

5. ACKNOWLEDGEMENTS

The research described in this paper is the result of partnerships between the National Research Council of Canada and the Canadian Steel Construction Council, Portland Cement Association, Canadian Portland Cement Association, Concrete Canada and the National Chiao Tung University in Taiwan.

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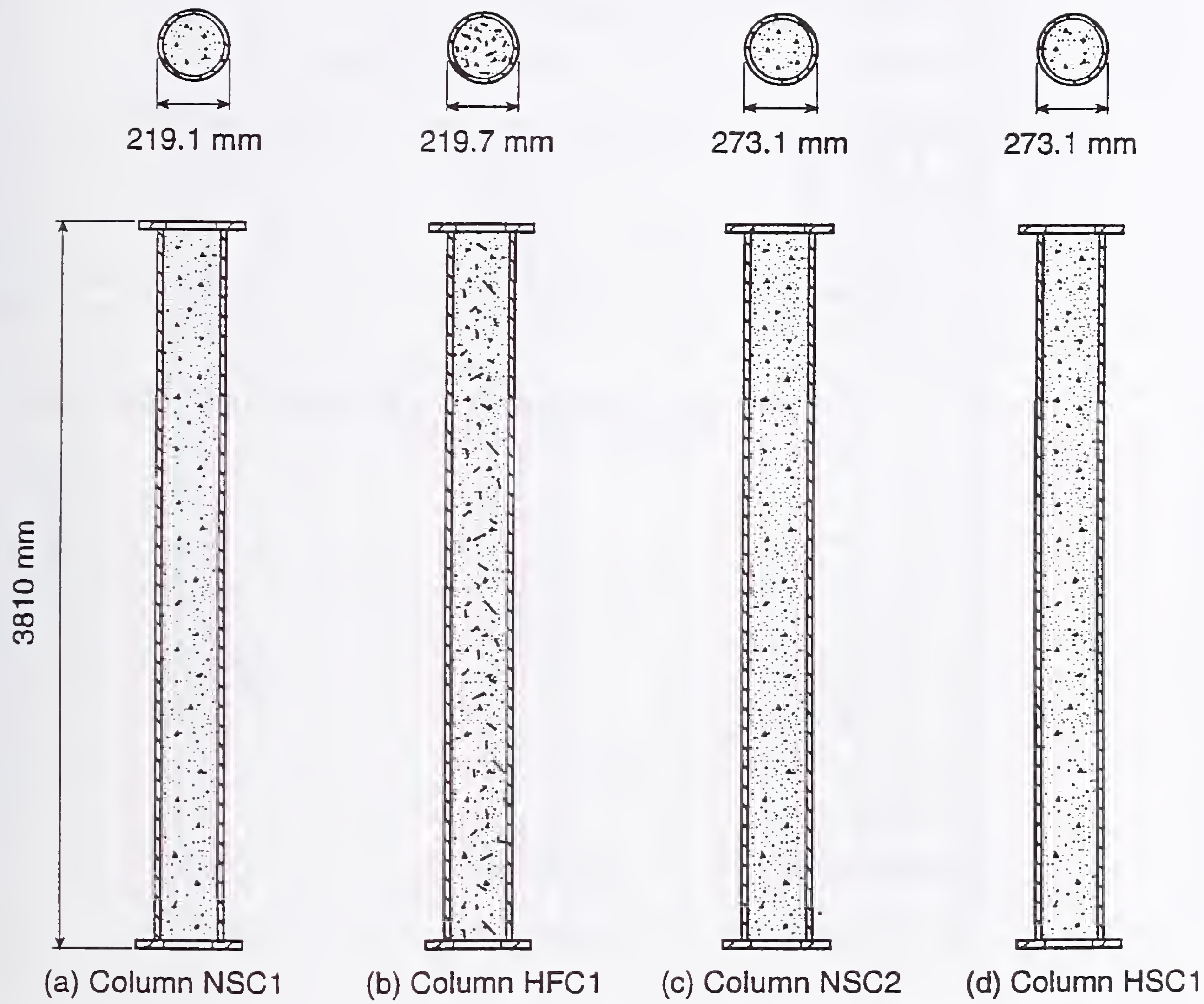

Figure 1 Elevation and Cross Section of Columns

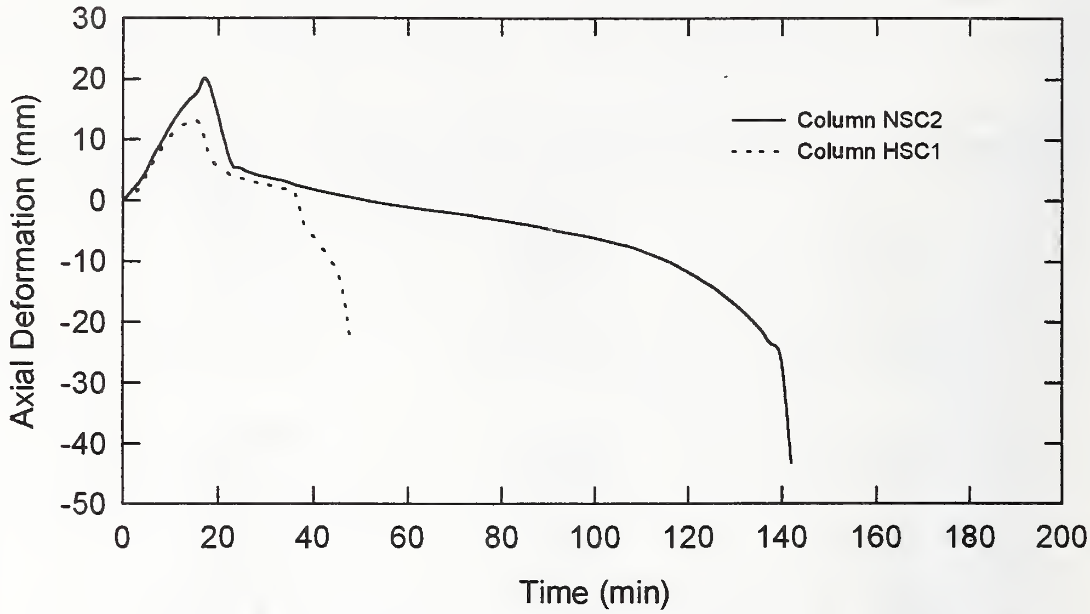

Figure 2. Axial deformations of Columns NSC2 and HSC1 as a function of exposure time

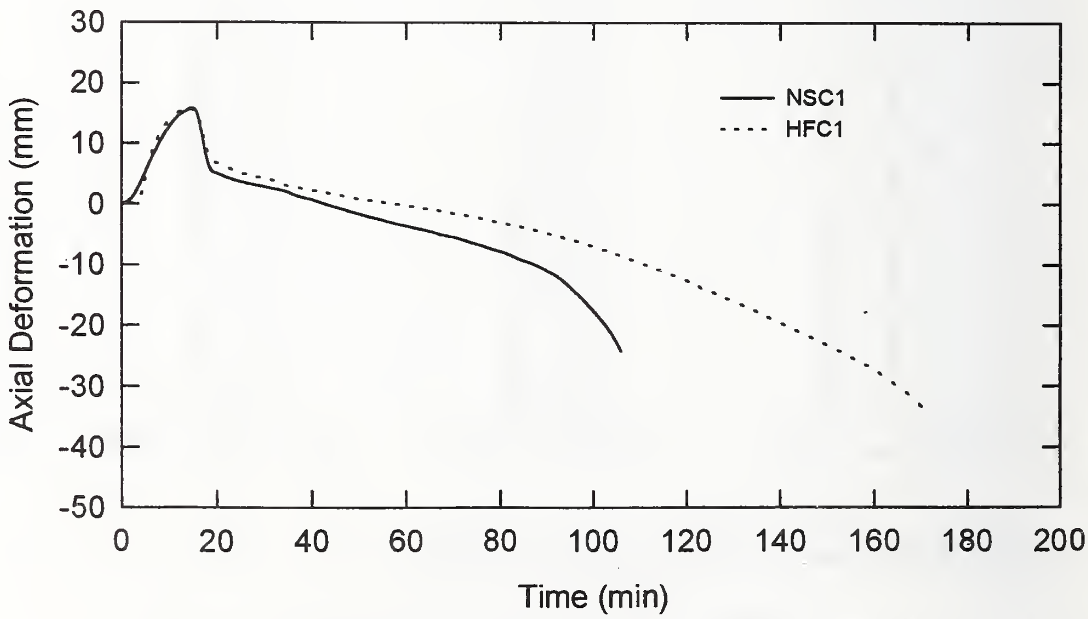

Figure 3. Axial deformations of Columns NSC1 and HFC1 as a function of exposure time.

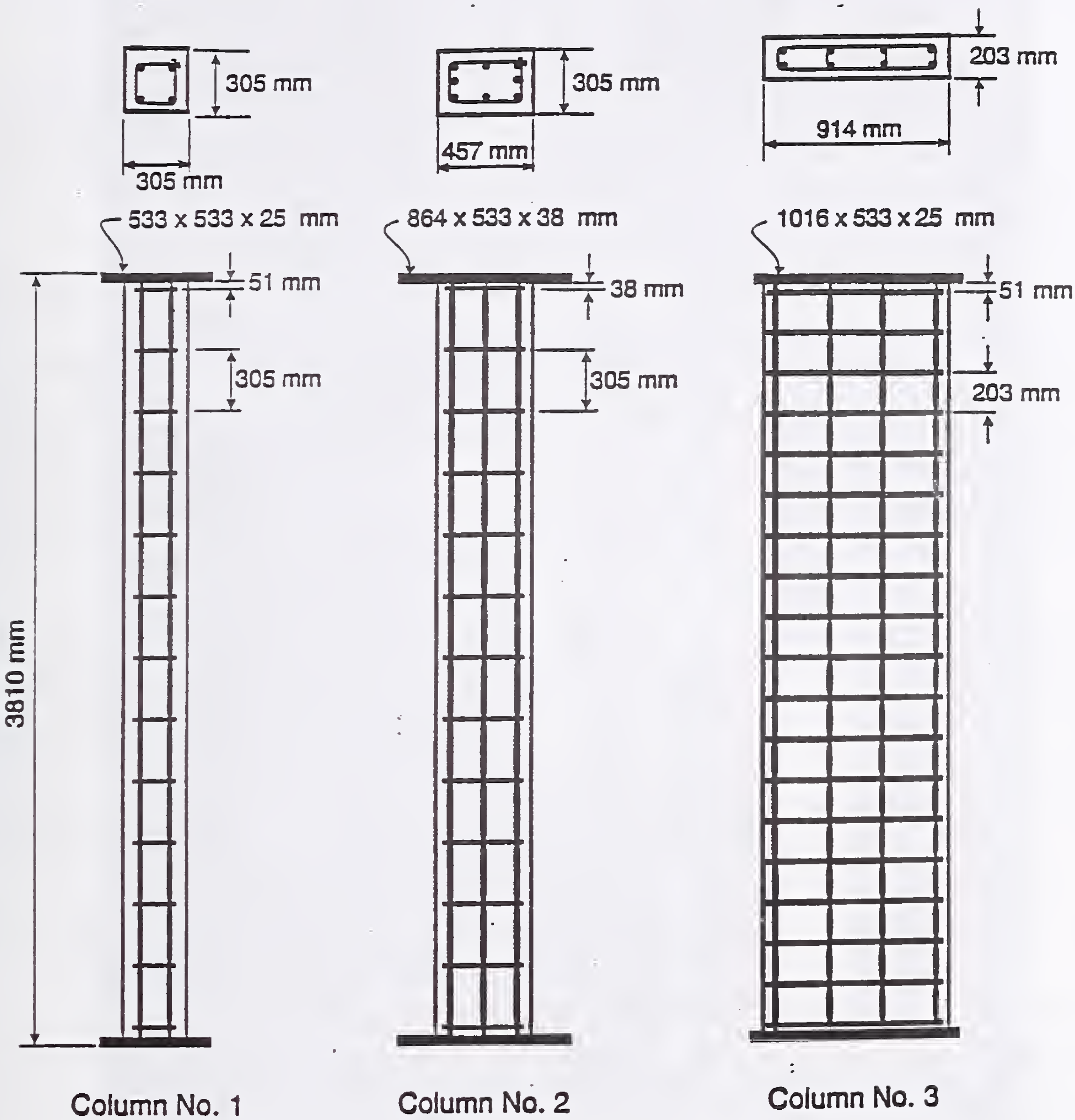

Figure 4 RC Columns Layout

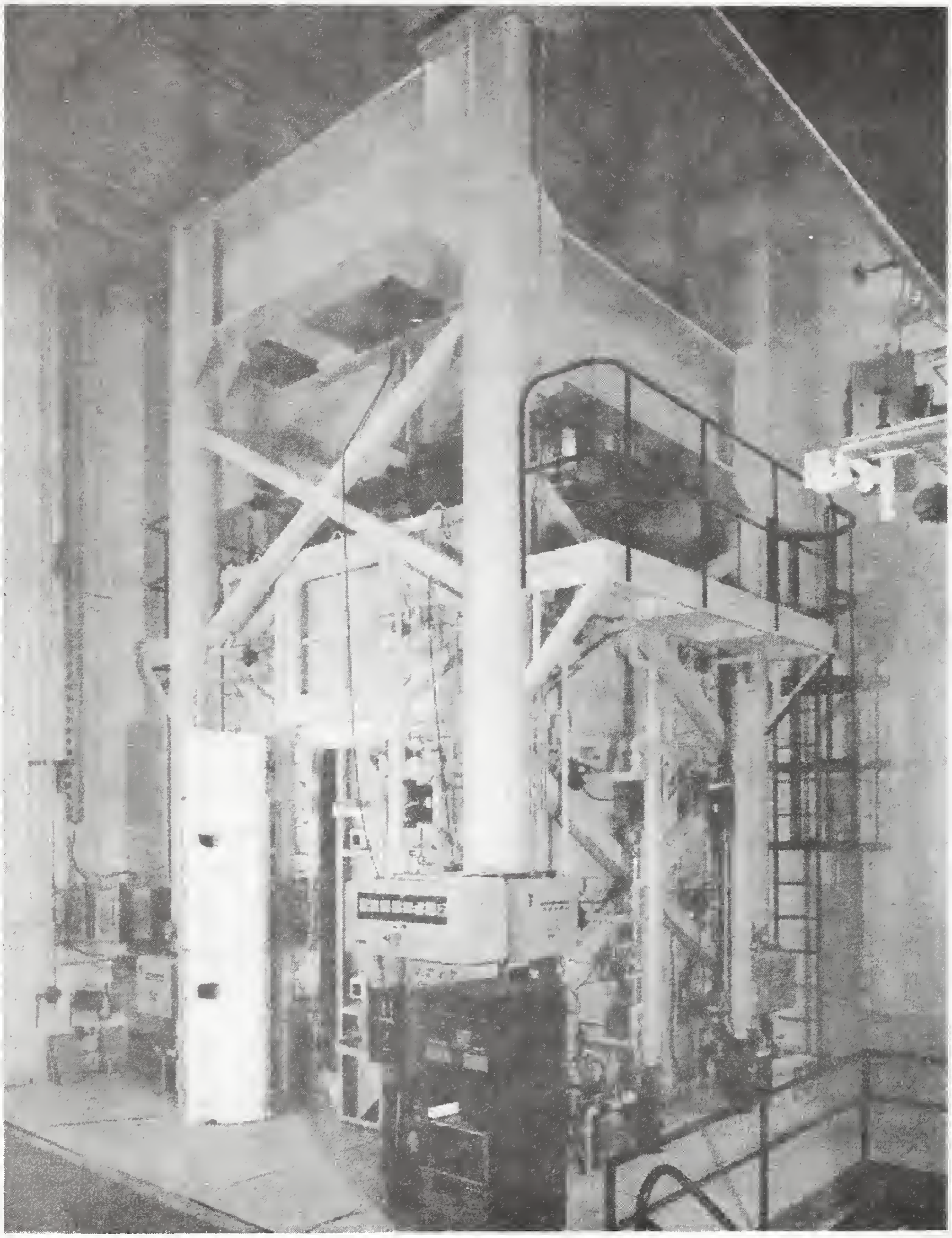

Figure 5 Column Test Furnace

B.5 Limitation of Current U.S. Standards and Challenges of Proposed Performance-Based Standards

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Background

There is widespread interest in developing performance-based standards in the U.S. for building applications. Such standards will differ from the current system of standards by explicitly identifying fire safety goals and objectives which will be achieved by a particular design. Statements of goals and objectives will be presented in terms which are amenable to evaluation via quantitative methods. Performance measures will need to be identified along with acceptance criteria for each of the measures to determine the acceptability of a design.

Development of a performance-based standard for fire resistance will require a reformulation of the traditional process of evaluating fire resistance. Explicit statements of goals and objectives are needed. In addition, the appropriateness of the standard test method, related measurements and acceptance criteria needs to be assessed.

Fire resistance refers to the ability of a building assembly to withstand the effects of fire. The goals for fire resistant assemblies are to accomplish one or both of the following:

• restrict the spread of fire beyond the compartment of fire involvement
• support a load, despite exposure to a fire

Failure of a barrier to restrict fire spread may be caused by excessive heat transmission to the unexposed side of the barrier. Heat transmission limits are established to prevent the ignition of combustibles in contact with the unexposed side of the assembly [Schwartz and Lie, 1985]. Typically, heat transmission limits are expressed as a maximum increase in temperature on the unexposed side [ASTM, 1995][1].

Failure of a barrier to restrict fire spread may also be caused by a breach of the barrier as a result of burn-through, development of large cracks or failure to maintain its structural integrity. A breach

[1] The standard test method is documented in ASTM E119. NFPA 251 and UL 263. For simplicity. the standard test method will be referred to as ASTM E 119 throughout this paper.

in the barrier may alter the ventilation characteristics of the fire compartment or provide additional paths for smoke and fire spread from the fire compartment.

Structural failure or collapse is relevant for load-bearing members. Failure of a loadbearing member may result in a local collapse or wide-spread structural failure if load transfer to adjoining members is unsuccessful. To a limited extent, structural failure of non-load-bearing assemblies is of interest, because the assembly still must be able to sustain its own dead weight and maintain integrity to restrict fire spread.

Another possible goal receiving increased attention is the post-fire integrity of building assemblies. This interest reflects concerns for scenarios where the structure is able to withstand the impact of the fire exposure during the incident, but requires substantial repair prior to returning to use.

Possible objectives related to the three goals include the following:

A barrier needs to limit the heat transmission to the unexposed side such that ignition of ordinary combustibles in contact with the barrier is prevented. A structural member needs to have sufficient load-carrying ability to sustain applied loads, despite the increase in temperature and possible imposition of temperature gradients within the member. A structural member needs to have sufficient residual load-carrying ability so that the member will be reusable after the fire without repair.

Considering the noted goals and objectives, the following performance measures can be proposed to assess the fire resistance of construction assemblies:

<u>Thermal</u> temperature on unexposed side
• temperature of steel structural components

<u>Structural load or moment capacity</u> (as a function of temperature)
• stability
• deflection

<u>Post-fire usability</u>
• residual load or moment capacity

Currently, fire resistance analyses are typically conducted via a standard test [ASTM, 1995]. The test is used only as a comparative measure and is not intended to provide data for predicting the response of an assembly exposed to actual fire conditions. The endpoints for the test include the two thermal performance measures and the ability to sustain the applied load, comparable to the first two structural performance measures. Post-fire serviceability is not addressed by the standard test.

Because the test intends to be comparative in nature, application of the results from the standard fire resistance test is constrained until the following aspects are addressed. Given that performance-based design will consider a variety of design fires, the relevance of the heating conditions associated with the standard test to those of selected design fires needs to be demonstrated. Loading conditions associated with a particular project may be different than those used in the standard test. Whereas the loading conditions associated with the standard test intend to provide the greatest applied stress to the component, tests of flexural elements are only designed to develop the maximum normal stress in the element and not the maximum shear. Samples are large-scale samples, though not full scale, without any attempt to provide structural end conditions to replicate full-scale behavior. Finally, the objectivity of the endpoint criterion "sustaining the applied load" can be improved by adding deflection criteria.

Development of an Engineering Practice Standard

In lieu of conducting very specialized fire resistance tests to address the specific aspects of a particular design, engineering practice standards can be developed which document calculation methods to determine the response of structural assemblies to a fire exposure. This is a current area of activity within the American Society of Civil Engineers and Society of Fire Protection Engineers.

Analysis of the response of fire-exposed structural assemblies requires consideration of the following four aspects:

- fire exposure
- material properties at elevated temperatures
- thermal response of the structure
- structural response of the heated assembly.

The relationship of these four aspects in a performance-based approach for evaluating fire resistance is reflected in Figure 1. As indicated, one aspect provides input to one or two other aspects. However, in reality, the aspects are actually inter-related, suggesting that the arrows in the diagram should point in both directions in many cases. For example, the thermal response of a wall assembly affects the temperature of the exposing smoke by altering the energy exchange between the smoke and the enclosure. In addition, if the wall assembly collapses, additional ventilation will be provided to alter the course of the fire.

A description of the fire exposure is used to characterize the radiative and convective heating conditions associated with a particular fire scenario. The heating conditions are described in terms of parameters such as the temperature history of the gases or smoke layer within the compartment, radiation characteristics of the smoke layer and flames, and duration of the exposure. Results from the fire exposure analysis are used as input for the thermal response analysis.

Both the thermal and structural response analyses are influenced by the material properties at elevated temperature. Thermophysical and mechanical material properties are temperature dependent. Thermophysical properties used in the thermal response analysis include the thermal conductivity, specific heat, density, porosity and permeability. The mechanical properties of interest include the elastic moduli, strengths, coefficient of thermal expansion and creep parameters. In addition, heat absorption or generation due to changes in material composition or physical phase occurring at elevated temperature also need to be considered.

Thermal response is analyzed for two reasons: heat transmission to the unexposed side of the assembly and impact on structural integrity of load-carrying members. The temperature on the unexposed side of an assembly can be determined from a heat transfer analysis. Temperature on the unexposed side of the assembly is limited in order to prevent ignition of combustibles or injury to occupants in contact with the unexposed side of the assembly. In addition, results from a thermal response analysis are important in providing input for the analysis of structural response, accounting for thermal strains, creep strains and the dependence of material properties on temperature.

Generally, the thermal response of a construction assembly is evaluated via a conduction heat transfer analysis. Boundary conditions are stipulated for any fire exposed surfaces based on the characteristics of the fire exposure and for any unexposed surfaces based on environment conditions. Where cavities are provided within the assembly, the convection and radiation across the cavity needs to be considered. For materials containing moisture, moisture migration and evaporation will affect the heat transfer within the assembly and should be considered in the analysis.

Evaluation of structural response addresses the impact of degraded materials, reductions in material property values and thermally-induced stresses on the integrity of load-carrying members. Examples of structural response analyses include moment-bearing capacity analyses for beams and slabs, stability analyses for slender columns and deflection analyses for beams and slabs. In addition to the analysis of structural response on the integrity of a particular load carrying member, the effect of the response of the fire-exposed member on adjoining structural members also needs to be evaluated.

In 1985, an SFPE task force concluded that analytical methods were available to determine the fire resistance of a wide variety of assemblies comprised of concrete, steel and wood [Milke, 1985]. This conclusion was repeated by Pettersson in 1986. Summaries of calculation methods to conduct performance-based analyses of the fire resistance of many different assemblies have been published recently [Lie, 1992][Milke, 1995][Fleischmann, 1995] [White, 1995] [Hosser, et al., 1994].

Existing analytical methods range from parametric expressions to numerical calculations. Typically, parametric expressions are limited to comparisons of the fire resistance of one assembly to another. Numerical calculations range from the application of graphical analyses and empirical correlations to finite element computer models to conduct heat transfer or structural analyses, accounting for unique property values, loading conditions and fire exposure attributes.

Integrated analysis methods involving the fire behavior, material effects, thermal response and structural response have been documented. One of the earliest versions of such an analytical approach was developed by Pettersson, Magnusson, and Thor for steel members [1976].

Subsequently, many other documents have been compiled, such as: ECCS [1983], ECCS [1985], CIB [1986], Eurocodes standards for each of the major structural materials and a recent design guide for steel members [Schleich, 1993]. All of these documents address the response of a building assembly to an uncontrolled, fully-developed fire.

Of particular interest in the integrated design guides are the following:

1. establishment of material properties as a function of temperature
2. safety factors to add conservatism in the areas of applied loads/moments, fire severity and duration.
3. establishment of charring rates for wood
4. establishment of heat transfer parameters describing fire exposure

All of these calculation methods require input data pertaining to the four aspects illustrated in Figure 1. In particular, heating conditions associated with the fire exposure need to be described. Heating conditions are described in terms of the heat flux as a function of time. Heat flux may be described explicitly or implicitly via the provision of temperature, convection coefficient and radiation parameters associated with the exposure. Heat flux or temperature is routinely provided in fire growth models [Walton, 1995] [Babrauskas, 1979]. Convection and radiation parameters are generally assumed and rarely determined.

Material properties as a function of temperature are required for the thermal and structural response analyses. For the thermal response analysis, the following properties are among those needed:

<u>thermophysical properties</u>
thermal conductivity, specific heat, density

<u>chemical changes</u>
decomposition, pyrolysis

<u>physical changes</u>
phase change, moisture migration, spalling, swelling/shrinkage

For the structural response analyses, the following mechanical properties are among those needed:

<u>mechanical properties</u>
yield strength/ultimate strength, modulus of elasticity, shear modulus, Poisson's ratio, coefficient of thermal expansion, creep parameters.

In each case, test procedures need to be agreed upon to yield consistent property values. For example, the strengths and moduli are functions of the heating and loading rate and sequence of heat and load imposition [Phan, 1996]. A task group within the Fire Tests Committee of the National Fire Protection Association is currently involved in listing standard test methods to determine the thermophysical and mechanical properties at elevated temperature.

Conclusion

Engineering practice standards to determine fire resistance are being developed to support the development of performance based codes. However, one of the principal constraints on the ability of calculation methods to predict fire resistance is the shortage of material property data at elevated temperature and the lack of widely-accepted methods to determine such properties.

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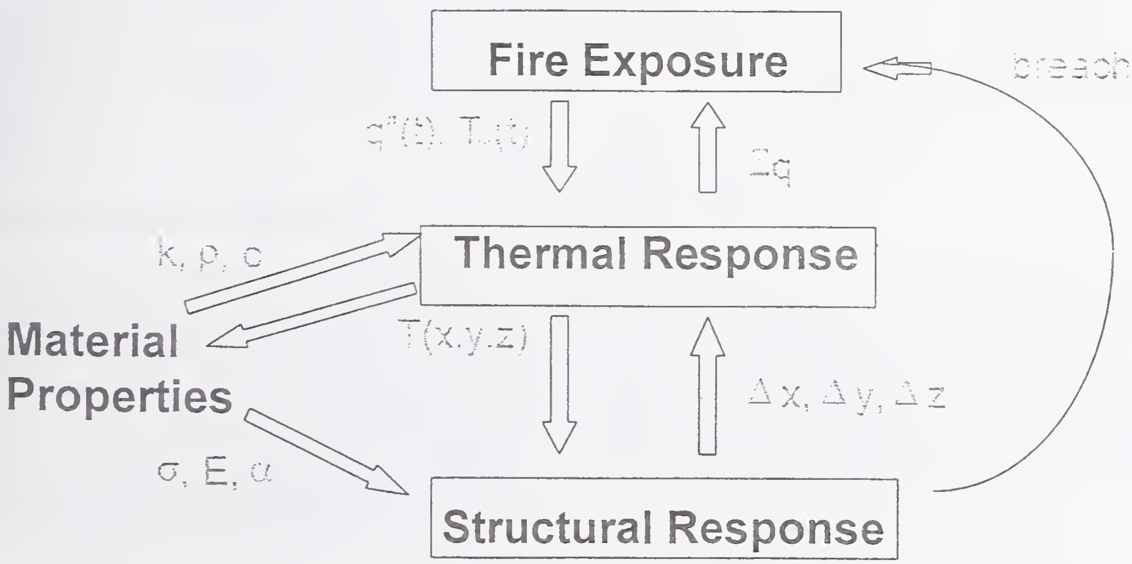

Figure 1. Procedure for Performance-Based Assessment of Fire Resistance

B.6 An Analytical Approach for Investigating the Causes of Spalling of High-Strength Concrete at Elevated Temperatures

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Background

Explosive spalling of high-strength concrete (HSC) elements and cylinder specimens has occurred unpredictably and on an inconsistent basis during laboratory fire tests. Differences in the structural fire performance of specimens constructed of HSC versus normal-strength concrete (NSC) have been attributed to differences in the mechanical properties of the two types of concretes at elevated temperatures. Because of these differences, structural design provisions for NSC may not be applicable to HSC for use in structures required to be fire resistance rated. The inconclusive nature of fire tests involving HSC columns suggests that additional research is needed, not only to gain a better understanding of the cause or causes of spalling, but to obtain a clearer picture of the fire performance of HSC structural members in general.

Purpose

This paper will primarily focus on the issue of spalling. The objectives are as follows: to present an overview of the performance inconsistencies of HSC at elevated temperature based on laboratory fire tests of HSC columns; to propose an analytical approach for investigating the cause or causes of spalling; and to recommend work that is needed in support of the analytical study.

Behavior of high strength concrete exposed to fire

Results from research projects sponsored by the Portland Cement Association (PCA) and others involving fire tests of HSC have shown that the material performs significantly differently under fire exposure than does NSC. Table 1 provides column specifications and other pertinent information for 3 carbonate aggregate, 406 mm x 406 mm HSC columns that were tested at the National Research Council of Canada test facility. Fig. 1 shows the temperature history results from the 3 fire tests. Thermocouple measurements were taken at distances normal to the surface and along the centerline of each column.

Table 1. Concrete Mixtures for HSC column fire test specimens

Column designation	Column HS-1	Column HS-2	Column HS-4
Test date	11-4-94	7-3-96	6-19-96
Cement type I, lb (kg)	800 (362.8)	820 (371.8)	653 (296.1)
Coarse agg., SSD*, lb (kg)	1800 (816.3)	1800 (816.3)	1563 (708.8)
Aggregate type	carbonate	carbonate	carbonate
Water cement ratio	0.338	0.320	0.395
Water cementitious material ratio	0.287	0.291	0.359
% Silica fume:cement	5.00	9.76	9.95
% Fly ash:cement	12.50	0.0	0.0
Cylinder strength, ksi (MPa)	14.5 (100.0)	18.35 (126.5)	12.7 (87.6)

* SSD is saturated surface dry condition.

Although the columns were all made with the same aggregate and cast at the same time, Column HS-1 was tested 19-20 months earlier than HS-2 and HS-4. Of the three columns, the shorter drying period of HS-1, and thus, its higher initial moisture content, typically would have been expected to produce the lowest data readings for temperature history. This is clearly not the case, however, as Fig. 1 shows just the opposite is true. Aside from the influence of drying time, all three columns contained the same aggregate type, and therefore, should have had similar thermal conductivity properties. Since thermal conductivity has the most dominant influence on temperature profile, it would be expected that the data from the 3 column tests should reflect close agreement in temperature histories. Again, this was not the case. These expectations would have held true had the columns been produced with normal strength concrete. The inconsistencies in fire performance of these HSC specimens from the anticipated behavior make the results of such testing inconclusive at best.

Fig. 2 compares the PCA heat and mass transfer model predictions of temperature history against the data from HS-1. Column HS-1 was selected for validation purposes because it was the only column specimen tested in an unloaded condition. One can see from the figure that the agreement between model results and test data is good.

In an attempt to force the model predictions into agreement with the lower temperature histories of the other two columns, computer runs were performed using artificially low and unrealistic thermal conductivity relationships as input data. These efforts, however, proved unsuccessful, as it was impossible to bring the curves down to the levels indicated by the test data. The fact that the experimental temperature curves are not consistent with physical laws indicates a problem for which there is no explanation at present. Again, these types of inconsistencies support the need for additional research.

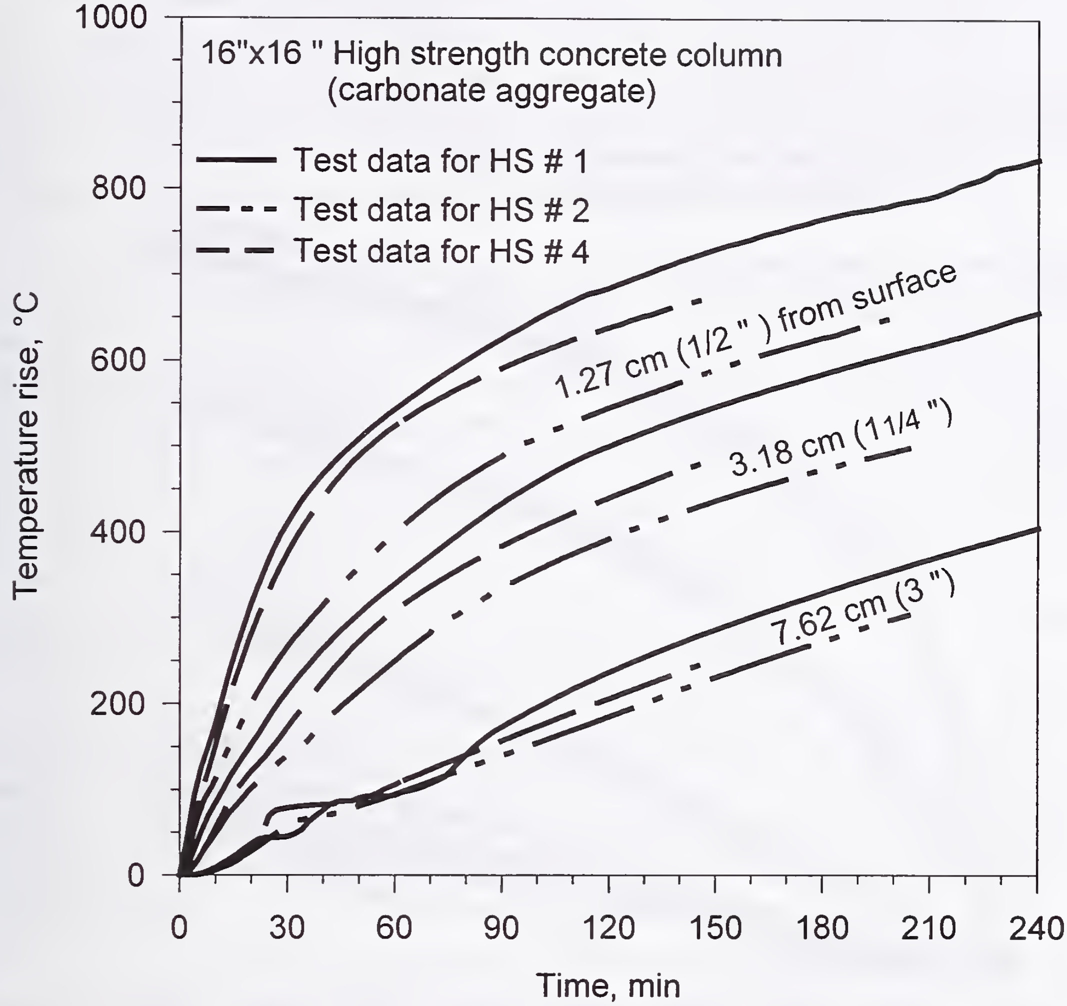

Figure 1. Temperature history data for columns HS # 1, 2, and 4 subjected to ASTM E 119 fire.

Potential causes of spalling

Over the years, several explanations have been offered regarding the primary cause of concrete spalling at elevated temperature. Spalling has been attributed to thermal stresses due to temperature gradient, as well as thermal expansion of unlike materials such as concrete and reinforcing steel. Excessive loading or inadequate reinforcement has also been suggested as the source of spalling. In other theories, pore pressure buildup has been said to have the greatest influence. In fact, the spalling phenomenon is likely to be caused by the cumulative effect of all of these factors. With respect to which one plays the dominant role, the authors' beliefs are aligned with those of the pore pressure perspective. This perspective is based on the following discussion.

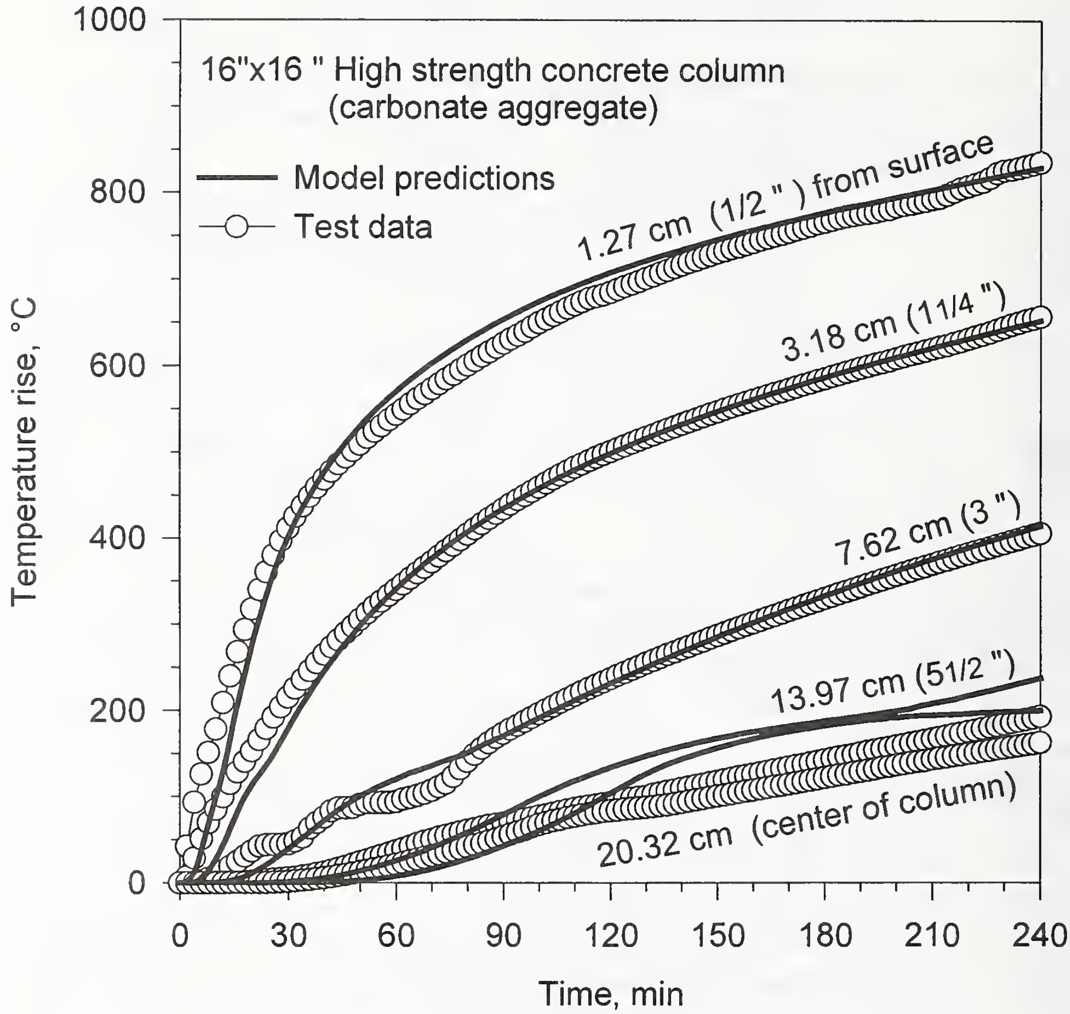

Figure 2. Comparison of the predicted temperature history of column HS # 1 against ASTM E 119 fire test data.

Researchers who have suggested thermal stresses as the primary cause of spalling, generally dismiss the effects of pore pressure as negligible. If thermal stresses were truly the governing factor, however, then NSC of a given aggregate type would likely be susceptible to the same type of spalling problems as its HSC counterpart due to similarities in their thermal conductivities. Contrarily, this behavior has not been evident from field experience, and the issue of spalling associated with structural members constructed of normal strength concrete has not warranted cause for concern.

Others have felt that the spalling of high-strength concrete at elevated temperature is more of a structural problem than a fire problem. If this were true, then concretes used in unloaded applications, such as refractory concretes for furnace liners, would not be expected to have spalling problems. This, of course, is not the case, as spalling is very much a concern for concretes exposed to high-temperature environments. In practice, the standard method that is used to eliminate spalling is to pre-condition the concretes through a specialized drying process. Removing the moisture reduces the possibility of pore pressure build up.

Furthermore, it is widely known that the addition of polypropylene fibers has been successful in reducing the spalling problem in HSC member subjected to fire. Again, if spalling were primarily the result of loading conditions or thermal effects, there is no reasonable explanation as to why this technique would have succeeded. Melting and/or shrinkage of fibers at elevated temperature increases concrete permeability, which is shown to have a strong influence on pore pressure buildup (see Fig. 8). The fact that the addition of fibers has proven successful in alleviating spalling is a solid testament that pore pressure plays a significant role in the occurrence of spalling. To date, this assertion is primarily qualitative. The section that follows offers a methodology that will lead to a quantitative resolution of this.

Proposed approach for investigating the cause of spalling

The question of degree of influence of the factors that may contribute to spalling can only be answered through a robust analytical procedure involving parametric studies and a stress analysis. The proposed approach for the stress analysis (for a member subjected to a standard fire test) is to determine the total stress at a given depth due to thermal gradient, thermal expansion, load, pore pressure, etc., and compare it with the heat-reduced strength of the material at a desired time.

Possibly, the most reasonable and efficient way of achieving this is to merge an appropriate thermal model with a compatible structural analysis model. The heat and mass transfer model discussed in this paper serves well in this capacity because of its relatively unique capability of predicting pore pressure, which is identified as a critical factor in the spalling process. In addition, the model provides temperature history results that are necessary for determining the change in the material's temperature-dependent mechanical properties. Parametric studies of parameters affecting pore pressure can also be done with the model, and some examples of these are presented later in this paper.

Synopsis of the model

As a precursor to the parametric examples, a brief synopsis of the model is given with respect to some of its characteristics, assumptions, and considerations. An explanation of the coupling relationship between temperature, moisture content, and pore pressure histories and distributions is also presented. Detailed information about the model is provided in Refs. 1, 2, and 3.

Model characteristics

Some of the primary characteristics of the model can be summarized as follows:

- heat and mass transport phenomena are coupled
- conservation of mass, momentum, and energy equations coupled to constitutive relations of the material drive the model
- the model works with any specified heat source
- the model handles various geometries for one- and two-dimensional heat and mass transfer
- model output includes moisture content, pore pressure, and temperature distributions and histories

Model assumptions and considerations

Some of the main model assumptions and considerations are summarized as follows:

- local equilibrium moisture content is related to the relative vapor pressure and temperature using sorption isotherms
- physical and thermal properties of concrete are functions of temperature, pore pressure, and moisture content
- conductive and radiative heat, and mass and heat transfer by convection and diffusion are considered
- evaporation/condensation and dehydration phenomena and their effect on the material pore size are considered
- convective heat and mass transfer are driven by pore pressure gradients
- diffusive transport is driven by mass concentration gradients
- conductive heat transfer is driven by temperature gradients

Coupling relationship

One of the most important attributes of the model is the coupling relationship previously mentioned. Figs. 3, 4, and 5 show the model's predictions of temperature, moisture content, and pore pressure distributions, respectively, for 406 mm x 406 mm carbonate aggregate HSC column, and are used to illustrate this relationship. The depths indicated in the figures represent distances along the diagonal of the cross section.

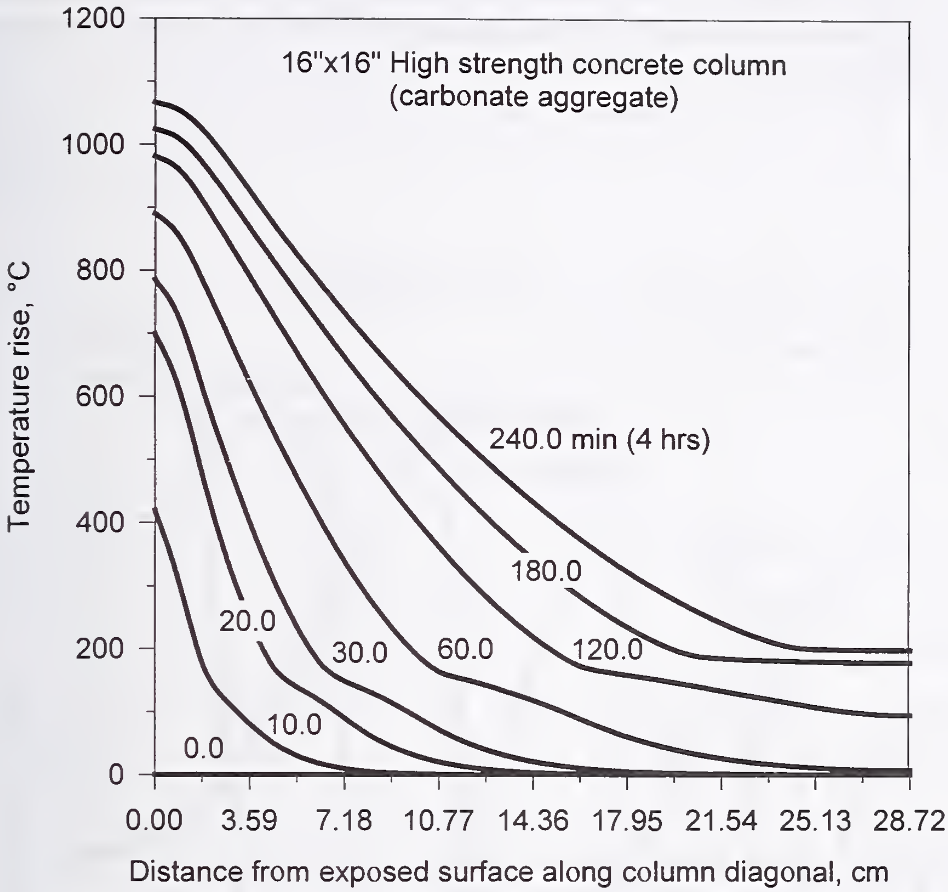

Figure 3. Model-predicted temperature distribution at various times of HSC column subjected to ASTM E 119 fire.

Before getting into the coupling discussion, a brief description of the heat and mass transport phenomena is provided. When a depth of concrete becomes sufficiently hot, the evaporation of the free moisture and chemically bound water takes place. As the water evaporates, pore pressure builds up driving some of the gaseous mixture of air and water vapor toward the column surface. The rest is driven into cooler zones toward the center of the column where it condenses and accumulates as liquid. This accumulation can often exceed the initial moisture content, as seen in Fig. 4. Continued application of heat in the presence of moisture continues to build pore pressure, which in turn, repeats the process of moisture transport followed by moisture condensation and accumulation. This interdependent cycle is repeated until either all of the moisture is gone or the heat source is removed.

In Fig. 3 at 20 minutes, the evaporation process is occurring at a depth of about 72 mm from the fire-exposed surface (where the concrete temperature is at or above 100 °C). In Fig. 4 at this depth and time, the moisture content of the concrete is almost at its initial value because virtually no dehydration of the chemically bound water has yet occurred. It follows from the relatively low temperature at this depth that the pore pressure would also be low under these conditions, and this is confirmed in Fig. 5.

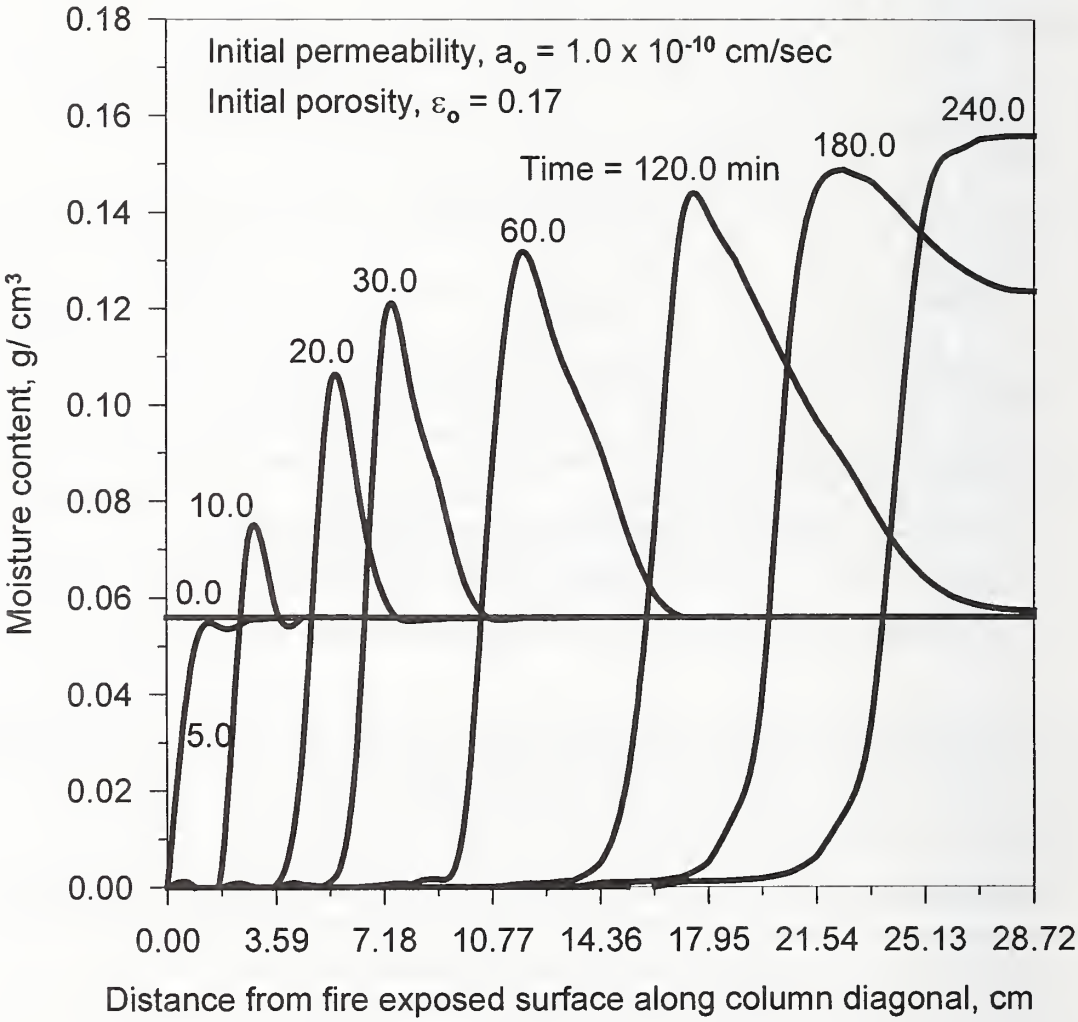

Figure 4. Model-predicted moisture content distribution at various times of HSC column subjected to ASTM E 119 fire.

From Fig. 4 at 20 minutes, the concrete reaches its maximum moisture content at a depth of 54 mm and becomes dry at 36 mm. This portion of the curve (from maximum moisture content to zero) represents the evaporation front or zone experiencing the highest rate of evaporation. In cross referencing this to Fig. 3, the slope of the temperature curve at 54 mm is moderate, reflecting the moisture's ability to absorb heat as it evaporates. Closer to the surface, where the available moisture has diminished (Fig. 4), the amount of heat that can be absorbed also becomes less. This is reflected by a corresponding increase in steepness of the temperature rise curve in Fig. 3. At 36 mm, where the drying front is located, there is no available moisture to further retard the rate of temperature rise. This is confirmed in Fig. 3 by the sharp increase in temperature rise that is seen in the region bounded by the drying front and the fire-exposed surface of the column.

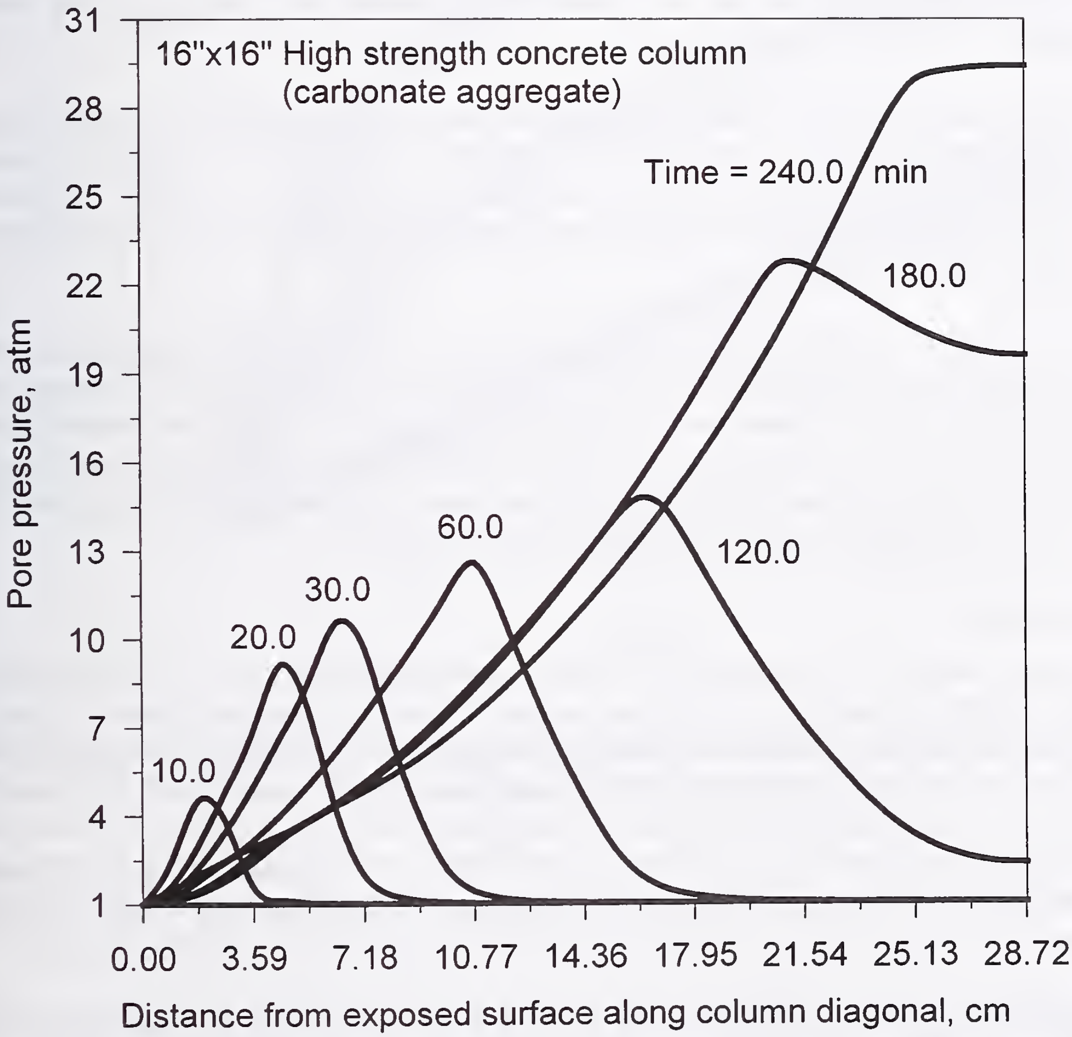

Figure 5. Model-predicted pore pressure distribution at various times of HSC column subjected to ASTM E 119 fire.

In looking at Fig. 5, the peak pore pressure at 20 minutes occurs at a depth somewhere along the evaporation front. In general, as the pore pressure builds, the evaporation front moves toward the center of the column. The pore pressure and moisture content peak at different depths for a given time. At a given time, the pore pressure reaches its maximum value closer to the surface as it continues to force the moisture deeper within the column. At the depth of maximum moisture content, the pore pressure has dropped from its peak value due to lower temperatures that are insufficient to sustain its buildup.

With respect to the temperature associated with the point of maximum pore pressure at 20 minutes, Fig. 3 shows this to be at or near the temperature just prior to where the curve experiences its sharpest change in temperature rise. This is logical, since it corresponds to a region of high evaporation, preceding the elimination of moisture and resulting in the rapid temperature rise.

In cooler zones where no moisture has accumulated, for example, at 20 minutes and depths beyond 90 mm (Fig. 4), corresponding to a temperature of about 50 °C (Fig. 3), the pore pressure is essentially atmospheric. This is reasonable in consideration of almost ambient conditions, and once again, confirms the coupled or dependent relationship of the pore pressure, moisture content, and temperature.

From a physical standpoint, fairly drastic changes are occurring within the column at the 20-minute mark between the depths of 36-72 mm. Since this is a common range of thickness in which spalling occurs, it is no coincidence that spalling has been observed in fire tests of HSC within the 20-30 minute time frame. As an aside, the pore pressure will reach its maximum value at the center of the column (287 mm) if the application of heat continues long enough. This trend is evident in Fig. 5 by the curve representing 240 minutes.

Parametric studies

In order to gain a better understanding of the parameters that affect pore pressure buildup and therefore, spalling potential, the model can be used to perform parametric studies. This is significant, in that a desired behavioral response may be able to be controlled or produced at the mix design stage if the phenomenon in question is sufficiently understood. Figs. 6-8 provide model output from parametric investigations that have been done for a 406 mm x 406 mm carbonate aggregate HSC column. For Fig. 6, the depths are measured along the column centerline normal to the surface. In Figs. 7 and 8, depths represent distances along the diagonal of the column.

Fig. 6 shows model predictions of the effect of initial moisture content on temperature history compared with the data for Column HS-1. The curves indicate that increases in initial moisture content result in lower temperature histories. This is reasonable since higher moisture levels are capable of absorbing more heat.

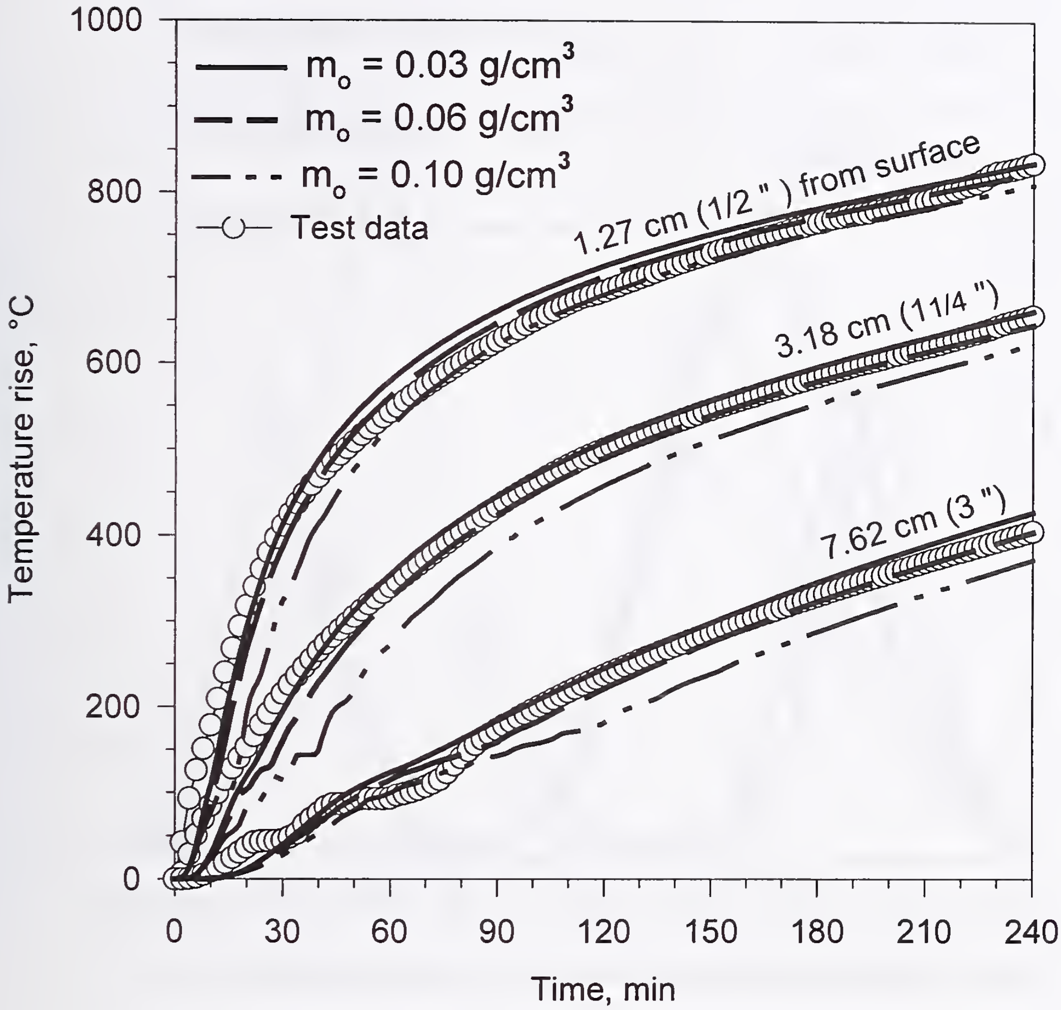

Figure 6. Model-prediction of effect of initial moisture content on temperature history of column HS # 1 compared with E 119 fire test data.

Fig. 7 illustrates the effect of initial moisture content on the pore pressure distribution. The figure indicates an increase in pore pressure as the initial moisture content is increased.

Fig. 8 shows the effect of initial permeability on the pore pressure distribution and clearly indicates the sensitivity of pore pressure to permeability. As previously mentioned, the ability of polypropylene fibers to increase the permeability of concrete is why they have proven to be effective in reducing the spalling of HSC exposed to fire.

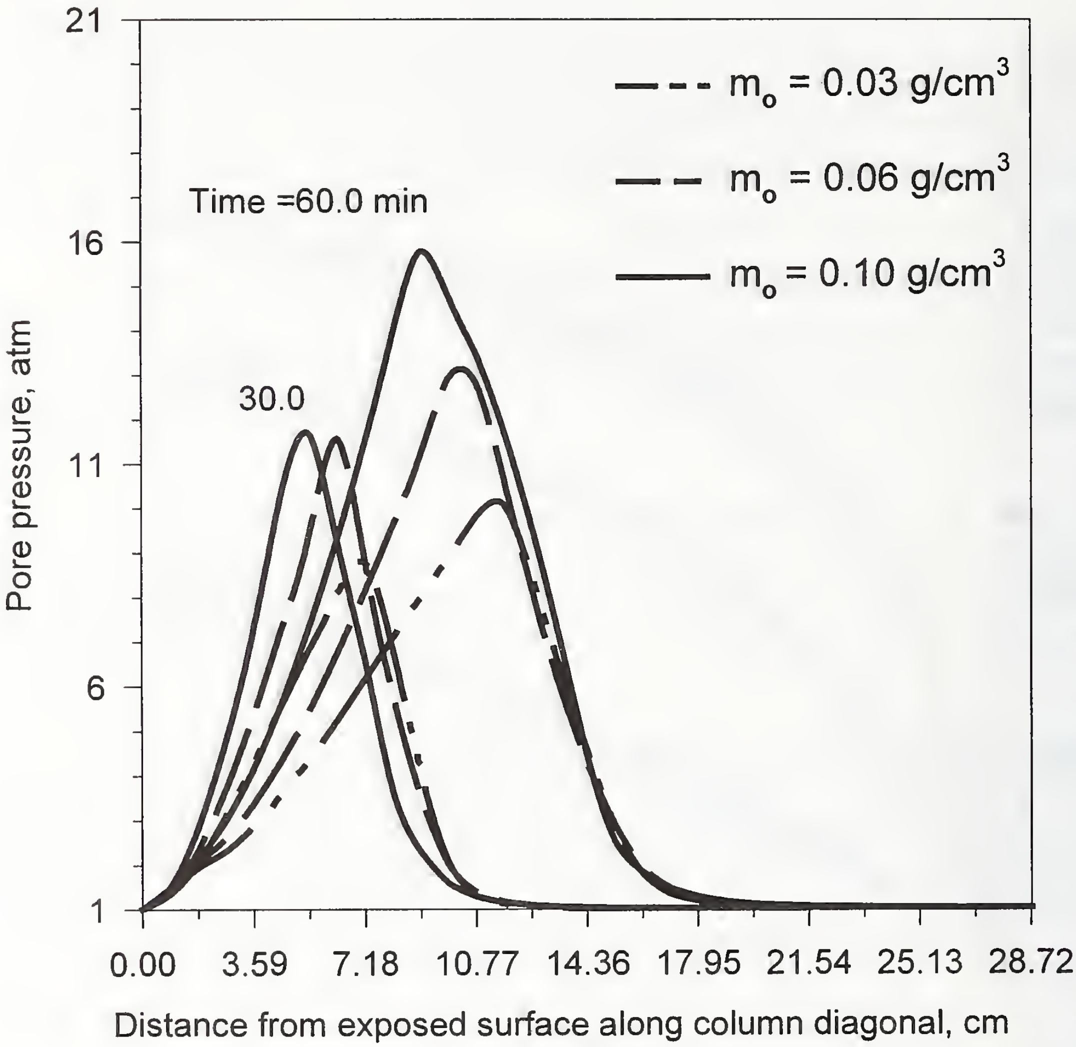

Figure 7. Model-prediction of effect of initial moisture content on pore pressure distribution of 406 mm x 406 mm carbonate aggregate HSC column subjected to E 119 fire.

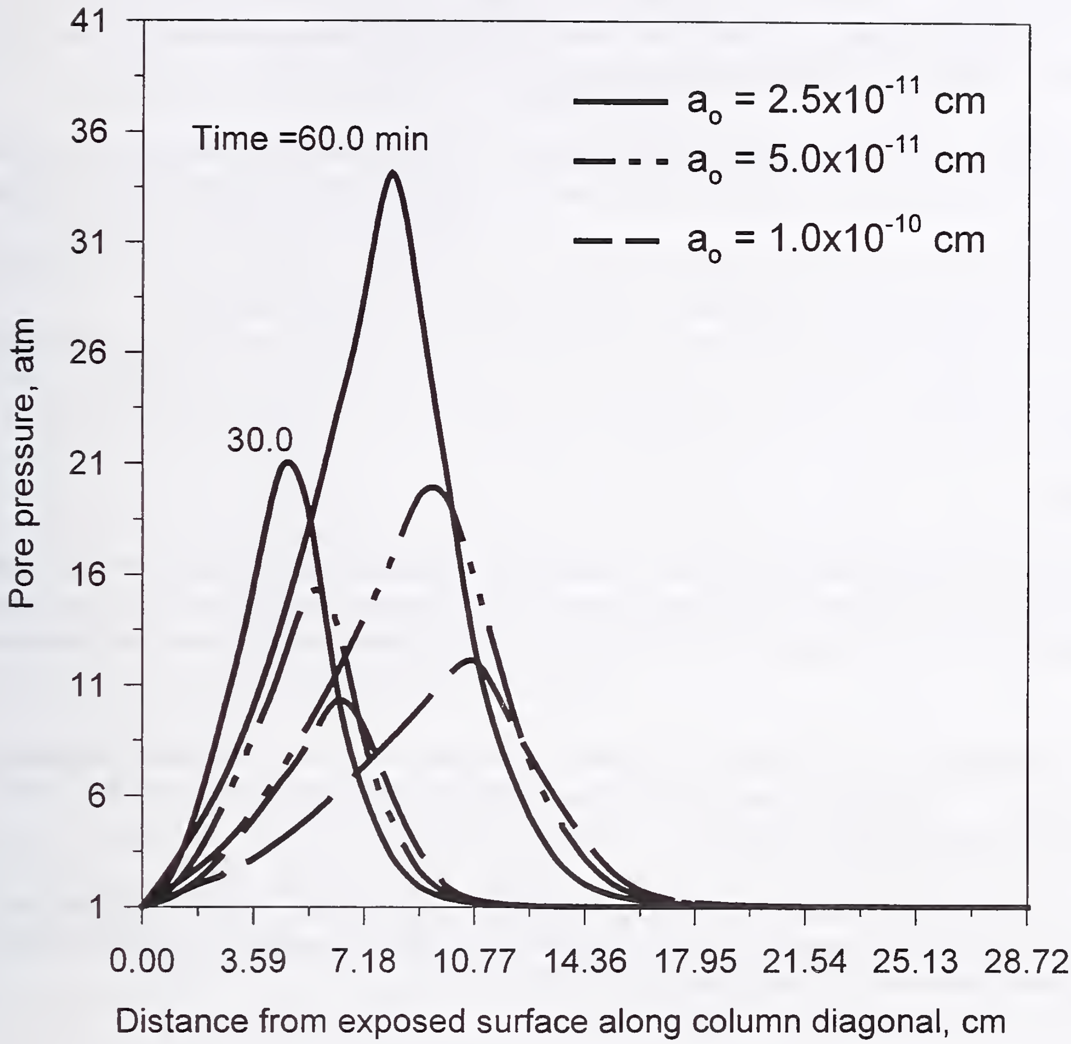

Figure 8. Model-prediction of effect of initial permeability on pore pressure distribution of 406 mm x 406 mm carbonate aggregate HSC column subjected to E 119 fire.

Additional parametric studies are necessary to study the affect of various parameters on HSC fire behavior. These can include the investigation of moisture migration, pore pressure build up, and eventually include the spalling potential and fire performance of HSC. These types of studies are also beneficial in advance of formulating fire test programs for purposes of identifying and eliminating tests that are not expected to yield useful results.

Recommendations in support of the modeling effort

An overall approach for investigating the spalling of HSC under fire conditions has been described. The goal is to develop a computer model that can determine the cause of spalling for purposes of developing a design solution that will eliminate the spalling potential. In order for such an effort to succeed, the following is recommended.

1. Tests involving thermal conductivity, sorption isotherms, permeability, porosity, initial moisture content and others must be performed for high-strength concretes for use as input data.
2. Validation data from full-scale element tests and bench-scale cylinder tests are needed to validate temperature, moisture migration, and pore pressure model predictions.
3. Decisions must be made regarding the merging of a thermal model with a structural analysis model, or whether it is better to start with a thermal model and expand it to include a stress analysis part.

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B.7 FIRE TEST ON NORMAL AND HIGH-STRENGTH REINFORCED CONCRETE COLUMNS

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ABSTRACT

The occurrence of spalling is a major factor in determining the fire resistance of concrete constructions. This paper presents an experimental investigation of fire spalling of normal and high strength concrete in order to provide recommendations for fire safety of constructions. Six short reinforced concrete columns in compression were studied under standard fire conditions. Parameters considered were: reinforcement, by number and diameter of steel rebars, and type of concrete (normal strength concrete and high strength concrete). Test results showed comparable behavior and no spalling of normal strength concrete columns and spalling with a considerable reduction in fire resistance of high-strength concrete.

INTRODUCTION

Although reinforced concrete elements generally exhibit satisfactory behavior at high temperatures, especially when subjected to fire, sudden spalling of external concrete layers is sometimes observed and, consequently, the longitudinal reinforcement may be exposed directly to fire. In such cases failure occurs prematurely and sometimes fire resistance is reduced to half of the original value. The occurrence of spalling is a major factor in determining the fire resistance of concrete constructions (1). Many references in the literature refer to this phenomenon (2,3).

Among the factors that have been identified as influencing spalling of concrete structures subjected to fire, some are related to material properties, such as porosity, tensile strength, thermal elongations, moisture content or thermal properties. Other factors, although directly influenced by the material properties, are related to the structure, the stress distribution depending on the loading and support system, and the presence of steel rebars. Analytical study of spalling should involve consideration of coupled thermal, mechanical and hydraulic phenomena.

A recent experimental program of full-scale tests made on 21 loaded concrete columns (4) showed that Eurocode 2 recommendations (5) are not safe, even when applied to normal strength concrete. Although the rules mentioned in Eurocode 2 suggest that no spalling should occur, some significant spalling did happen during the tests. It was also found that spalling was much more likely to occur in columns with longitudinal rebars of large diameters than in columns with smaller bars. As the first experimental program was not particularly dedicated to spalling, a new experimental program was set up to analyze this question for normal and high-strength concrete columns.

STUDY OBJECTIVES AND RESEARCH SIGNIFICANCE

Study objective was to quantify some of the parameters influencing fire spalling of normal and high-strength concrete in order to provide recommendations for fire safe constructions. Experiments were performed and numerical simulation was planned in order to compare experimental and numerical results. Six short reinforced concrete columns of the same dimensions submitted to compression were studied under fire conditions. The following parameters were considered: reinforcement, by number and diameter of steel rebars; and type of concrete (normal strength concrete C20 and C50, and high strength concrete C90).

The goal of this research work was first to compare the structural behavior of normal and high-strength concrete under fire conditions. Another purpose was to examine a structural effect noticed in the previous experimental study (4), i.e., the influence of the diameter of the rebars on spalling of concrete

EXPERIMENTAL PROGRAM

Test series and mix proportions

Concrete columns were tested at the University of Liège, in Belgium. Six short columns with identical : square 290 x 290 mm cross sections, 2.10 m long were tested in one of the furnaces of the Fire Test Laboratory, University of Liège. The length of the columns was limited by the height of the existing furnace. Test series included columns made of three different mix compositions (Table 1): normal strength concrete C30 and C50, and high strength concrete C90, and 2 different longitudinal reinforcement types, 8 Φ 12 and 4 Φ 25 (Figure 1). Concrete cover was 3 cm. Stirrups with 8 mm diameter were placed 200 mm apart along the columns, except at the ends, where 100 mm spacing was used along the remaining 300 mm (Figure 2). Another three columns, one for each of the mix compositions, were cast in order to determine material characteristics only (Figure 3, section type 1). Compressive strength and tensile strength were determined on 112.5 x 246 mm, 28-day old cores drilled from the concrete columns without reinforcement .

Compression and Fire Tests

Each column was simply supported at the ends. The furnace was provided with an external frame specially designed to apply compressive and tensile stresses. Specimens were loaded by means of 2 double-acting (compressive and tensile) hydraulic jacks.

Thirty two thermocouples were placed in each column before casting of concrete in order to measure temperature evolution. The thermocouples were symmetrically placed at significant locations in the cross sections, such as: in the corners of the concrete section next to stirrups, on both sides of the longitudinal reinforcements, in the concrete core, and on the longitudinal axis.

Thermocouples were placed in 4 different sections along the column: in 2 sections containing stirrups, 9 thermocouples per section, and in 2 sections without stirrups, 7 thermocouples per section (Figures 4 and 5).

Test procedure

The columns were tested in compression and under standard fire conditions. A compressive force representing 50% of the column design load (6,7) was applied first (Table 2). Heating was applied in the gas furnace according to the standard ISO 834 curve (8). The change in length of the columns and temperatures in the 32 thermocouples were recorded every minute during the tests. The column condition was examined basically every 30 minutes during the fire tests, or more frequently when spalling was noticed. This was based on previous research and observations suggesting that spalling usually occurs within a time frame between 30 and 60 minutes after the beginning of heating.

EXPERIMENTAL RESULTS

Comparable behavior of normal strength concrete columns was observed in the experimental program. Both C20 and C50 columns showed a few longitudinal cracks near the edges (Figure 8), with progressive crushing of concrete and buckling of the steel rebars (Figures 7 to 9). Fire resistance proved comparable (Table 3 and Figure 6). High-strength concrete columns showed early spalling at the corners, premature heating of the steel rebars in the reduced section, buckling of the steel rebars just before a sudden failure by crushing of the concrete core (Figure 10). Consequently, a considerable reduction in fire resistance was noticed.

COMMENTS AND CONCLUSIONS

1. Spalling of normal strength concrete columns under fire action was not noticed.
2. High strength concrete columns showed spalling phenomena after 8 minutes (C90, 8 ϕ 12 mm) and 11-12 minutes (C90 4 ϕ 25 mm). In both cases, corner spalling was observed. This type of spalling also referred to as sloughing-off is a consequence of concrete losing its tensile strength at elevated temperatures, and has proved to be particularly significant in determining the fire resistance of columns (1). These experimental results confirm the fact that high strength concrete is more susceptible to spalling than normal strength concrete.

3. Longitudinal cracks along the main reinforcement were noticed for normal strength concrete after one hour of fire test and developed until the end of the test corresponding to crushing.
4. Tests showed that the material behavior has a more significant influence on failure than the structural behavior.
5. Experimental results proved that additional experimental research together with numerical modeling need to be carried out in order to better understand, the spalling phenomena.

FUTURE RESEARCH

1. Other parameters will be considered: the shape of the cross section and the load level.

   - circular cross sectional columns of same length (2.10 m), 300 mm diameter and 2 types of longitudinal reinforcement (6 ϕ 12 mm and 6 ϕ 20 mm) will be tested.

   - compressive load level will be 50% of the design load, as previously considered, and 70% of the design load, corresponding to a more important variable loading.

2. Attention will be focused on a better understanding of the spalling phenomena and of the most significant parameters to influence it and also on the development of a numerical model, considering coupling between thermal, mechanical and transport phenomena, to be included in the SAFIR computer code.

ACKNOWLEDGEMENTS

This research project has been carried out at the Université de Liège, Service des Ponts et Charpentes. The financial and material support of the National Fund for Scientific Research (FNRS) Belgium and NATO (grant CRG 960621) through grants to the Université de Liège, Service des Ponts et Charpentes is greatly appreciated.

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Table 1. Mix Compositions

Concrete	Normal Strength Concrete				High Strength Concrete	
	C20		C50		C90	
Mix Ingredients	kg	%	kg	%	kg	%
Cement	280	1	410	1	47	1
Sand	800	2.86	750	1.83	780	1.66
Aggregate	1100	3.93	1050	2.56	1030	2.19
Water	185	0.66	175	0.43	145	0.31
Superplasicizer	-	-	10	0.024	12	0.026
Silica Fume	-	-	-	-	94	0.2

Note: river sand (Meuse), MS 0/5 mm
limestone aggregate, MSA 7/14 mm
cement P40 (C20), P50 (C50 and C90)
superplasticizerRHEOBUILD 2000PF
columns were cast at PARTEK-ERGON

Table 2. Compressive Loading

Test Series		50% Design Load (tf)	
		8 ϕ 12	4 ϕ 25
NSC	C20	46.46	63.71
	C50	96.40	113.01
HSC	C90	165.29	181.03

Table 3. Fire resistance

Concrete	**Fire Resistance (hours and minutes)**	
	8 ϕ 12	**4 ϕ 25**
C20	3 hours 54 minutes	3 hours 13 minutes
C50	2 hours 32 minutes	3 hours 29 minutes
C90	1 hour 46 minutes first spalling after 8 minutes	1 hour 29 minutes first spalling after 12 minutes

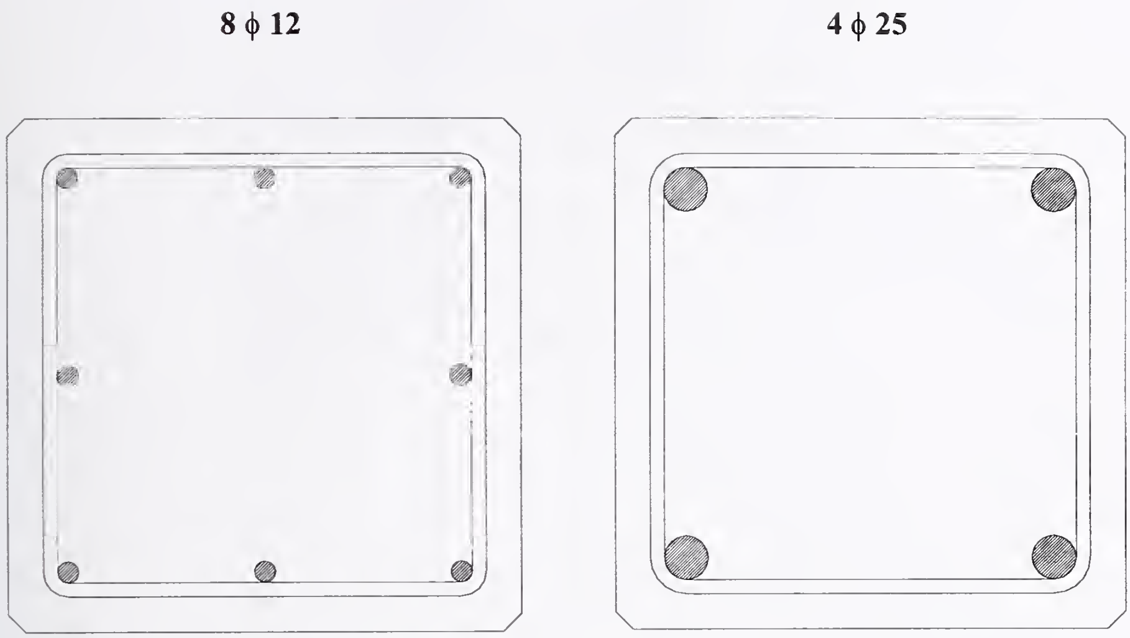


Figure 1. Concrete cross sections (29 cm x 29 cm); longitudinal reinforcement 8 ϕ 12 mm and 4 ϕ 25 mm. Concrete cover 3 cm

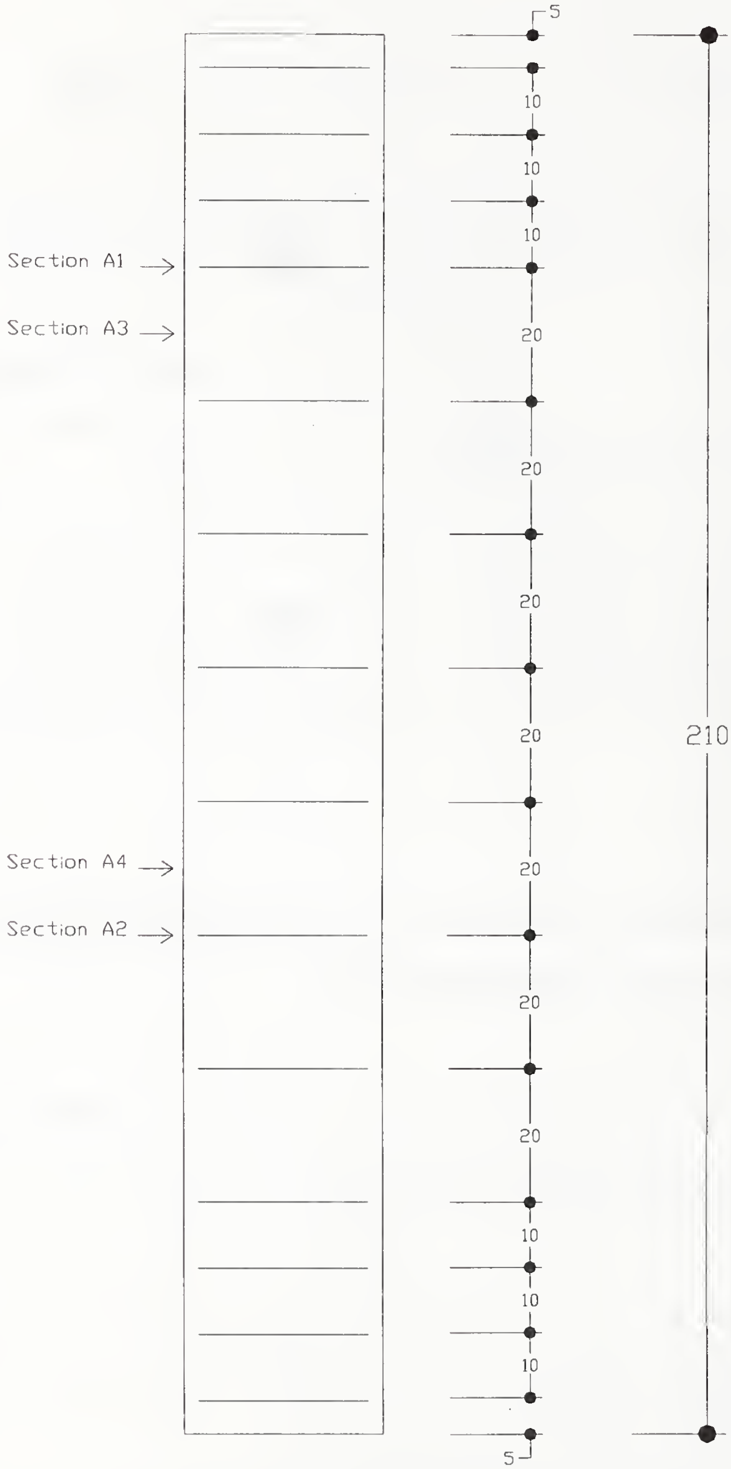


Figure 2. Section type 2 and 3. Position of thermocouples. Column used for fire test. Note: A1 and A2 sections with stirrups, A3 and A4 sections without stirrups

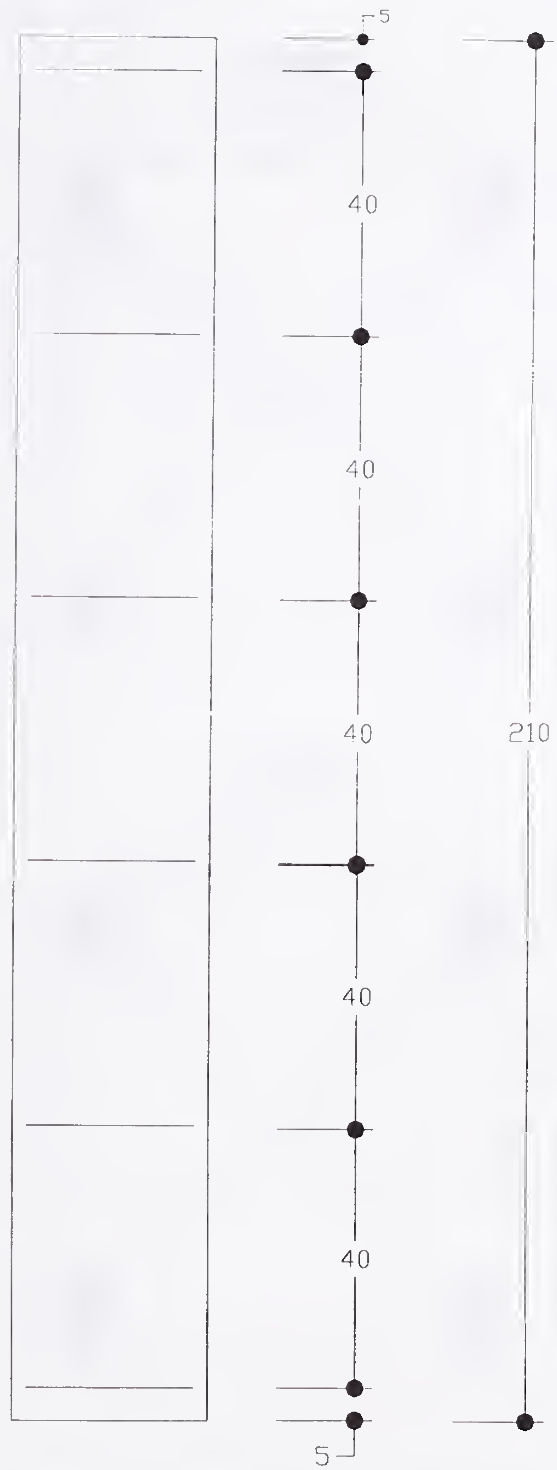
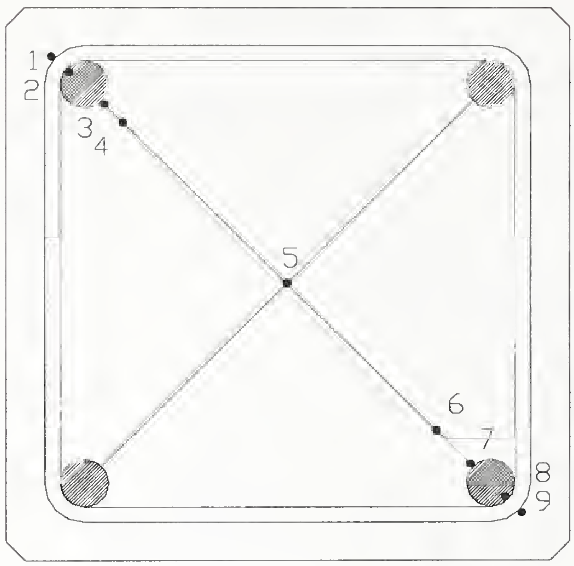


Figure 3. Section type 1. No thermocouples. Column used for material characteristic determination only. No fire test performed

Section A1



Section A2

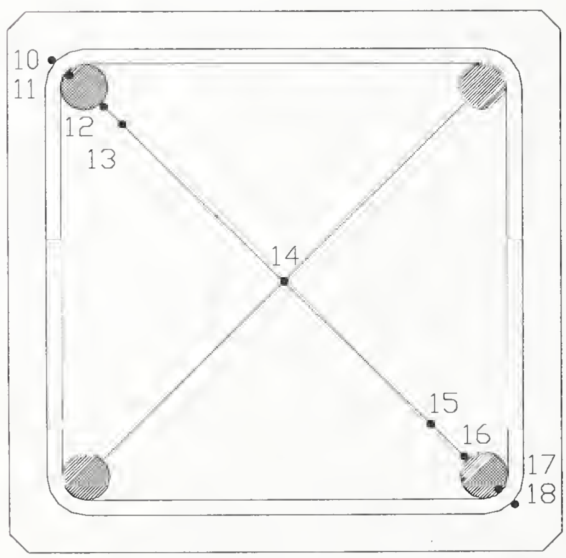
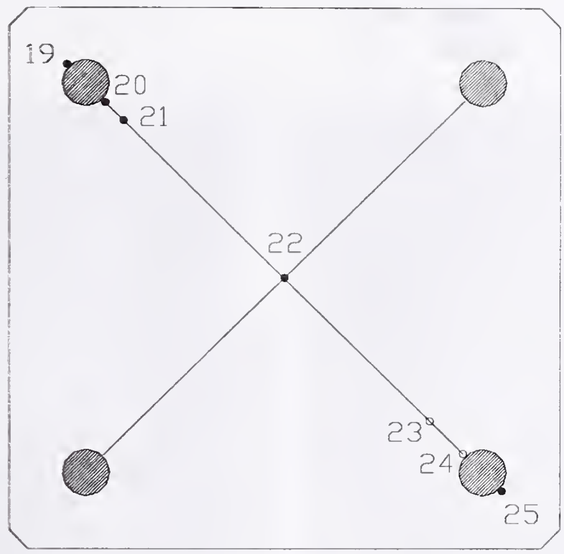


Figure 4. Position of thermocouples in the cross section. Sections with stirrups, 9 thermocouples per cross section

Section A3



Section A4

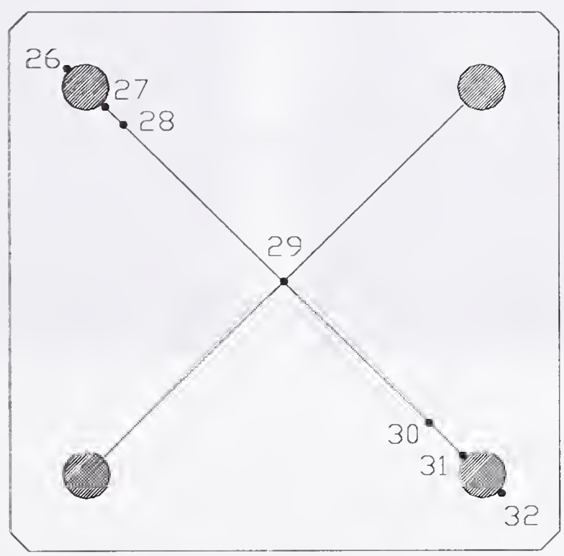


Figure 5. Position of thermocouples in the cross section. Sections without stirrups, 7 thermocouples per cross section

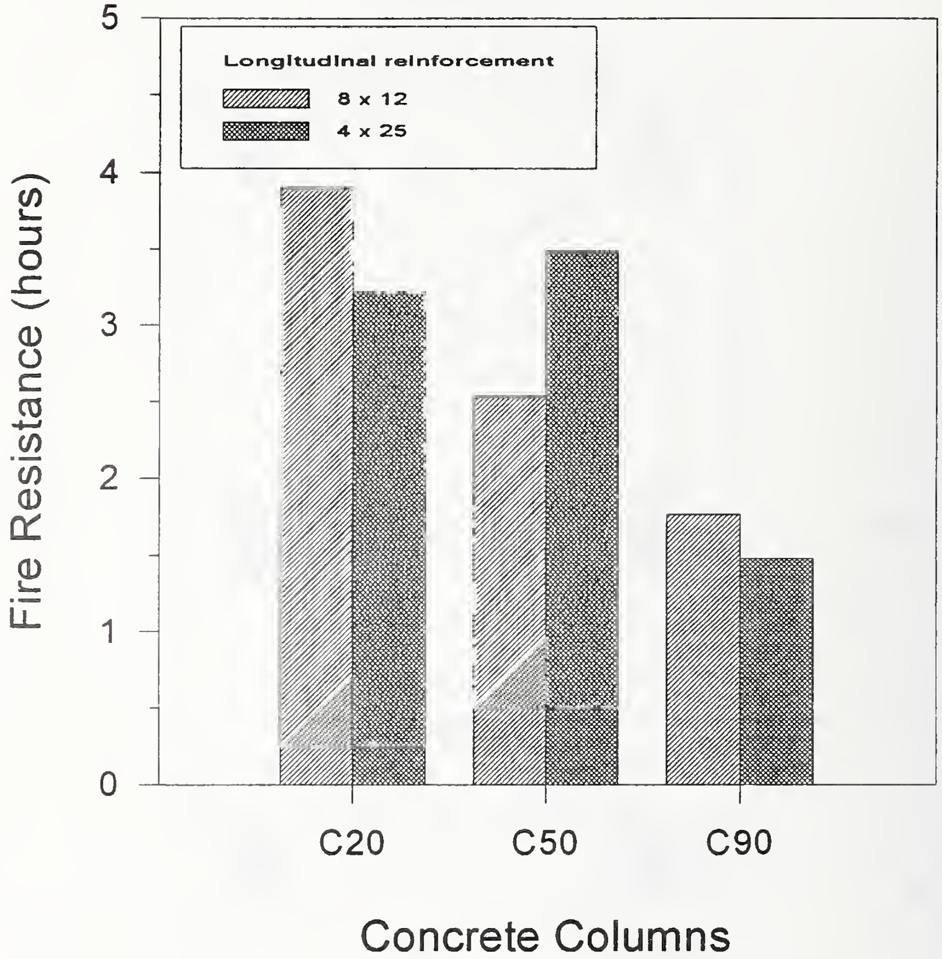


Figure 6. Fire resistance of concrete columns during tests

C20, 8 x 12

(b) C20, 4 x 25

Figure 7. Concrete columns after the test. Crushing of concrete and buckling of steel rebars

Figure 8. Concrete column during the test: C50, 8 x 12, t=1h 30 min.
Longitudinal cracks

(a) C50, 8 x 12

(b) C50, 4 x 25

Figure 9. Concrete columns after the test. Crushing of concrete and buckling of steel rebars

(a) C90, 8 x 12

(b) C90, 4 x 25

Figure 10. Concrete columns after the test. Buckling of the steel rebars and crushing of the concrete core

B.8 Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperature

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Jeff W. Rish III [3]

ABSTRACT

When a partially saturated porous medium is subjected to a high temperature heating source, pore pressures large enough to initiate explosive spalling may be developed within the pore spaces of the material. The level to which these pore pressures ultimately rise depends on the saturation and permeability of the medium as well as the rate at which heat flows into the material. In this paper, experimental and numerical studies involving the measurement and prediction of pore pressures and moisture flow in concrete are presented. The results of isothermal flow tests are presented in order to evaluate the accuracy of Darcy's law and the influence of Klinkenberg's effect in gas flows. Pore pressure data are presented for experimental tests in which saturated cement mortar specimens were subjected to high temperature radiant heating conditions. A numerical modeling technique is then presented and is used to numerically simulate the experimental tests. Close agreement is shown between the pore pressures and temperatures recorded experimentally and those predicted through simulation.

INTRODUCTION

Evaluation of airfield pavement degradation and fire safety evaluation of concrete structures are examples of situations that involve moist porous media (e.g. concrete) subjected to severe thermal loadings. The presence of moisture in heated porous media gives rise to internal pore pressures that, in combination with differential thermal stresses, can cause explosive spalling of the material. Spalling of this type can cause rapid degradation of concrete airfield pavements as well as presenting fire safety considerations for concrete structures subjected to fires. In addition, some experimental studies (Sanjayan and Stocks 1993) have suggested that, due to its lower permeability, high-strength concrete may be more prone to explosive spalling than normal-strength concrete.

Internal pore pressure buildup for porous media subjected to thermal loading is more severe for materials that have lower permeability. However, there is conflicting experimental data on this issue (Jahren 1989). Therefore, gaining an understanding of moist porous media subjected to fires and formulating a model to predict its behavior under such circumstances is highly desirable.

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ISOTHERMAL FLOW STUDY

The primary impetus for the work presented herein originated from problems involving spalling of concrete airfield surfaces. Concrete surfaces located where they are subjected to streams of hot jet exhaust often sustain significant surface spalling. To study the influence of pore pressure on spalling, the United States Air Force initiated steady state and transient testing of cement mortar.

To model both the mass and heat migration through cement, coupled partial differential equations concerning the conservation of mass, momentum and energy must be solved. In the case of the momentum of the fluid, Darcy's (1856) expression is used, whereas for gas, Darcy or Klinkenberg's (1941) equation is employed. The former is linear with pressure gradient and the latter is nonlinear.

In this portion of the work, the primary concern was quantifying the error of Darcy's expression over Klinkenberg's equation for gas flow in cement under elevated temperatures. The effort involved eighteen isothermal steady state flow tests with pressures varying from 5 to 20 atmospheres for which flow and pressure across the specimens were monitored. Both superheated steam and nitrogen gas were employed.

For the isothermal transient tests, both nitrogen and superheated steam were passed through specimens while monitoring flow rates. Results of the testing (McVay and Rish 1995) revealed that the flow of gases and vapors at the pressures expected (1350-3500 kPa) resulted in slip flow, not laminar flow, thus requiring a modification to Darcy's law. Using Klinkenberg's modification, a theoretical expression for pressure under stead-state conditions was developed that compares favorably to experimental data. It was found that Klinkenberg's expression was capable of predicting all the flow and pressure results within a few percent, whereas Darcy's expression was in error by 15% to 25% for both pressure and flow results.

MOISTURE CLOG SPALLING

Spalling of moist concrete and other moist porous materials subjected to high temperature heat sources can be attributed primarily to two mechanisms—thermal gradients and pore pressures. Steep thermal gradients in a solid material—whether a porous solid or not—can cause significant differential thermal stresses to be developed. If these thermal stresses are sufficiently large, spalling may occur. In moist porous materials, i.e. porous materials that are at least partially saturated, build up of pore pressures during heating can also have a very substantial influence on the likelihood of spalling. As liquid pore water vaporizes and migrates through the porous solid skeleton of the material, pore pressures can become large enough to cause spalling. In most cases of heat induced spalling, a combination of these two mechanisms is in effect.

Moisture clog spalling (Hamarthy 1965, Smith 1978) is the name given to the process by which large pore pressures can be produced when a moist porous medium is heated. The presence of entrapped moisture in a porous media exposed to high temperature can be either beneficial or detrimental, with one of the primary deciding factors being the rate of heating, the permeability of the material, and the moisture level. Porous materials such as concrete and cement mortar contain free liquid water, adsorbed (bound) water, vaporized water, and air in their pore spaces. The quantity of such pore water is a function of many factors including the initial water/cement (w/c) ratio at time of casting, the age of the material, and environmental conditions. The rate of heating will be a function of the temperature of the heat source and the nature of the heat transfer (i.e., conduction, convection, radiation) from the source to the porous medium.

During severe thermal loading, heat flow into the material will result in an increase in the temperature of the solid skeleton and the pore water. When the pore water reaches a high enough temperature—which is dependent on, among other things, the pore pressure—it will begin to vaporize. A portion of the heat flow into the material will be consumed by this pore water vaporization process (Šelih et al. 1994). As such, the presence of pore water is beneficial because it slows the rate at which the temperature of the solid skeleton rises. However, when the pore water vaporizes, an increase in pore pressure will result. As the pore pressures increases, a pressure gradient will form between the zone of vaporization and lower pressure regions deeper inside the concrete and at the exterior surface of the material. This is illustrated through numerical simulation later in this paper. Also, as the pore water temperature increases, thermal expansion of the liquid phase will occur (Kodres 1996) which can also increase the pore pressure. As the vapor migrates along the pressure gradient, it will either escape to the atmosphere, or move inward in the material reaching a lower temperature region and condensing. Such vapor migration will relieve the buildup of pore pressure at the zone of vaporization but will also increase the saturation level.

The portion of the vapor that migrates deeper into the concrete will condense because the temperature in this region will generally be cooler than that at the vaporization region. As the migrated vapor condenses, it will add to the liquid pore water already present in the pore spaces of the cooler region. As the vaporize-migrate-condense cycle continues, accumulation of pore water will build up in the cooler regions until finally a completely saturated layer is formed. Once this layer forms, vaporized pore water is severely impeded from migrating inward in the concrete due to the saturated front. Instead it is forced to migrate through the dry region to escape into the atmosphere. If the permeability of the material is sufficiently low or the rate of heating sufficiently high, vaporized water will not be able to escape fast enough to keep internal pore pressures from rising inside the material. Spalling will occur when the tensile strength of the concrete is exceeded by the combination of pore pressure and thermal stresses. The complete process is illustrated in Figure 1.

The "moisture clog spalling" concept presented above has been substantiated in various forms by other researchers (Sahota and Pagni 1979, Kodres 1996). A fundamental aspect of this scenario is that the rate of heating, the saturation level, and the permeability of the material can determine whether or not spalling occurs. If the rate of heating or the saturation level are sufficiently low or the material permeability is sufficiently large, vaporized pore water will be able to escape under a smaller pressure gradient. Alternatively, if rate of heating and the saturation level are high or the concrete permeability is small, then the rate at which vapor is produced at the saturated front can exceed the rate at which it escapes to the atmosphere and very large pore pressures can result.

EXPERIMENTAL PROGRAM

The experimental program consisted of subjecting two nearly saturated cement mortar specimens to a high temperature radiant heating source and measuring the transient pore pressures and temperatures from the resulting thermally driven flow. To obtain repeatable results, as well as to remove the influence of aggregate type and size, the tests were performed on cement mortar as opposed to concrete. Two mortar specimens were cast in steel circular molds and consolidated through vibration. They were then allowed to hydrate (cure) for two days in the molds after which they were placed in a water bath so that they could reach a nearly saturated state. Tests on identically prepared cement mortar samples revealed a porosity (volume of voids to total volume) of 17.5% and a permeability of approximately 8.324E-17 m^2.

The two specimens were instrumented by installing thermocouples and pore pressure transducers in the positions shown in Figure 2. The thermocouples were installed by drilling holes from the bottom of the specimen up to the desired vertical elevation, inserting the thermocouples, and then cementing them into the drilled holes. Since high temperatures and pressures were anticipated for the experiment, special sealed, thermally compensated pore pressure transducers (PPTs) were used to measure pore pressure. The PPTs were installed in such a way that they could be recovered for reuse after the experiment was completed. First, a metal lag bolt was hollowed out by drilling a hole lengthwise through the bolt. A PPT was then epoxied into the hollow portion of the bolt such that the transducer was at the tip of the bolt. A larger diameter hole was then drilled into the mortar specimen and the lag bolt was cemented into the drilled hole.

A portable cylindrical oven of approximately the same diameter as the specimens served as the radiant heat source. The sides of the oven walls consisted of heating elements embedded in ceramic material while the top (cap) of the oven consisted of insulation. A thermocouple was placed inside the oven near the top surface to monitor the transient air temperature in the oven. Just prior to testing, the temperature of the oven was raised to approximately 925C.

Testing consisted of heating the oven to the testing temperature, then lifting it up and placing it adjacent to the top of the specimen. In this manner, each specimen "saw" the heat as being applied in a rapid fashion rather than experiencing a gradual increase in temperature during oven warm-up. Rapid heating is consistent with the type of thermal loading experienced by concrete runways subjected to jet exhaust. Two test runs were performed—one on each cement mortar specimen. In each case, the test was allowed to continue until it was determined that the PPTs would soon experience damage. At that point (around 500 seconds into the tests), the oven was removed from the specimen. In each test, spalling of the mortar surface was observed prior to removal of the oven. Temperature and pore pressures inside the specimens continued to be recorded after the heat source was removed so that the cool down behavior of the material could be observed as well.

Transient temperatures for the two test runs are shown in Figure 3. In each case, the point at which the oven was removed is evident from the shape of the temperature curves for the thermocouples nearest the specimen surface (i.e., at 1.5 mm for test-1 and at 3.5 mm for test-2). A sharp decline in temperature near the surface and a more gradual decline in temperature deeper inside the specimen can be observed after removal of the oven.

One can see from the figure that there is a sharp temperature gradient in each specimen. For example, by looking at the temperatures near the surface (at 1.5 mm and 3.5 mm) and those deeper in the specimens (at 19 mm) one observes that as time increases (up to the oven cutoff time), there is a considerable temperature difference. This temperature difference occurs over only a distance of 17.5 mm for test-1 (19 mm-1.5 mm=17.5 mm) and 15.5 mm for test-2 (19 mm-3.5 mm=15.5 mm).

Pore pressures for the two tests are shown in Figure 4. As was anticipated, significant pressures—on the order of 3100 kPa—were developed in each case. Thus, the concept of pore pressure buildup as a contributor to the initiation of spalling was confirmed experimentally. The unique, and somewhat curious shape of the pore pressure curves, i.e. the double pressure peaks and the dip in between them, is due to a peculiarity of the PPT installation. After the tests were completed, the PPTs were removed and the depth of the drilled shaft measured carefully. By subtracting the known length of the bolt, it was found that in each case there was a small cavity—approximately 1 to 2 mm in size—just above the locations at which the PPTs had been installed.

The cavities had been formed when the lag bolts were cemented into the holes in the specimen. Later, during numerical simulation of the experiments, it was determined that the presence of the cavities was the cause of the dip in the pore pressure plots. Without a cavity, the plots rise to a peak value and then subsequently decrease without a later increase. With a cavity, a dip in the pore pressure plot is encountered followed by a subsequent rise back to the previous peak pressure. The difference in the clock time at which the second peak occurred during test-1 and test-2 is attributed to the differing sizes of the cavities present in each case.

NUMERICAL SIMULATION PROCEDURES

After concluding the experimental program, the next goal in the present study was to develop a numeric simulation tool capable of predicting the pore pressure buildup in heated moist porous media. Development of such a simulation model is desirable because it can be used to perform parametric studies numerically instead of experimentally. Since numeric simulation is simpler to setup and less costly than experimental testing, it's usefulness is clear. Data predicted by the numeric models can be used either in designing further experimental studies, or as a predictive tool to be used for design and evaluation purposes.

In this study, the TOUGH code (Pruess 1987) developed by Lawrence Berkeley Laboratories at the University of California was used as the basis for the numerical modeling. TOUGH, an acronym for "transport of unsaturated groundwater and heat" is a numerical model for simulating the coupled transport of water, vapor, air and heat through porous media. It has the ability to simulate thermally driven flow and, although it was developed primarily for use in geothermal problems, the authors have successfully modified it for use in modeling moist cement mortar and concrete subjected to high temperatures.

Radiation Boundary Condition Modeling

The boundary modeling approach adopted in this work (Consolazio, McVay, Rish 1996) consists of converting the radiant boundary condition into an "effective" conductive boundary condition. In this approach, illustrated in Figure 5(b), the radiation boundary condition is represented using "effective" conductive properties. The oven (i.e. the heat source) is modeled using superelements of prescribed temperature while the specimen is modeled using "normal" size elements having the properties of cement mortar. The properties and interface distances[1] of the oven superelements are then given "effective" values. When these effective values are used within the framework of a conduction heat analysis (e.g. in TOUGH), the resulting heat fluxes are the same as would occur in a true radiant heat analysis. Thus, both the radiant boundary condition and the modeling of heat and moisture transport through the specimen can be analyzed using a conduction analysis framework.

Note that in this method of modeling the boundary condition, the oven superelements and the specimen elements are in "contact" in the sense that there are connections between them, interface areas, etc. It is across these fictitious "contact" areas that conductive heat transport occurs. The fact that these elements are in contact in the numerical model, however, in no way violates the fact that they are not connected in the actual physical (experimental) setup. The contacts are simply a construct of the numerical modeling method and nothing more.

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[1] The interface distance is the distances between the centroid of an element and the interface between it and an adjacent element.

In creating the model, the parameters k_2 and d_2 shown in Figure 5(b) are not variables. They are the conductivity and center-to-interface distance for an element in the cement mortar model (i.e. the specimen). The conductivity k_2 is the conductivity of cement mortar and the distance d_2 is established based on the spatial discretization (i.e. "meshing") of the specimen. Thus k_2 and d_2 are fixed. However, we can choose either k_1 or d_1 arbitrarily and solve for the remaining variable to construct our "effective" boundary condition. In the present case, we choose to set $d_1 = d_2$ and solve for the "effective" conductivity k_1 of the oven superelements.

To find the effective conductivity k_1, let us denote the conductivity of the interface between two elements as the *interface conductivity*. For two elements in contact and having different conductivities we desire to determine a value of conductivity at the interface between the elements. A particularly good choice of interpolation scheme suitable for this purpose is to make k_i the harmonic mean of k_1 and k_2 (Patankar 1980). In this case

$$k_i = \left(\frac{1 - f_i}{k_1} + \frac{f_i}{k_2} \right)^{-1} \tag{1}$$

where

$$f_i = \frac{d_2}{d_1 + d_2} \tag{2}$$

Then, by equating the energy flux across the interface due to radiant heating and conductive heating (Figure 6), we can solve for an effective conductivity of the boundary superelement (Consolazio, McVay, Rish 1996). Doing so, we find that if we denote

$$h_r = \frac{\sigma\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right)}{\dfrac{1-\varepsilon_1}{\varepsilon_1}\dfrac{F_{12}}{F_{21}} + \dfrac{1}{F_{21}} + \dfrac{1-\varepsilon_2}{\varepsilon_2}} \tag{3}$$

then k_1 can be shown to be

$$k_1 = \frac{k_2\, d_1\, h_r}{k_2 - d_2\, h_r} \tag{4}$$

which is the "effective" conductivity of the oven superelement. Note that k_1 is a function of both T_1 and T_2 since h_r is a function of T_1 and T_2. Therefore, we have an effective conductivity that is temperature dependent (as it should be for radiant heat transfer). In implementing this modeling scheme in TOUGH, the effective conductivities are updated at each iteration during the analysis, always taking into account the most current temperatures of the connected elements.

Calculation of Radiation Viewing Factors

Since radiant heat transfer occurs across space between two surfaces that are not in contact, the relative positions and orientations of the surfaces in space must be taken into account. This is accomplished by computing view factors between the surfaces and using the factors in the heat flux equations. In modeling the experimental setup of this paper, view factors corresponding to radiant heat originating from the oven surface and striking the specimen surface had to be computed. These view factors were then used in modeling the radiation boundary condition by inserting them into Equation (3) during the TOUGH analysis.

To compute the view factors for this case, a numerical procedure was developed. The procedure consisted of discretizing the inner surface of the oven and the top surface of the specimen into a large number of elements. For efficiency, only one quarter of the specimen was modeled since it was known that the view factors would be axisymmetric over its surface. The following expressions were then derived which yield the view factor between two composite surfaces—i.e., surfaces comprised of smaller flat surface patches (see Figure 7).

$$F_{a-b} = \sum_{j=1}^{m} \left\{ \frac{\sum_{i=1}^{n} A_{a_i} F_{a_i - b_j}}{\sum_{i=1}^{n} A_{a_i}} \right\} \tag{5}$$

$$F_{a_i - b_j} = \frac{cos(\theta_i) cos(\theta_j)}{\pi r^2} A_{b_j} \tag{6}$$

In these expressions, F_{a-b} is the (total) view factor from composite surface A to composite surface B, A_{ai} is the area of the i-th patch in composite surface A, A_{bj} is the area of the j-th patch in composite surface B, and $F_{a_i - b_j}$ is the patch-to-patch view factor.

Using the expressions given above, several numerical "runs" were made using increasing levels of refinement in the surface discretization. The most refined model consisted of discretizing the oven surface with 160 patches in the vertical direction and 640 patches in the circumferential direction for a total of 102,400 patches. The surface of the specimen was discretized using a total of 300 elements (finer discretizations were also tried (for lower levels of oven discretization) but resulted in little change in the computed view factors). The resulting view factors computed using this procedure, and converted to view factors per unit area, are shown in Figure 8.

COMPARISON OF SIMULATION DATA AND EXPERIMENTAL DATA

Using the numerical simulation procedures described in the previous section, several numerical models were constructed and analyzed to try to predict the pore pressure and temperature results obtained from the experimental program. The models constructed included 1-d, 2-d, and limited 3-d models. Radiation view factors were computed as described earlier. In addition, the voids which were found to be present near the PPTs in the experimental program were modeled in some cases. Recall from earlier discussion that it was found that these voids were responsible for the "dips" in the experimental pore pressure plots.

Table 1 lists the key physical quantities that were used in the modeling. Note that the temperature of the oven was not constant throughout the simulation. It was noted during the experimental tests that the temperature in the oven dropped to approximately one-half of its initial value during the early portion of the test. This was attributed to the release of steam from surface of the specimen. The piecewise linear temperature profile used in the simulations (see Table 1) was an attempt to approximate this effect. It was found that the exact shape of the temperature profile had little effect on the analysis results and even less effect on the peak pore pressures predicted.

Table 1. Key Physical Quantities Used in the Numerical Simulations

Cement Mortar

Density = 2100 kg/m^3
Porosity = 17.5%
Permeability = 8.324E-17 m^2
Specific heat = 921.12 J/kg C
Conductivity = 2.3 W/m C
Emmisivity = 0.88

Oven

Peak temperature = 925 C
Low temperature = ≈460 C
Emmisivity = 0.92

Oven Temperature Profile

Exp-1 Time (sec)	Exp-2 Time (sec)	Oven temperature (C)
0.0	0.0	463
100.0	100.0	740
200.0	200.0	925
550.0	450.0	925
555.0	455.0	25
1000.0	1000.0	25

2-d Simulation

In the 2-d simulation model, one-half of the specimen cross section was discretized using a variable density mesh (see Figure 9(a)). This model accounted for the following components.

- Cement mortar specimen
- Void at tip of pore pressure transducer
- Lag bolt
- Epoxy inside lag bolt

Only half of the specimen was modeled due to axisymmetry of all the components and axisymmetry of the thermal loading. Zero-flux (no flux of heat or mass) boundary conditions were used along the vertical boundaries of the model. Along the top boundary, the radiant boundary condition of the oven was modeled. The bottom boundary was modeled using very permeable superelements. Since these were superelements, the base material also acted as a heat sink. (The precise manner in which the base was modeled was found to have little effect on the results obtained due to the relatively short time frame that was of interest).

Pore pressure data and temperature data predicted by the 2-d simulation models are compared with the experimentally determined data in Figures 10 and 11. The pore pressures plotted are those occurring at a depth of approximately 19 mm from the top face of the specimen (i.e., at a position just below the void). Temperatures are plotted for the thermocouples nearest the surface (1.5 mm and 3.5 mm) and those at the level of the PPT (19 mm). One can see that there is very favorable agreement for pore pressure and favorable agreement for temperatures. Most notably, the peak pore pressures predicted by the numerical simulation very closely match the actual peak pore pressures measured experimentally.

The differences in the location of the pore pressure dips for the experimental and simulated cases are attributed to the fact that the only an approximate geometry of the void was modeled. Since the dip is a product only of the specific instrumentation setup and not a phenomenon that would normally occur in a non-instrumented specimen, the difference in the location of the dip is not of great concern. What is significant is the fact the initial peak for the experimental and simulated curves match favorably in magnitude and location (time) and that the subsequent peaks match in magnitude. Also plotted in Figure 10 is the simulation pore pressure curve for the case in which the void is omitted. It is clear from this plot that the pore pressure dip is an artifact of the void, since in this simulation no subsequent pressure rise is observed.

Good agreement between experimental and simulated temperature data is indicated by the curves in Figure 11. Transient temperatures predicted at 19 mm are seen to match quite closely with experimental data indicating proper modeling of conductive heat transfer through the specimen. At locations nearer to the surface (1.5 mm and 3.5 mm) the simulated data diverge more significantly from the experimental data. Simulation results indicated that, for points near the surface, the peak temperature reached varies considerably with change in depth. Therefore, small errors in the assumed location of the thermocouples could account, at least in part, for the difference between experimental and simulated temperatures.

3-d Simulation

The 3-d model developed to simulate the experiments consisted of a one-quarter "pie slice" (shown in Figure 9(b)). Only the inner 4mm core of the specimen was able to be modeled due to size limitations present in TOUGH[1]. The void, lag bolt, and epoxy were not modeled so that the pore pressures inside a non-instrumented specimen could be determined. In Figures 12 and 13, the pore pressure and temperature data obtained from the 3-d models are plotted through the entire depth of the specimen as time progresses. From Figure 12 one can clearly identify the interface between the fully desaturated zone and the fully saturated zones—pore pressure is seen to maximize at the boundary between these two zones. Pore pressures vary non-linearly from the peak value near the interface to atmospheric pressure at the top and bottom surfaces. As time progresses, the desaturated zone penetrates farther into the specimen. One can also clearly see the development of a very steep temperature gradient through the specimen. This suggests that not only pore pressures, but also differential thermal stresses, may play a significant role in causing spalling.

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[1] The size limitations in TOUGH are related to the equation solver, not the ability to store model data. Complete 3-d models will be constructed in the near future using the newer TOUGH2 which contains conjugate gradient equation solvers appropriate for the solution of large 3-d models. Modifications for radiation boundary condition modeling and Klinkenberg's equation are currently being made to TOUGH2.

CONCLUSION

Experimental tests in which saturated cement mortar specimens were exposed to a high temperature (925C) radiant heating source have been presented. The mortar specimens were instrumented with thermocouples and pore pressure transducers so that the transient response of the specimen to thermal loading could be measured. It has been shown that very significant pore pressures—on the order of 3.1 MPa—can develop under such conditions and can be a major contributing factor to the initiation of explosive spalling.

A numerical simulation procedure has been developed and used to predict the experimental data. Radiation boundary conditions in the numerical simulation model are handled by converting radiant heat transport to "effective" conductive heat transport. Results from various simulations compare favorably with the experimentally measured data, especially with respect to predicting peak pore pressures. This suggests that the numerical modeling procedures developed herein may be used in predicting the conditions under which spalling is likely to occur. Furthermore, it means that parametric studies may be performed using numerical models to determine the effect of key material parameters (e.g., permeability, porosity, saturation level) on the buildup of pore pressure and the initiation of spalling.

Pore pressure buildup has been clearly shown to be a major factor in the occurrence of spalling but differential thermal stresses will also have an significant influence. Coupled pore pressure and differential thermal stress analyses are needed to quantify the relative importance of pore pressure buildup and thermal stress.

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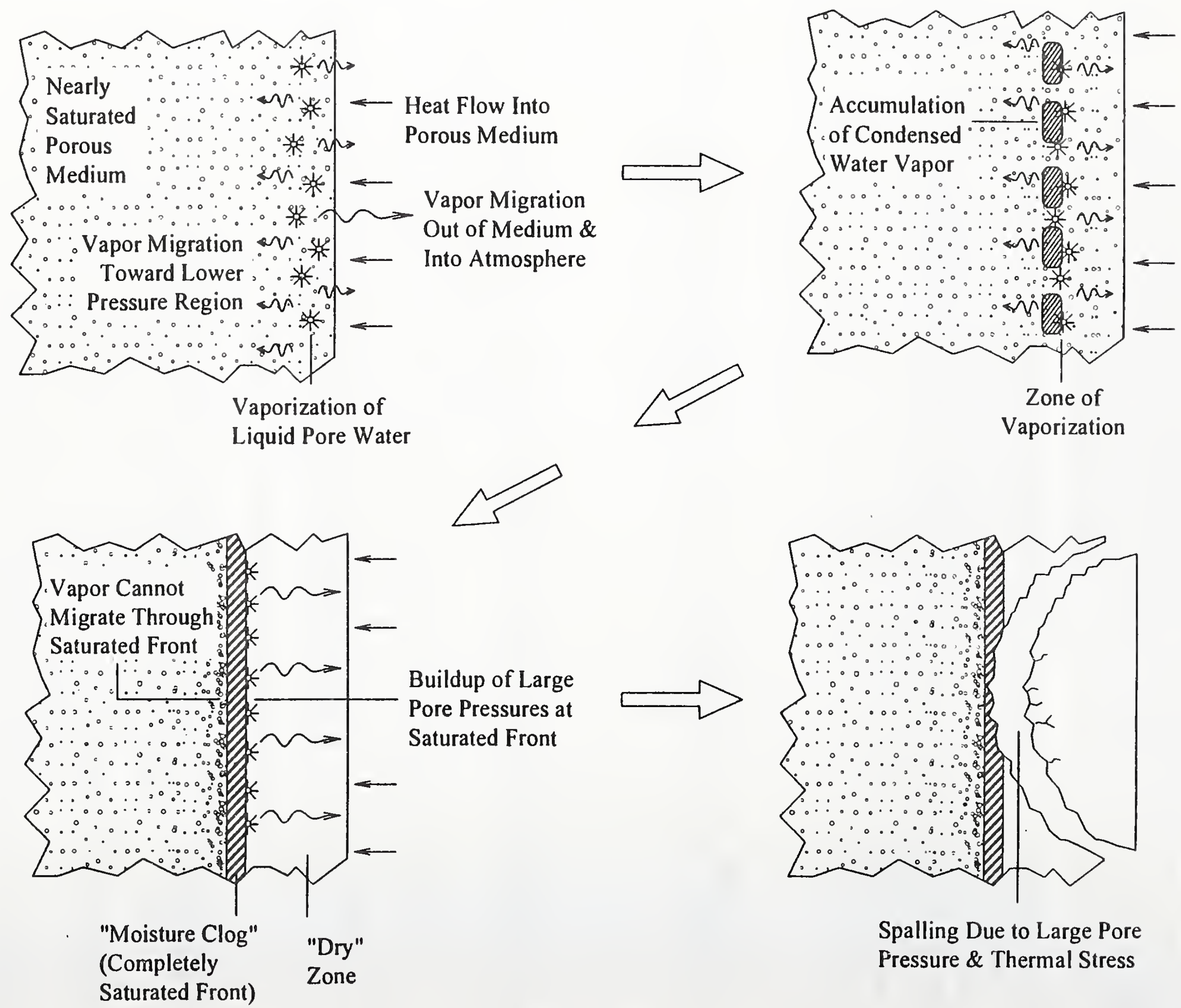


Figure 1. Sequence of Steps Leading to Fire Induced Spalling

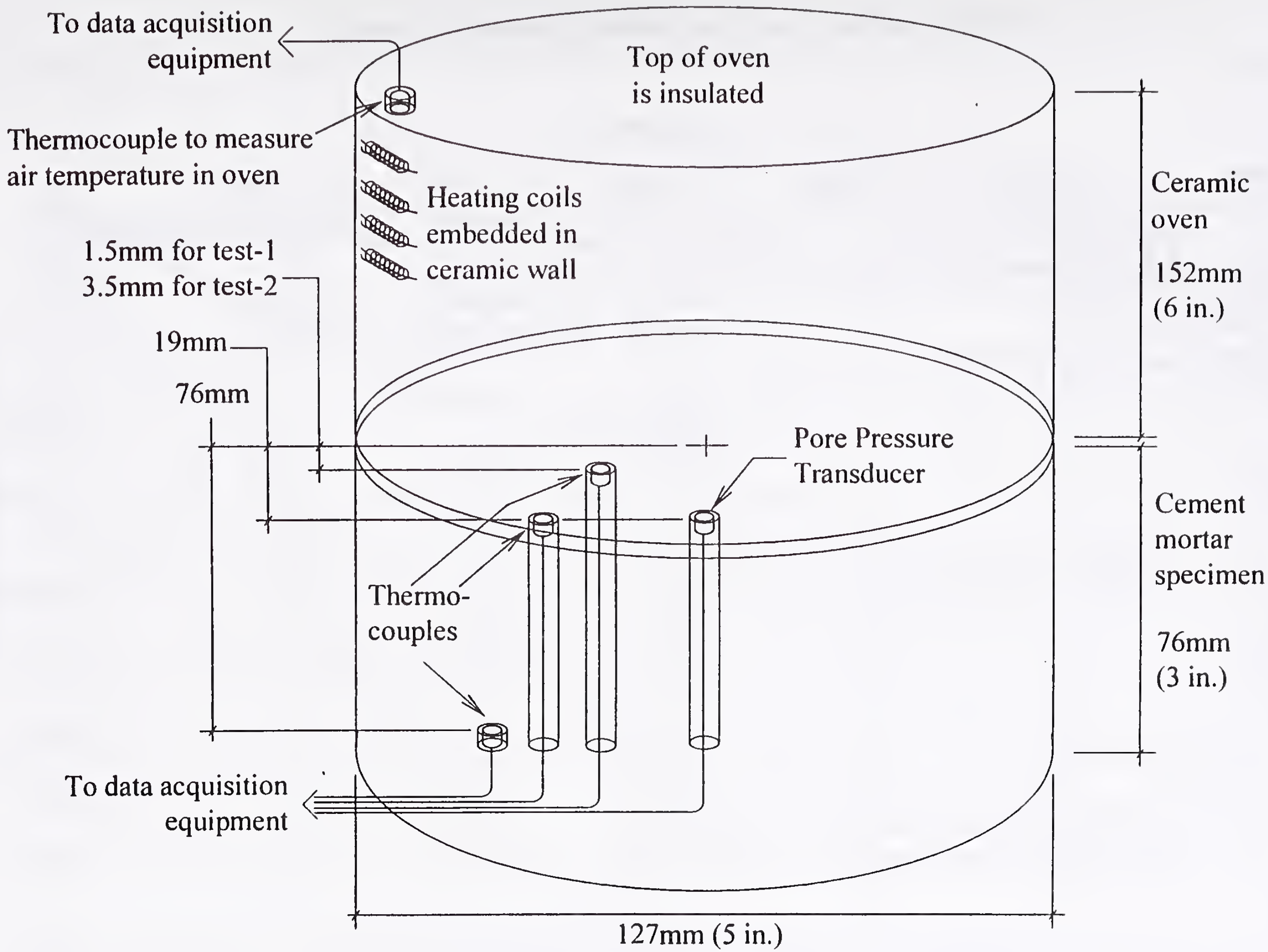


Figure 2. Instrumentation of Cement Mortar Specimen

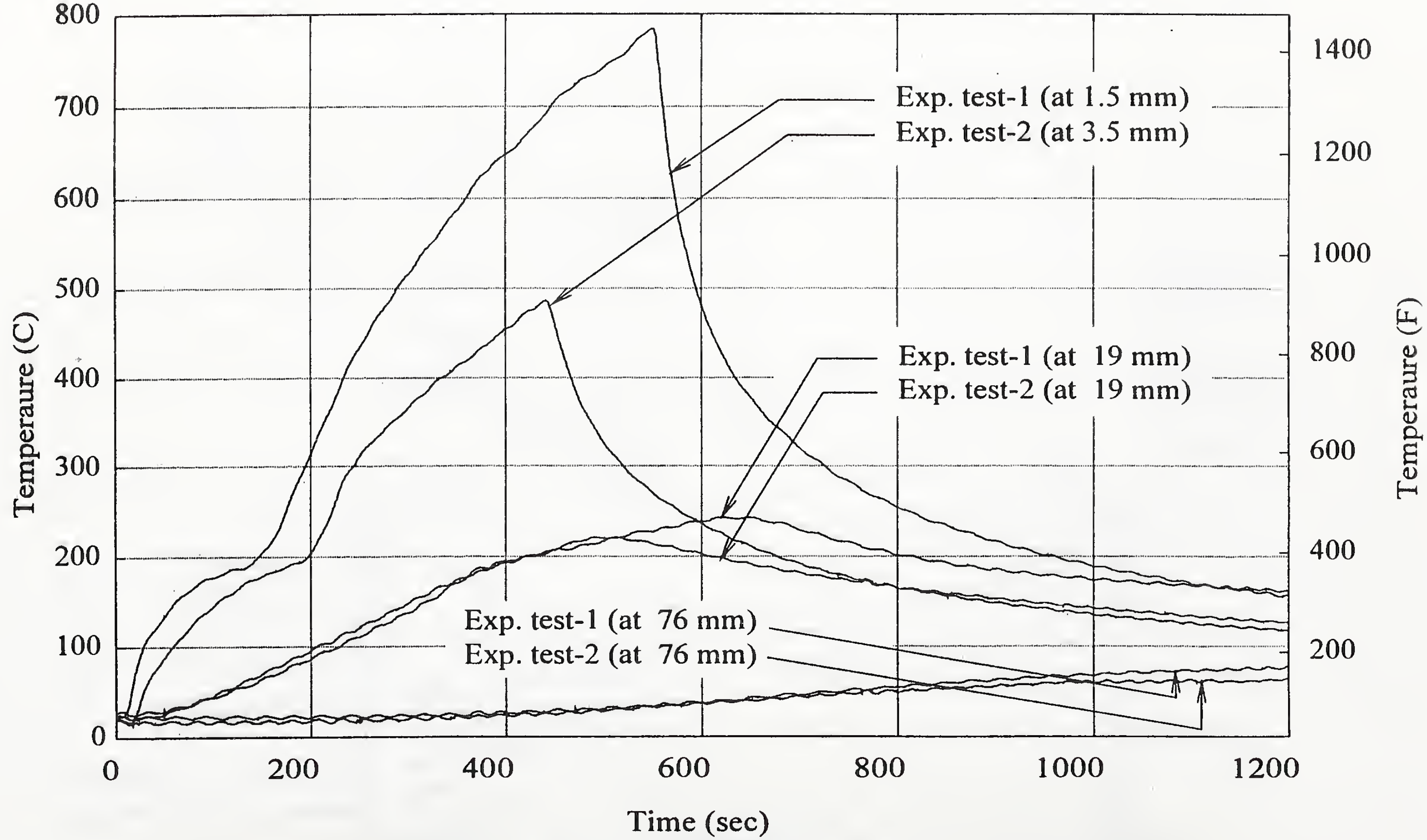


Figure 3. Transient Temperatures Due to Radiant Heating

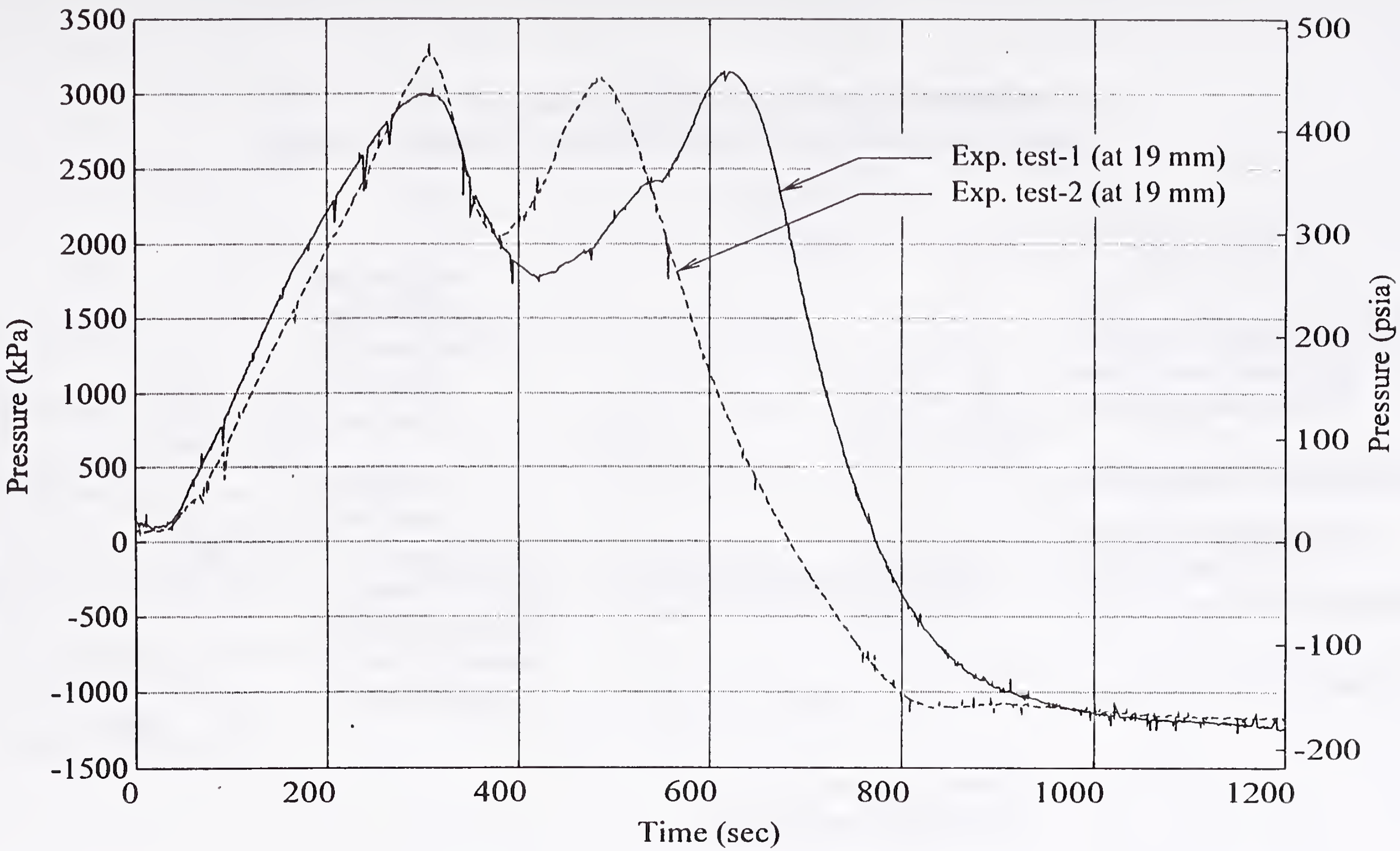


Figure 4. Transient Pore Pressures Due to Radiant Heating

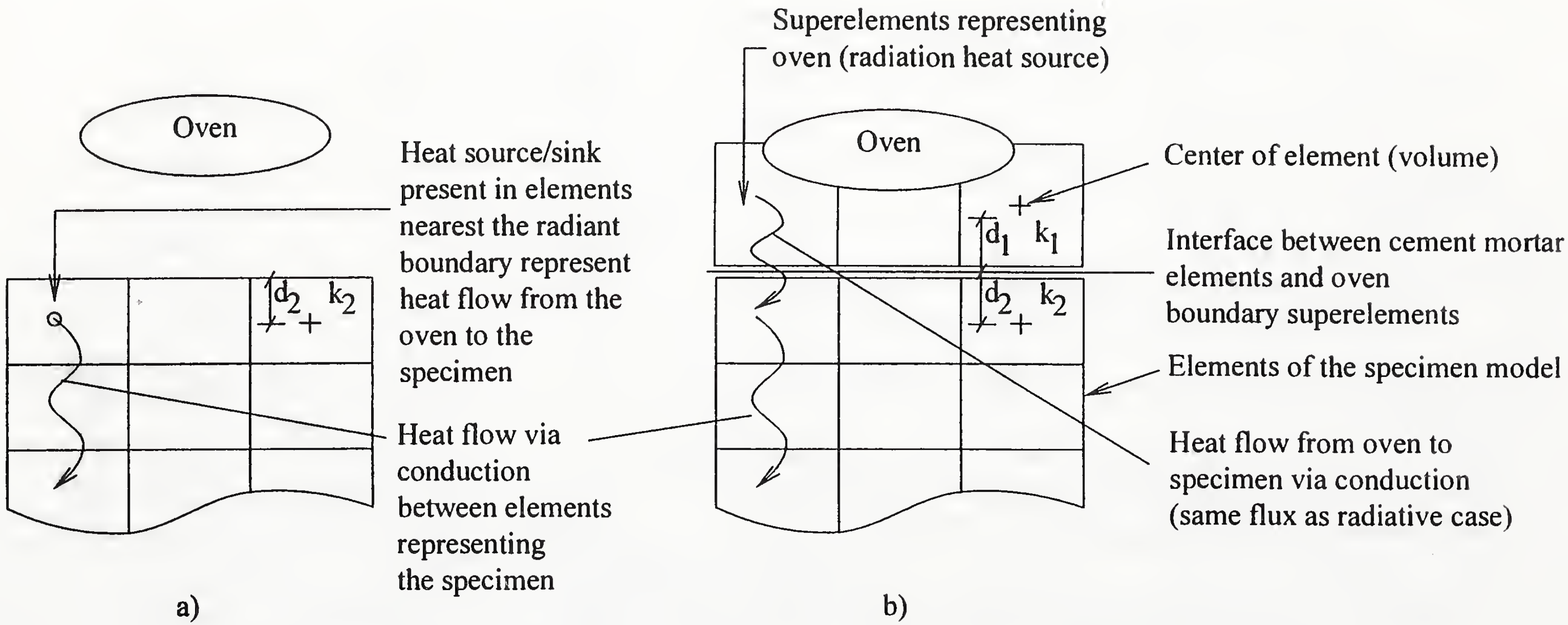


Figure 5. Modeling the Radiation Boundary Condition With a) Direct heat flux terms, and b) Effective Conduction Properties

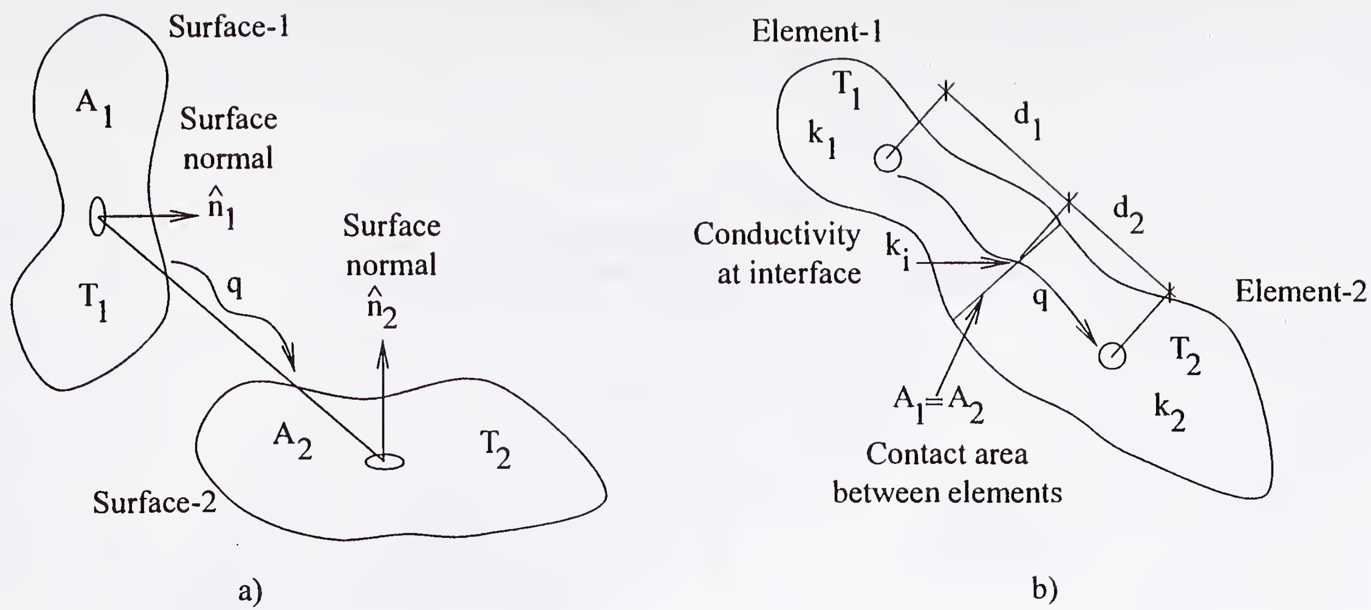


Figure 6. Heat Flux From One Body to Another
by a) Radiation and b) Conduction

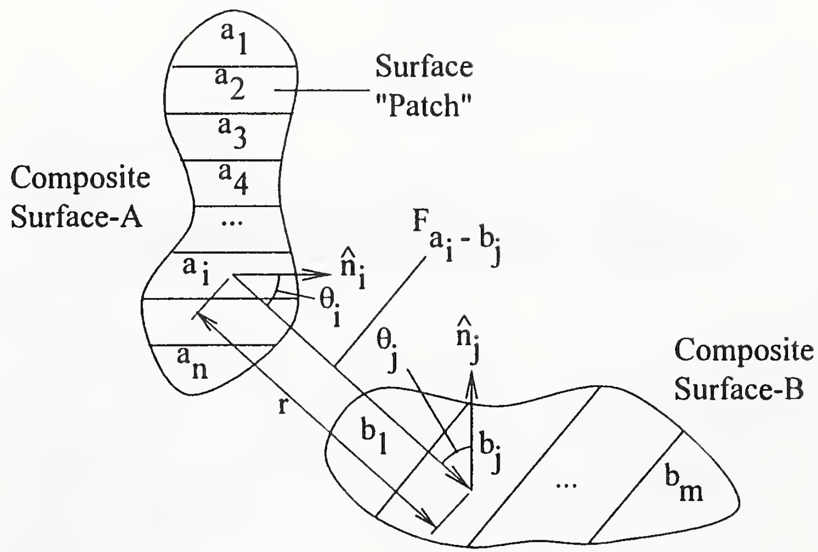


Figure 7. Computation of View Factor Between Two Composite Surfaces

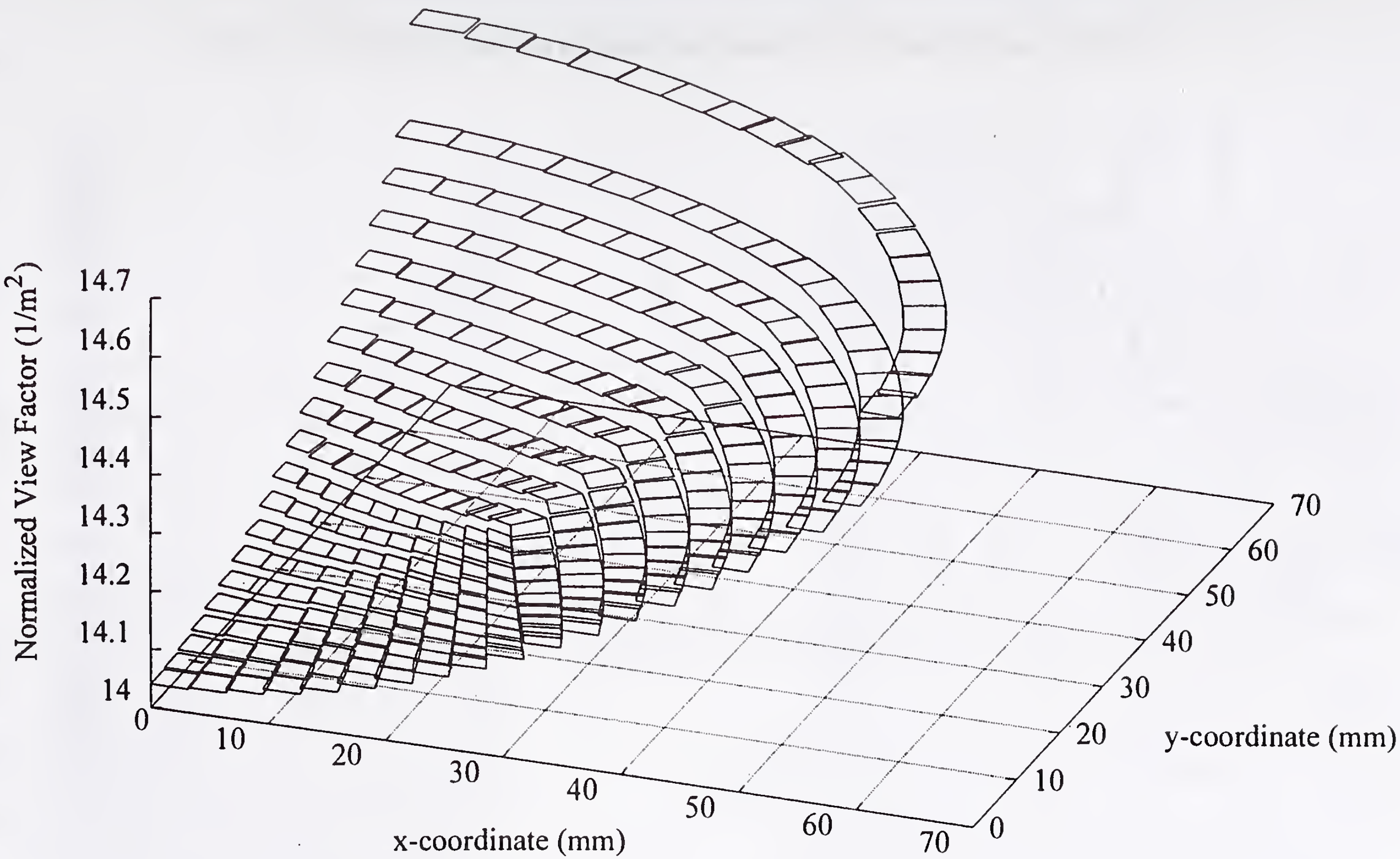
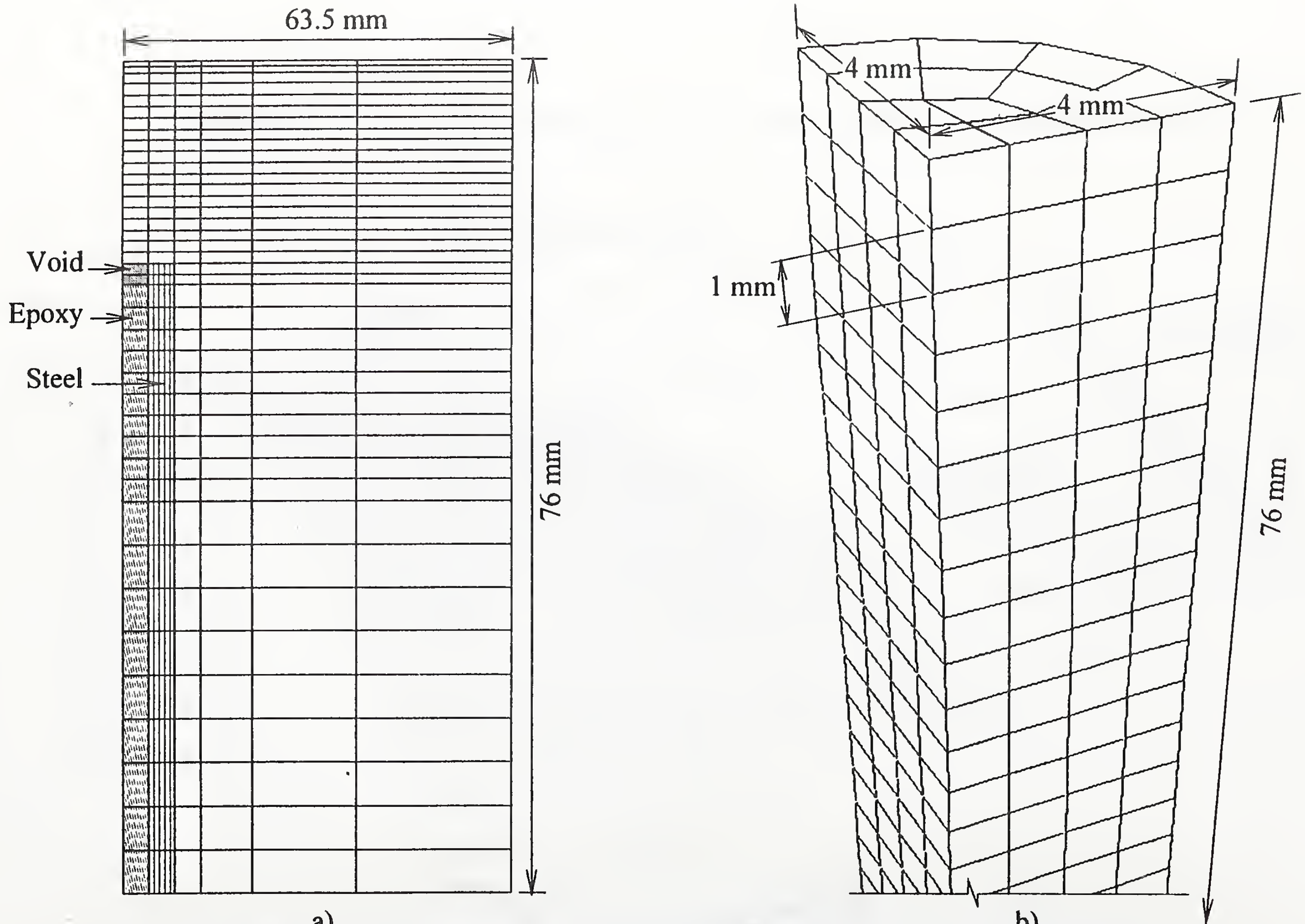


Figure 8. View Factors (Normalized Per Unit Area) Computed for Oven-Specimen Setup



a) b)

Figure 9. 2-D and Limited 3-D Simulation Models of Cement Mortar Specimen

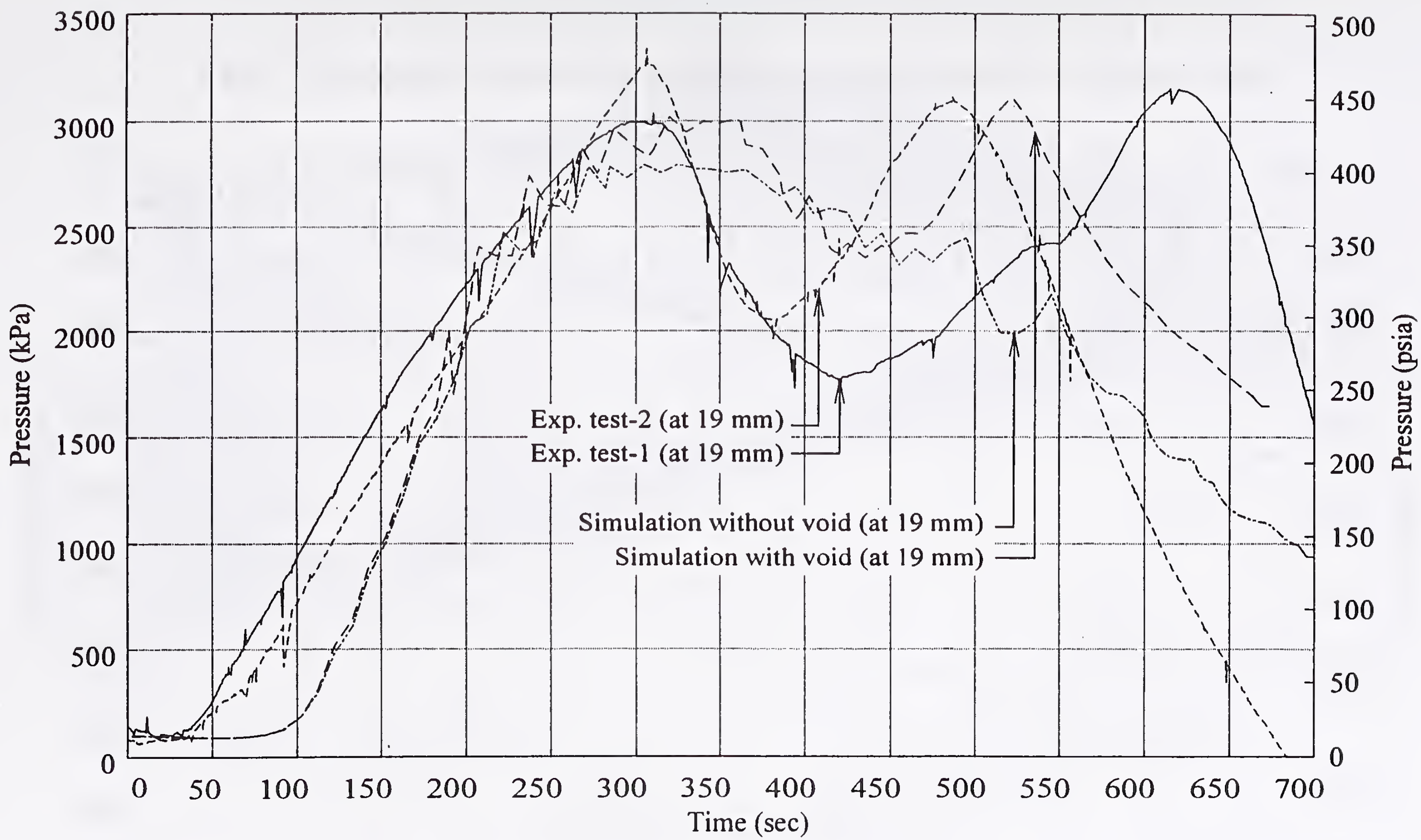


Figure 10. Pore Pressures Measured Experimentally and Predicted Using a 2-D Simulation

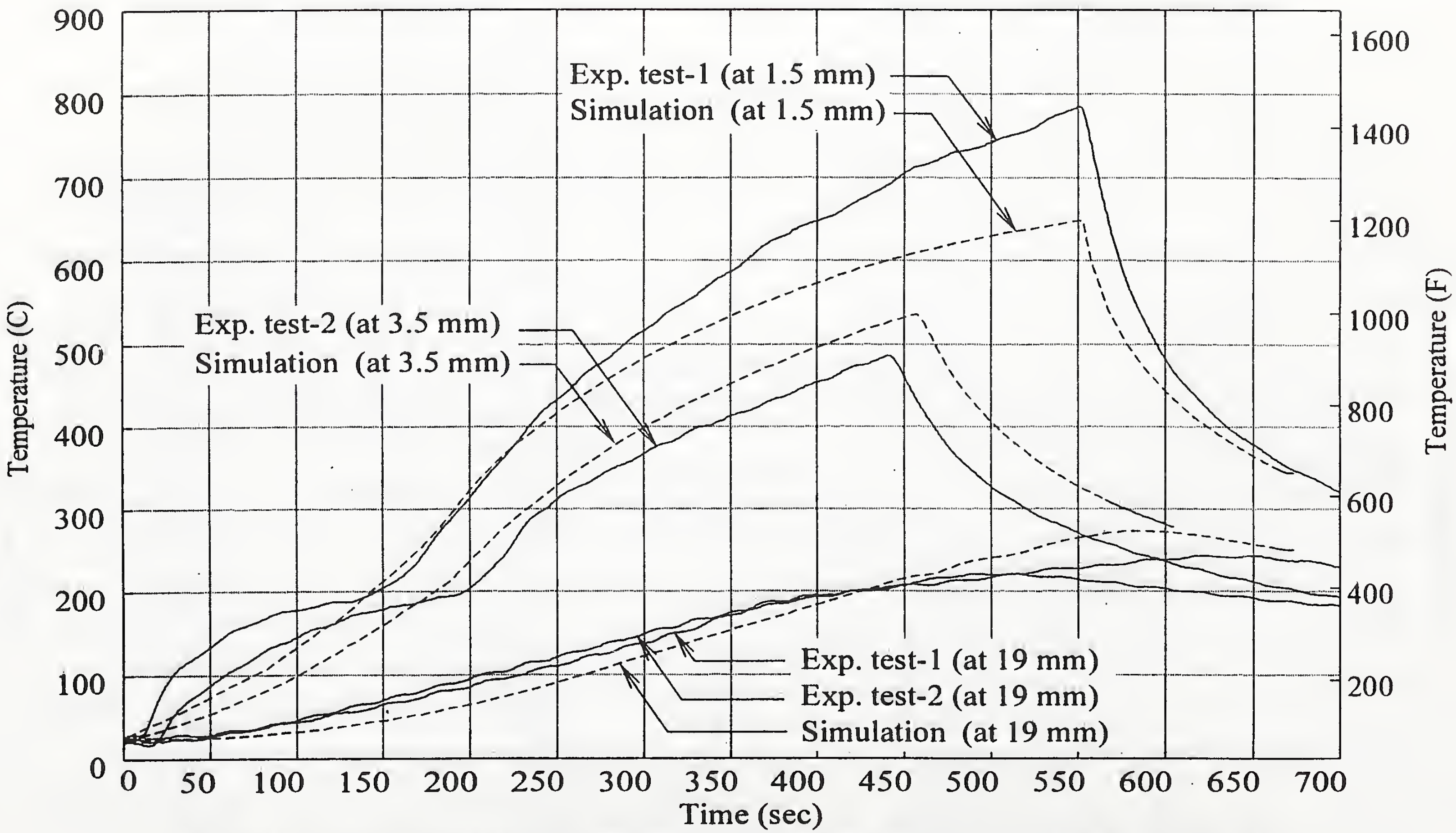


Figure 11. Temperatures Measured Experimentally and Predicted Using a 2-D Simulation Model

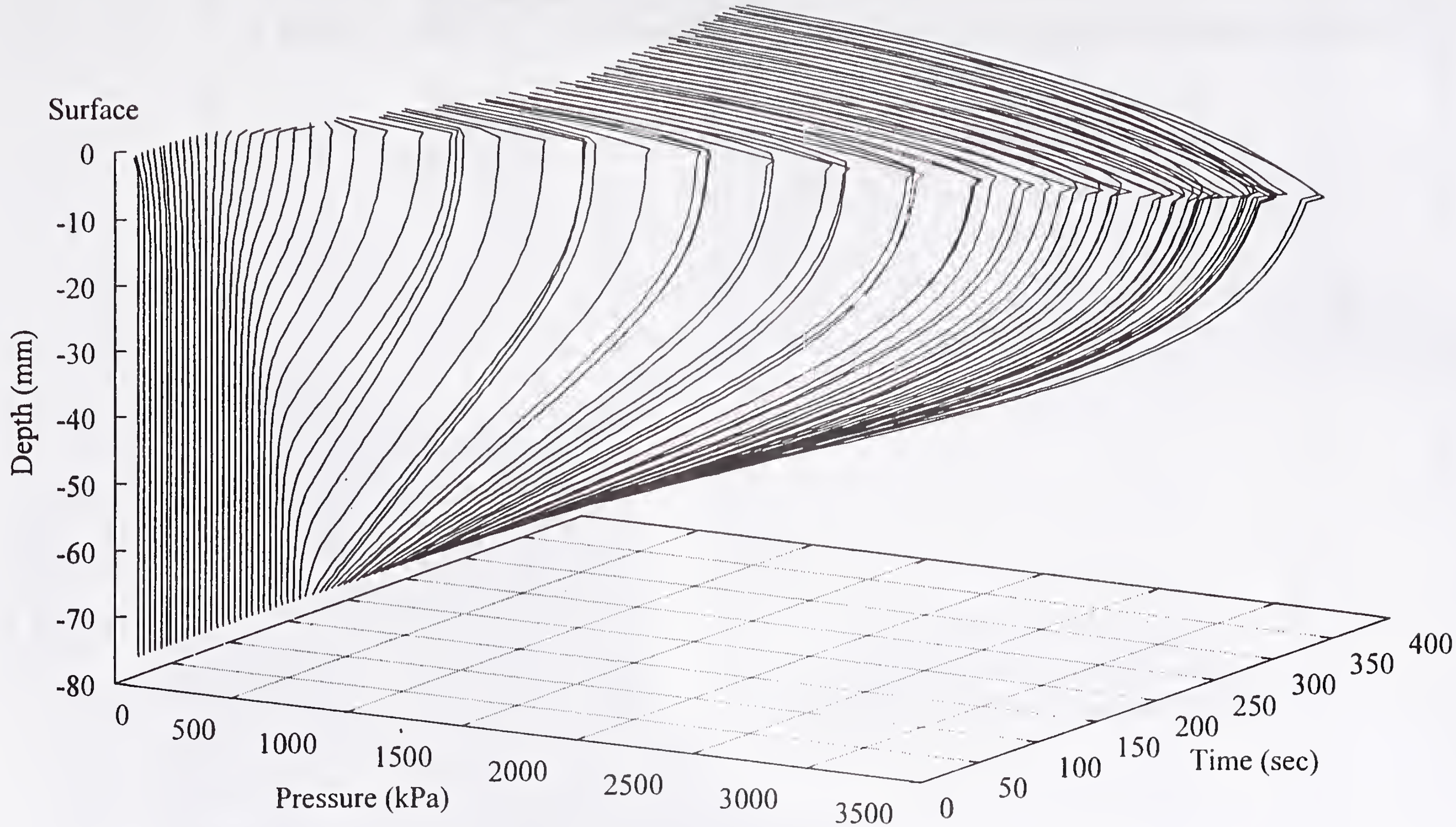


Figure 12. Variation of Pressure (as Predicted by a 3D Simulation) Through Depth of Specimen as Time Progresses

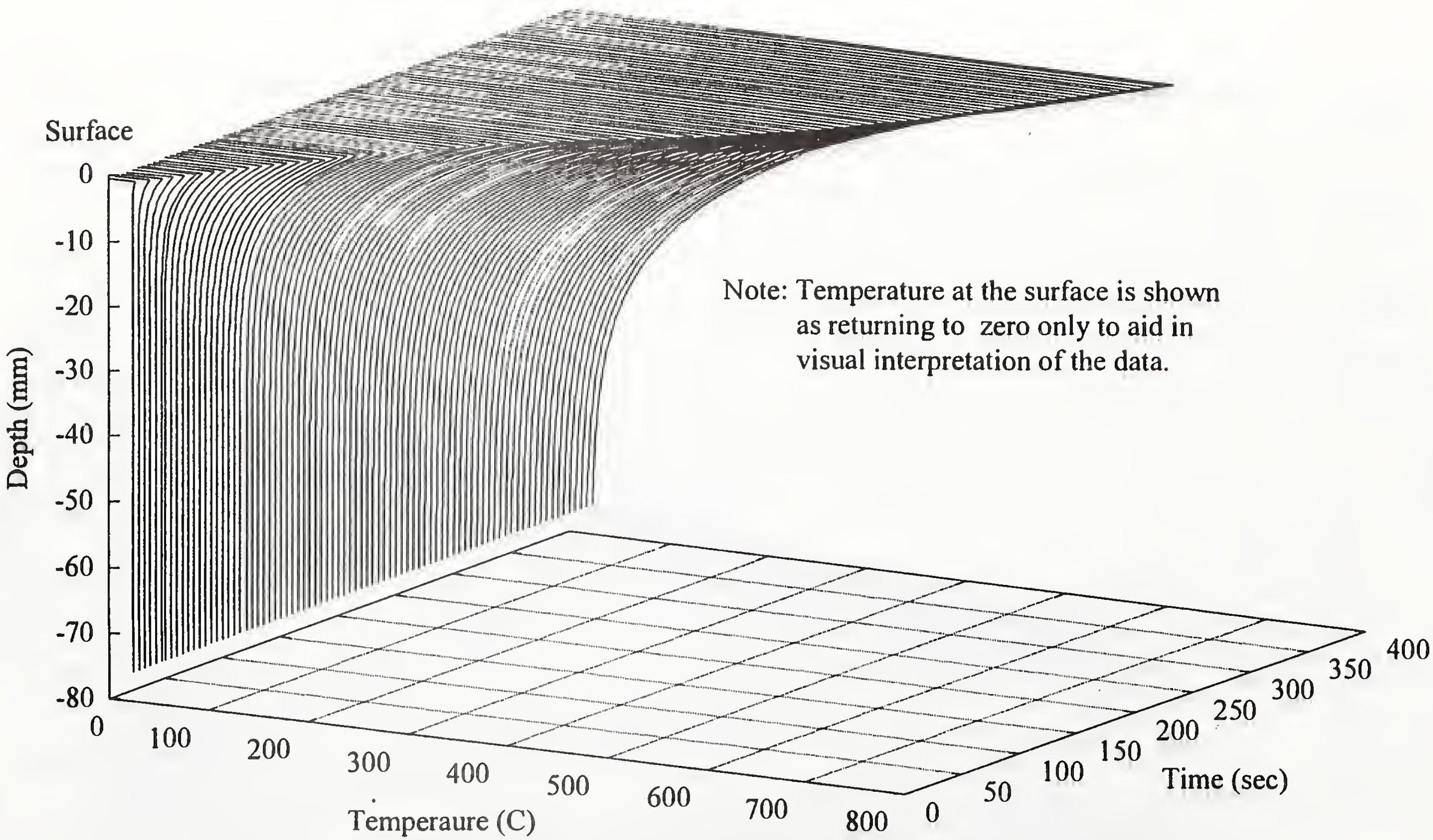


Figure 13. Variation of Temperature (as Predicted by a 3D Simulation) Through Depth of Specimen as Time Progresses

B.9 Mechanical Properties of Siliceous HSC Subjected to High-Temperature Cycles

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Highly-stressed structural members rely more and more on high-strength concretes and -- in certain specific cases -- on very high-strength microconcretes, which are quite sensitive to severe thermal loading (high temperature), particularly when highly-siliceous aggregates are used. As part of a joint Research Project financed by the European Communities, a number of industrial partners and research institutions (like the Italian National Agency for Energy, New Technologies and Environment - ENEA), a many-faceted research program in the domain of siliceous high-strength concretes (f_c = 72-95 MPa) and special microconcretes (Reactive Powder Concretes and Compact Reinforced Concretes, f_c = 170-200 MPa) is in progress in Milan. The objectives of the project regard the measurement of the complete stress-strain curves in compression and in tension both at room temperature and after or during a cycle at high temperature (T = 105-500°C), and the evaluation of a few fracture parameters (fracture energy, characteristic length, toughness index), as a function of the temperature of the thermal cycle. Both the material and the structural behavior are investigated, since the thermally-induced softer behavior of the concrete favors stress redistribution in a structure, making the overall structural behavior less sensitive to high temperature than the material itself.

The research project in progress at Milan University of Technology consists of 4 different phases:

- Compression and tension strength of flint-based, high-strength concretes: residual properties are measured after a cycle at 105, 250, 400 and 500°C (heating and cooling in quasi-steady conditions, with 12 hours at the maximum temperature) [1, 2], Figs. 1 and 2; notched (tension) and unnotched (compression) cylinders (f_c = 72 and 95 MPa) are used.

- Deep beams subjected to 3-point bending and circular slabs subjected to punching (both reinforced and unreinforced): residual capacity is measured (load-displacement behavior included) after a thermal cycle at 105, 250 and 400°C (flint-based concrete with f_c = 72 MPa); deep beams and circular slabs are typical structural elements in plane stresses and subjected to shear and bending [2, 3], Figs. 3 and 4.

- Tension behavior of flint based high-strength concretes (f_c = 72 and 95 MPa): evaluation of the fracture energy per unit volume in the case of multiple or distributed cracking (PIED prisms, for evaluating the damage density in tension [4], Fig. 5, and the characteristic length), after a cycle at high-temperature (T = 105-400°C). The unnotched specimens are loaded by means of steel or aluminium rods, which are glued to the lateral surface.

- Tension behavior of one high-strength calcareous concrete (f_c = 95 MPa) and of two very high-strength fiber-reinforced microconcretes (RPC and CRC): the stress-strain and stress-crack opening curves will be measured at high temperature (T = 105-400°C). Special dumbbell-shaped and notched specimens (Fig. 6) have been cast in order to make it possible to extract the measures from the specimens loaded inside the furnace. The specimens are provided with special threaded ends, which permit their attachment to the press platens. The tests will be displacement-controlled, as in all previous cases. This phase of the project is being carried out in close collaboration with Prof. Gabriel A. Khoury of London, taking advantage of the test facilities for high temperatures which are available at the Department of Civil Engineering at the Imperial College. Further tests regarding the residual behavior after the thermal cycle will be carried out in Milan, as well as most of the data processing.

Phases 1 and 2 are completed, while Phase 3 is well advanced and Phase 4 is in the initial stage, but all the measurements should be available and processed by October 31, 1997.

The results of phases 1 and 2 show clearly that the residual mechanical properties of highly siliceous concretes are dramatically affected by a long exposure to high temperature, both in compression and in tension, while the structural behavior is less affected, since the material becomes softer and the sensitivity to high temperature of the reinforcement, if any, is quite limited ($T \leq 500°C$).

As for distributed damage with multiple cracking (Phase 3), the softening branch of the stress-strain response is definitely less steep than with crack localization, and tends to flatten-off after exposure to very high temperature. At the same time the characteristic length tends to increase with the temperature.

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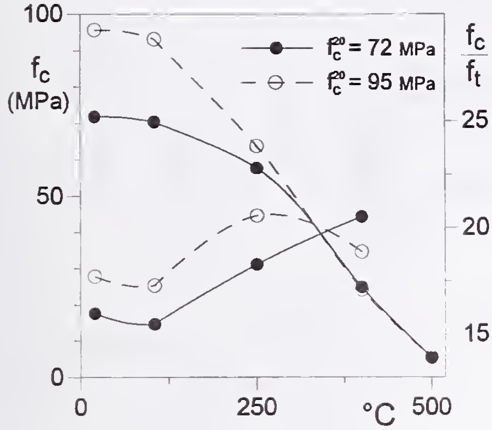


Figure 1

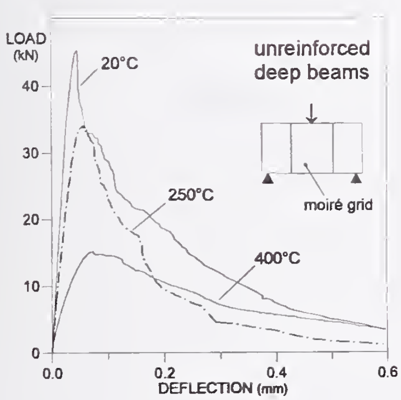


Figure 2

Figure 3

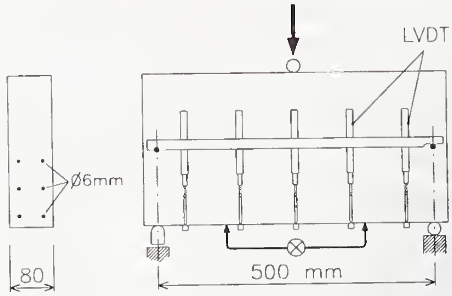
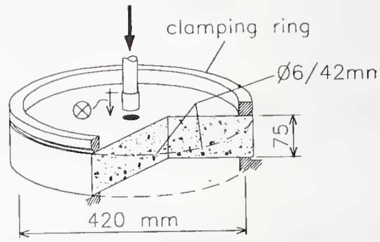


Figure 4



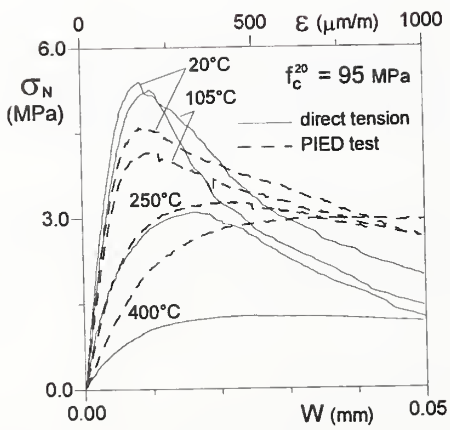


Figure 5

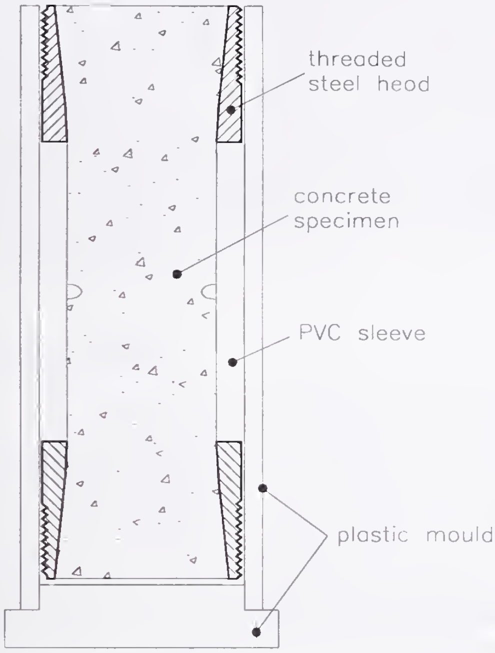

threaded
steel heod
concrete
specimen
PVC sleeve
plastic mould

Figure 6

B.10 Analysis of Pore Pressure, Thermal Stress and Fracture in Rapidly Heated Concrete

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Abstract. A brief review of the problem of calculating the evolution of the distributions of pore pressure and thermal stresses in rapidly heated concrete is presented. The difficulties caused by order-of-magnitude jumps in permeability as a function of temperature and in water content as a function of pore pressure are discussed in some detail and the conditions for the movement of the interface between the saturated concrete and unsaturated concrete are established. Some aspects of the numerical difficulties caused by the jumps are elucidated. A weak point in explaining the explosive spalling of rapidly heated high-strength concrete by pore pressures is pointed out and clarified. It is argued that the main driving force of the explosive thermal spalling must be the release of the stored energy due to the thermal stresses, which requires fracture mechanics. Finally, a simplified analysis of the pore pressure distribution, based on the calculation of the movement of the fronts of drying and wetting, is outlined and some other relevant literature is briefly reviewed.

1 Introduction

The problem of brittle failure of rapidly heated concrete, which has recently surfaced in experimental studies of high strength concrete columns and other structural members, was investigated during the 1970's and early 1980's in relation to the safety of nuclear reactor containments and pressure vessels, especially those for liquid metal cooled breeder reactors [1-4]. The results of that research have direct relevance to the present problem, including that of explosive brittle failure and the build-up of pore pressure in concrete exposed to high temperature. The purpose of this brief paper summarizing the workshop presentation is to review some pertinent results of the studies of this problem at Northwestern University and Argonne National Laboratory during 1975-1982.

2 Finite element analysis of pore pressure

One important factor in brittle failure of concrete at high temperature, including the high strength concrete, is obviously the pressure p of water vapor in the capillary pores of concrete. The evolution of pore pressure distributions $p(\mathbf{x},t)$ as a function of spatial coordinate $\mathbf{x}$ and time t is governed by the following three equations that must be satisfied in every point of the body:

$$\frac{\partial w}{\partial t} = -div\mathbf{J} + \frac{dw_d}{dt} \tag{1}$$

$$\mathbf{J} = -a \; grad \; p \tag{2}$$

$$dp = k \; dw \tag{3}$$

Here $\mathbf{J}$ = mass flux of water (dimension kg/s m^3), w = specific water content (kg of evaporable water per m^3 of concrete), T = temperature, a = permeability, measured in seconds ($a = \bar{a}/g$ where g = gravity acceleration and $\bar{a}$ = permeability with the dimension of velocity, m/s); $k = dp/dw$ = inverse slope of the desorption isotherm $w = w(p)$, and w_d = evaporable water released by the dehydration of hydrated cement caused by heating. Eq. 1 expresses the local mass balance at each point of the continuum; $\dot{w}_d$ (where the superior dot denotes the time rate) is a distributed source term, an important term which has a great influence on the calculation of pore pressures.

In writing Eq. 1 governing the mass transfer of water, all the four phases of water, that is, water vapor, liquid capillary water, free adsorbed water, and hindered adsorbed water, are treated as one. This means that a thermodynamic equilibrium between these four phases is assumed to exist within each capillary pore and the adjacent micropores at all the times, i.e., thermodynamic disequilibrium exists only macroscopically, on the scale of the continuum approximating concrete as a whole.

There are other models in which the vapor phase and liquid phase are treated separately, but a more complicated approach appears unnecessary, for two reasons: (1) If the vapor phase and liquid phase are treated separately, then the adsorbed water ought to be treated separately, too. (2) Separation of the phases implies that water molecules in the vaporized phase and in the liquid phase can travel freely and independently of each other over finite distances macroscopically through concrete. But the latter implication is unreasonable because there is nothing to prevent the water molecules in the vaporized and liquid states as well as the adsorbed state to readily exchange their Gibbs' free energy (chemical potential), and, even more importantly, because the water molecules in the vaporized state cannot pass through pores of subcapillary dimensions, which are known to block the passages through concrete. The reason is that the mean free path of a water molecule in the vaporized state is about $80\text{m}\times10^{-9}\text{m}$ at room temperature, and much more at high temperature, while the width of the necks on the passages through concrete is about 10^{-9}m or less. When the mean free path of water molecules is larger than the opening, the passage of a molecule through such opening is virtually impossible.

Some authors (e.g., Luikov) express the flux as a separate function of the gradient of pressure and the gradient of temperature, or use the gradient of water concentration w (distinguishing Fick's flux, Dufour flux and Soret flux in the coupled heat and mass transfer equations). However, fitting of extensive test data during the 1970's has shown that little can be gained by considering the temperature gradient as a separate driving force of diffusion.. It only complicates the formulation. The pore pressure p depends on both w and T and thus Eq. 1 implies the dependence of J on both grad w and grad T. Eq. 1 is of course nothing but the classical Darcy law for the permeation of a fluid through a porous medium.

An interesting phenomenon apparent in Fig. 1 (top left), which was deduced by indirect reasoning rather than direct measurements, is that the slope of the desorption isotherm in the saturation region $p > p_s(T)$ (the saturation vapor pressure) is apparently far higher than what one would calculate for liquid water fully filling a perfectly rigid container (as determined, e.g., from the ASTM Steam Tables) [9]. The explanation is that the micropores (gel pores of molecule dimensions) that are inaccessible to evaporable water at less than the saturation pressure become accessible to evaporable water at higher pressures, which is not an illogical hypothesis to make. If the isotherm in the over saturation region were assumed to have the same slope as calculated for liquid water completely filling a perfectly rigid container, the pressures calculated would be orders of magnitude higher than those observed in experiments, and all the concrete would have to explode when heated to high temperature.

The typical diagrams of permeability as a function of temperature and of the sorption and desorption isotherms at room temperature and high temperatures are shown in Fig. 1 (top right). From these diagrams, two difficulties become immediately apparent:

1) The permeability of concrete to evaporable water as a function of temperature exhibits an almost sudden upward jump of more than 2 orders of magnitude (about 200 times), a phenomenon that was discovered at Northwestern University in 1979 [5] and became in a milder, less conspicuous form also apparent from the experiments of England and coworkers [6]. The microscopic physical reason for this phenomenon has not been clarified experimentally, but a plausible hypothesis, advanced in [5] (see also [1]) is that, at high temperature, the surfaces of the pores become more smooth (less rough), and in particular the necks of gel-pore dimensions (only a few water molecules in thickness, containing hindered adsorbed water) become widened, without any significant change of porosity overall, thus opening continuous passages of capillary dimensions for the flow of water; see the illustration in Fig. 1 (inserted box on top right)).

2) The desorption isotherms in Fig. 1 (top left) at high temperature exhibit a sharp jump, by a factor of at least 50 $\times$, as the point of saturation of vapor, that is the pressure $p_s(T)$, is crossed.

The foregoing two phenomena, that is, the jump of permeability and the jump of water content on desorption isotherm, create considerable difficulties in numerical modeling.

During the years of collaborative research between Northwestern University and Argonne National

Laboratory in nuclear safety reactor problems, many typical problems of pore pressure evolution were analyzed by finite elements on the basis of Eqs. (1)-(3). Some typical results obtained are shown in Fig. 1 (bottom). Many further results and a comparison with some test data, calculation procedure, input parameters, etc., are giuen in [1, 5, 7, 8] and in further extensive literature quoted in [1]. In these studies, the heating was generally not as rapid as in fire because nuclear reactor structures were considered to be always protected by thick thermal insulation.

An interesting point is that the calculated pressures were considerably smaller than initially expected, and never exceeded about 10 bars (1 MPa, or 144 Psi). Likewise, experimental measurements of pore pressure in heated concrete never indicated pressures in excess of the aforementioned value. The reason is no doubt twofold: (1) the enormous increase in permeability upon exceeding 100°C, and (2) the aforementioned phenomenon of the inflation of pore space when the pressure exceeds the saturation vapor pressure, $p_s(T)$.

3 Explosive thermal spalling

The explosive thermal spalling, which was first observed by Harmathy in normal concrete exposed to fire, has recently been identified as a major problem for high strength concrete. The explosive thermal spalling is a brittle failure which can conceivably be caused by the following two phenomena:

1. Development of a high pore pressure caused by oversaturation of the region of concrete at the front of heating (called the "moisture clog" by Harmathy); and

2. brittle fracture, particularly the sudden unstable release of the potential energy of thermal stresses stored in the structure.

The relative importance of these two phenomena, however, is debatable. On careful scrutiny it appears that the second mechanism, that is, the fracture mechanics aspect, is the major one. The first mechanism, that is, the development of high pore pressure due to moisture clog can play only the triggering role. However, it is also clear that the first mechanism, the pore pressure, must have at least some effect because recent experiments have confirmed that the explosive thermal spalling occurs only in wet concrete in which over saturation by water can develop.

The problem is schematically illustrated in Fig. 2 (top left). Assume that a high pressure develops at a certain distance below the heated surface and creates a crack, as shown. However, as soon as the crack starts opening, the volume available to the water vapor and liquid in the crack is suddenly increased by several orders of magnitude. This means that the water is suddenly forced to expand enormously. Because additional water cannot flow into the crack from the surrounding concrete suddenly, the pore pressure must immediately drop to nearly zero, as soon as the crack starts opening up. Only after the passage of some time, which is certainly far longer than the fraction of a second during which an the explosive spalling occurs, additional water can flow from the pores of the surrounding concrete into the crack.

From this consideration, it appears that the pore pressure can only serve to trigger a crack but cannot drive the explosion, cannot force the crack to open widely. That must be caused by another supply of energy, which is of course available in the form of the potential energy of the thermal stresses.

In this context, it is not surprising at all that the high strength concrete appears to be much more prone to explosive spalling than the normal strength concrete. The high strength concrete is known to be far more brittle. The size effect method of the measurement of fracture energy revealed [11] that an increase of the strength of concrete from 5,000 to 14,000 psi was accompanied by no increase in the fracture energy, G_f, and a decrease of the fracture process zone size, c_f.

Thus it appears imperative to analyze the explosive thermal failure of high strength concrete on the basis of fracture mechanics. This of course further implies that the explosive thermal spalling should exhibit a pronounced size effect, which is observed in all brittle failures of concrete. Experiments checking the size effect in the explosive thermal spalling ought to be conducted.

4 Propagation of saturation interface

The jumps in permeability as a function of temperature and in the desorption isotherm (apparent in Fig. 1 top right) can cause major difficulties in finite element modeling. The time step required for numerical stability on each side of the interface is of a different order of magnitude. Furthermore, the roughness of the interface in finite element modeling does not make it possible to accurately capture the transfer of water.

There are two ways to overcome the problem:

1. To spread the jump of the curves in Fig. 1 (top right) over a sufficient width, replacing the jump of w with a gradual transition (e.g., introducing a linear change of w as a function of relative humidity $h = p/p_s$ in the range from 0.8 to 1.05), and, for the permeability, a linear transition from temperature 70° C to 120°C.

2. To model the movement of a sharp interface between the regions of saturated and unsaturated pores, or the regions of high and low permeability.

Consider the interface curve $f(x, y, t) = 0$, in two spatial coordinates x, y. During time dt, the interface moves as shown in Fig. 2 (top right), and a small element ds of the interface curve moves through the cross hatched rectangular region shown. The flux into this element is J_{n1}, and the water flux out of the element is J_{n2}. The area swept by the element is $ds\, v_n\, dt$ where v_n = velocity of the interface in the direction of the normal. Mass balance during time dt requires that the mass increase of the element

$$(J_{n1} - J_{n2})ds\, dt = (w_2 - w_1)ds(v_n dt) \tag{4}$$

in which $J_{n1} - J_{n2} = [J]$ = jump in flux across the interface, and $w_2 - w_1 = [w]$ = jump in specific water content across the interface. It follows that the velocity of the interface in the direction normal to the interface curve is

$$v_n = -\frac{[J_n]}{[w]} = \frac{[a \text{ grad } p]}{[w]} \tag{5}$$

For an accurate solution, the interface and its velocity according to Eq. (2) should be directly simulated in a computer program.

Due to the self-desiccation of concrete prior to rapid heating, the pores of concrete are never saturated even if there is no drying. The amount of water that needs to be added to the pores in order to achieve full saturation ($p = p_s$) is significant, and a long time is required for the diffusion through concrete to supply that water.

An example has been given in the calculation of the spread of pore pressure $p > p_s$ into a dam from a reservoir [12]. In that numerical example, it was found that, if there were no self-desiccation, i.e., $p = p_s$ as an initial condition, the hydraulic pressure from the reservoir would spread through the whole thickness of a concrete dam (about 80 m) in 56 days. However, taking into account the self-desiccation of concrete, it is found that the hydraulic pressure $p > p_s$ will spread from the reservoir across the dam thickness in 156 years. This difference is enormous.

So the problem is entirely dominated by the filling of the pores at the moving interface between hydraulic over pressure and the unsaturated concrete. The diffusivity of concrete has negligible influence. The rate of movement of the interface depends only on the permeability of concrete, a. The distribution of pressure between the interface and the boundaries is governed essentially by the Laplace differential equation, which does not contain time, that is, by the equation

$$\text{div } (a \text{ grad } p) = 0 \tag{6}$$

where $p = p(x, y, t)$ and permeability a depends on $T(x, y, t)$, and also possibly on p. Within a region in which the permeability is uniform, this differential equation is $\nabla^2 p = 0$.

Differentiating the equation of the interface curve, $f(x, y, t) = 0$, we have $f_{,x}\dot{x} + f_{,y}\dot{y} + f_{,t} = 0$, where $\dot{x} = v_{x,}.$, $\dot{y} = v_y$ with v_x and v_y being the components of the velocity vector of the interface points. It follows that $f_{,t} = -f_{,x}v_x - f_{,y}v_y$ or

$$\frac{\partial f}{\partial t} = -\frac{\partial f}{\partial x}\frac{1}{[w]}\left[a\frac{\partial p}{\partial x}\right] - \frac{\partial f}{\partial y}\frac{1}{[w]}\left[a\frac{\partial p}{\partial y}\right] \tag{7}$$

The right-hand side represents the jump conditions based on the velocities in the x and y directions, considered separately. This means that instead of a smooth interface curve, one may consider a zig-zag interface curve following the inter element boundaries, as shown in Fig. (top right), and the fluxes can be taken separately in the directions shown by the arrows across the element boundaries. This offers one possibility for numerical simulation of the movement of the saturation interface.

5 Simple one-dimensional analysis of pressure with moving saturation interface

Consider a wall uniformly heated on its surface, such that the surface temperature T is equal to a prescribed environmental temperature $T_e(t)$. Rapid heating will desiccate a layer up to depth $x = x_d(t)$. Below it, there will be a layer of saturated concrete up to depth $x = x_w(t)$. Further below it, there will be unsaturated concrete, either self-desiccated mass concrete or concrete that has lost water due to previous drying. Consider that the heating front reaches up to depth $x_h(t)$, which is also the front of pressure increase (Fig. 2 bottom).

For approximate analysis, one may assume the profiles of temperature, pore pressure and water content to be as shown in Fig. 2 (bottom). The profiles of T_p in the first two layers are assumed to be linear, with the interfaces moving, and in the third layer parabolic, with a horizontal tangent at the front. The slope of the temperature profile in the third layer is continuous with the slope of the temperature profile in the second layer, as sketched. The profile of the water content is piece-wise constant, as shown. With the notations defined by the figures, the equations for the fluxes are

$$\begin{aligned} J_d &= -a_1 p_d(t), \qquad a_1 = a/x_d \\ J_w &= -a_2[p_w(t) - p_d(t)], \qquad a_2 = a/(x_w - x_d) \end{aligned} \tag{8}$$

and the jump conditions for the interface velocities are

$$\begin{aligned} \dot{x}_d &= -\frac{J_w - J_d}{w_s - w_1} \approx \frac{J_d - J_w}{w_s} \\ \dot{x}_w &= -\frac{J_0 - J_w}{w_0 - w_s} \approx \frac{J_w}{w_0 - w_s} \end{aligned} \tag{9}$$

At the front of drying and at the front of saturation, the pore pressures must be equal to the saturation vapor pressures corresponding to the local temperatures, i.e.,

$$\begin{aligned} p_d &= f\left[T_d(t)\right] \\ p_w &= f\left[T_w(t)\right] \end{aligned} \tag{10}$$

where $p_s = f(T)$ = function defining the saturation vapor pressure corresponding to temperature T (according to ASTM Steam Tables [9]). Furthermore, the specific water content at saturation, w_s must be specified as a function of temperature T i.e.,

$$w_s = g(T) \tag{11}$$

The flux of water in the third layer of unsaturated concrete may be assumed $J_0 \cong 0$. The differential equation governing heat transport may be written as [1]:

$$\rho C\dot{T} = C_w \mathbf{J} \cdot \text{grad}T + C_a \dot{w} - \text{div}\,\mathbf{q} \tag{12}$$

in which the first term on the right hand side represents the heat convection, the second term represents a distributed source of heat due to the latent heat of the phase transition of water, and the last term repesents the heat conduction; C, C_w = specific heats of dry concrete and of pore water (per unit mass and per degree C); ρ_0, ρ = specific mass of concrete without or with water; C_a = latent heat of adsorption or condensation of water; and C_e = latent of heat of evaporation of water; and q = heat flux, determined by heat conductivity b,

$$\mathbf{q} = -b \text{ grad } T \tag{13}$$

Neglecting the effect of the latent heat of evaporation, the conditions of the heat balance in the wet layer (second layer) and the dry layer (the first layer) may be written as

$$\begin{aligned}(\rho C + w_s C_w)&\left[\frac{\dot{T}_d + \dot{T}_w}{2}(x_w - x_d) + (T_w - T_d)\frac{\dot{x}_d + \dot{x}_w}{2}\right] \\ = \quad & C_w J_w \frac{(T_w - T_d)}{(x_w - x_d)}(x_w - x_d) + \left(-b\frac{T_d - T_b}{x_d}\right) - \left(-b\frac{T_w - T_d}{x_w - x_d}\right)\end{aligned} \tag{14}$$

$$\begin{aligned}\rho C &\left[\frac{\dot{T}_b + \dot{T}_w}{2}x_d + (T_d - T_b)\frac{\dot{x}_d}{2}\right] \\ = \quad & C_w J_d (T_d - T_b) + q_b - \left(-b\frac{T_d - T_b}{x_d}\right) - C_e J_d\end{aligned} \tag{15}$$

in which the temperatures at the boundaries of the layer are averaged to obtain the mean temperature in the layer, the coordinates of the boundary are averaged to obtain the mean velocity of the layer, and the first terms represent heat supply due to convection. The surface temperature T_b may be assumed approximately equal to the prescribed environmental temperature $T_e(t)$.

The jump conditions at the moving interface yield the interface velocities:

$$\dot{x}_d = \frac{1}{g[(T_d + T_w)/2]}\left\{a_2\left[f(T_w) - f(T_d)\right] - a_1 f(T_d)\right\} \tag{16}$$

$$\dot{x}_w = \frac{a_2}{w_o - g[(T_d + T_w)/2]}\left[f(T_d) - f(T_w)\right] \tag{17}$$

Eqs. (14) and (15), provide the conditions:

$$\begin{aligned}&\left[\rho C + C_w g\left(\frac{T_d + T_w}{2}\right)\right]\left[\frac{\dot{T}_d + \dot{T}_w}{2}(x_w - x_d) - (T_d - T_w)\frac{\dot{x}_d + \dot{x}_w}{2}\right] \\ = \quad & -C_w(T_d - T_w)\, a_2 \left\{f(T_d) - f(T_w)\right\} + \frac{b}{x_d}(T_b - T_d) + \frac{b}{x_w - x_d}(T_w - T_d)\end{aligned} \tag{18}$$

$$\rho C\left[\frac{\dot{T}_b + \dot{T}_d}{2}x_d + (T_d - T_b)\frac{\dot{x}_d}{2}\right] = -C_w a_1 f(T_d)(T_d - T_b) + b\frac{T_d - T_b}{x_d} \tag{19}$$

Eqs. (16) -(19) represent a system of four nonlinear ordinary differential equations for four unknowns $x_d(t)$, $x_w(d)$, $T_d(t)$, and $T_w(t)$. These equations may be integrated in time by a standard library computer program for a system of nonlinear ordinary differential equations. In this manner, the maximum pore pressure that can develop in the wall, occurring at interface x_d, can be approximately calculated.

Fracture analysis of the brittle explosive failure requires knowledge of the fracture energy dependence on temperature. Some information in this regard has been reported in [13]. Furthermore, calculation of the energy stored by thermal stresses necessitates a good model for creep and thermal shrinkage of concrete at high temperature. Many studies have been devoted to this effect; see e.g., [15, 16, 17, 18, 20, 27, 28]. Further relevant information on the calculation of pore pressure and other aspects can be found in [21, 22, 23, 29, 24, 25, 26].

6 Conclusions

1. Calculations of pore pressure in rapidly heated concrete must take into account the jumps in permeability as a function of temperature and in water content as a function of pore pressure. The most realistic numerical simulation of these jumps requires following the movement of the interface curve over which the jumps occur.

2. The pore pressure may be realistically expected to serve only as a trigger of the explosive thermal spalling of high strength concrete. Whether the explosive failure actually occurs depends mainly on the amount of energy stored due to thermal stresses, whose release needs to be analyzed according to fracture mechanics.

3. A simplified analysis of the pore pressures may be based on the calculation of the movement of the interfaces between the dried hot zone, the wet heated zone, and the heated not yet saturated frontal zone.

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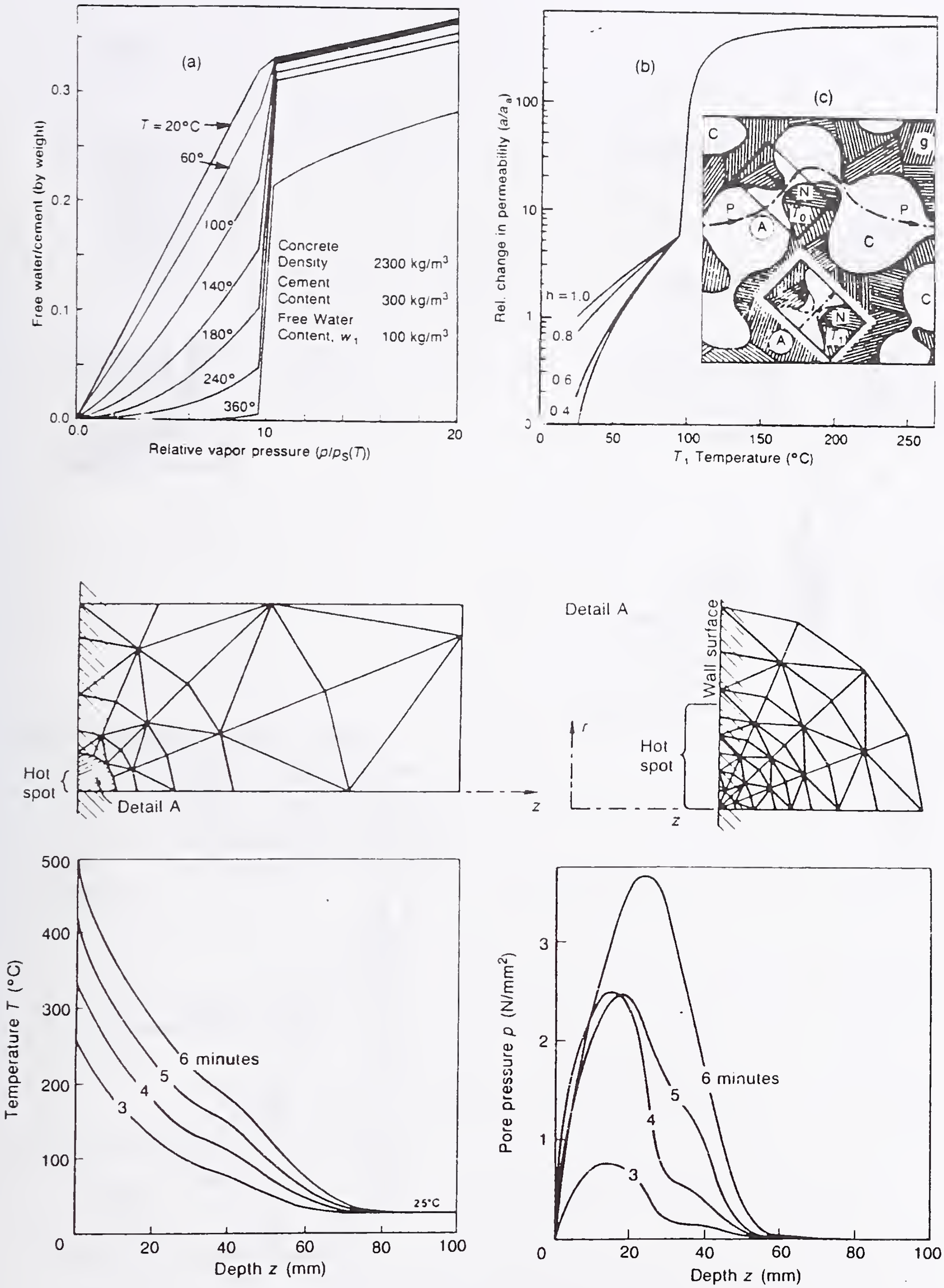

Figure 1: Top: Desorption isotherms at various temperatures (left) and permeability dependence on temperature (right), as established in [5]. Bottom: Two-dimensional finite element analysis of the temperature distributions and pore pressure caused by a rapid heating of a hot spot on a concrete wall, at various times [7, 21].

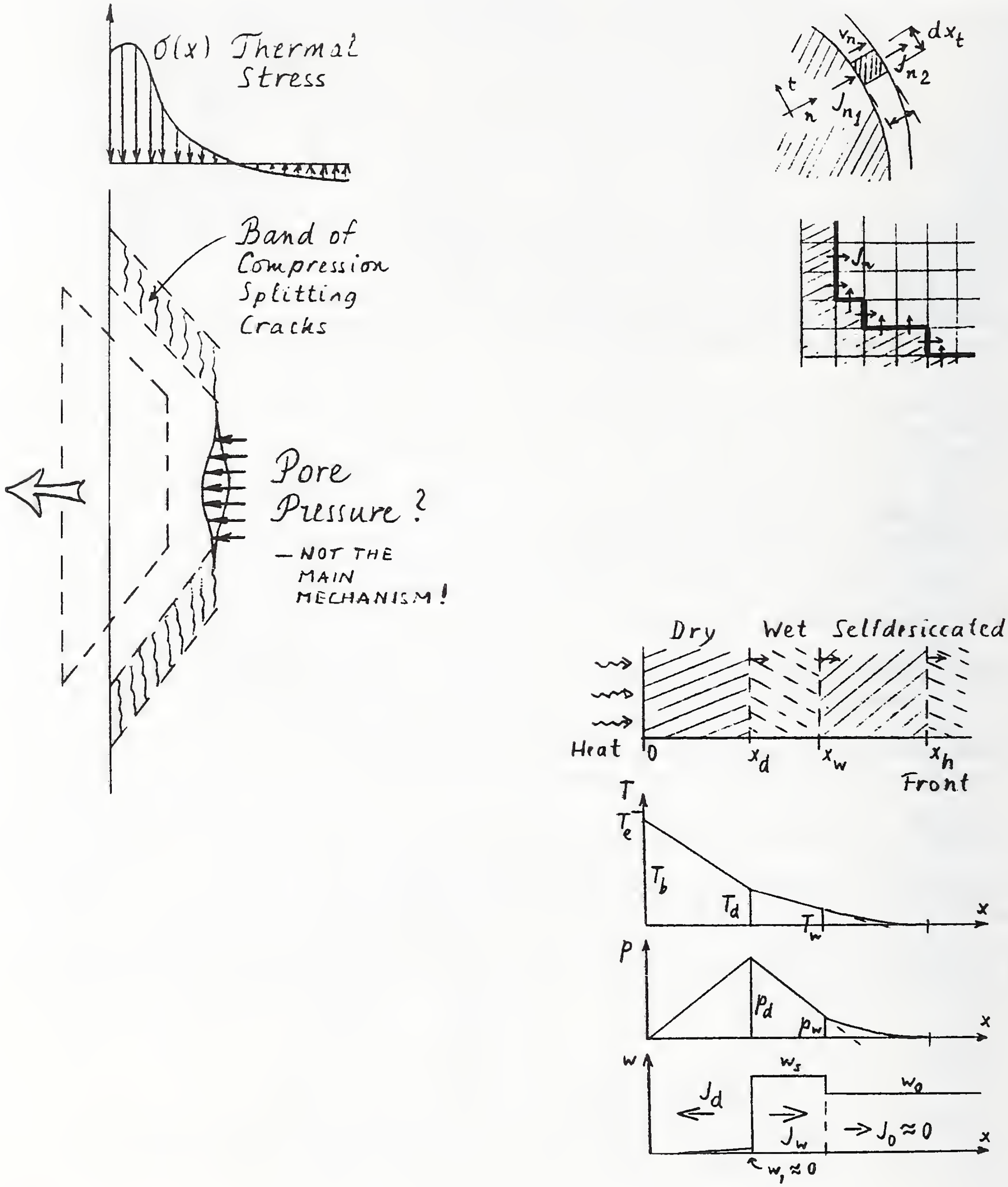

Figure 2: Top Left: Possible mechanism of explosive thermal spalling. Top Right: Moving interface between saturated and nonsaturated concrete, and its representation by a zig-zag interelement boundary. Bottom: Profiles of temperature T, pressure p and specific water content w in a rapidly heated wall, with moving interfaces and fronts.

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