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SLABS WITH DOLOMITE AGGREGATES

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NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE PROF. JOHN ADJELEIAN

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FIRE ENDURANCE OF
CONCRETE SLABS WITH DOLOMITE AGGREGATES

by

J. Mohan, B.Eng.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment
of the requirements for the degree of
Master of Engineering

Department of Civil Engineering

Carleton University

Ottawa, Ontario

April, 1981

The undersigned recommend to the Faculty of

Graduate Studies acceptance of the thesis:

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submitted by J. Mohan, B.Eng. in partial fulfillment
of the requirements for the degree of Master of
Engineering

Thesis Supervisor

Chairman, Department
of Civil Engineering

Carleton University
Ottawa

The objective of all dedicated engineers should be to thoroughly analyse all situations, anticipate all problems prior to their occurrence, have answers for these problems, and move swiftly to solve these problems when called upon

DEDICATED TO

BHAGWAN SRI SATHYA SAI BABA

ABSTRACT

The results of an investigation on the thermal performance of dolomite concrete slabs (concrete slabs made with dolomite aggregates) exposed to fire are presented in this thesis.

Fire endurance tests were conducted on two sets of 800 mm x 850 mm concrete slab specimens, each set comprising of slabs of thicknesses 60 mm, 100 mm and 150 mm. The first set of slabs were made with dolomite fine and dolomite coarse aggregates. The second set of slabs consisted of calcareous fines (composed of 80% dolomite and 12-15% silica) and dolomite coarse aggregates. The temperature distribution at various depths during the growth and decay periods of fire and the fire endurance characteristics of the two sets of slabs are studied. The results are compared with that available for siliceous concrete slabs (concrete slabs made with quartz aggregates) to study the influence of silica content in the aggregates, on the fire response of concrete slabs. The probable upper and lower bounds of fire resistance values for the concrete slabs are determined.

The thermal properties of dolomite aggregates and dolomite concretes that influence the fire endurance behaviour of concrete slabs were experimentally determined. The results were used in the Program FIRES-T3 and a three-dimensional non-linear transient heat flow analysis was performed with a finite element model of the slab. The temperature distribution in dolomite concrete slabs thus obtained are compared with the experimental values. The data for the theoretical model that would represent these types of slabs in the thermal analysis are then established. The concrete cover thickness, required for reinforcing and prestressing steels in dolomite concrete slabs, that will satisfy the heat transmission

end point requirements of the ULC-S101 standard are then determined.

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NOMENCLATURE

Notations

- °C - centigrade
- CF - calcareous fine aggregates
- CF/DC - concrete made with calcareous fine aggregates and dolomite coarse aggregates
- DC - dolomite coarse aggregates
- DF - dolomite fine aggregates
- DR - dolomite rock
- DF/DC - concrete made with dolomite fine and dolomite coarse aggregates (referred as 'dolomite concrete')
- L - Length
- L_o - Length, at the start of the test
- M - Mass
- M_o - Mass, at the start of the test
- mm - millimeters
- QF - quartz (silica) fine aggregates
- QC - quartz (silica) coarse aggregates
- QF/QC - concrete made with quartz fine and quartz coarse aggregates (referred as 'siliceous concrete')
- t - time
- th - thickness

Greek letters

- Δ - increment
- ϵ_f - fire emissivity
- ϵ_c - concrete emissivity
- σ - Stefan-Boltzmann constant

CHAPTER 1

INTRODUCTION

1.1 NEEDS and OBJECTIVES

The research on the fire resistance behaviour of building materials and components is gaining much importance in the modern days owing to the numerous fire hazards. The study of the behaviour of structural components during and after fire is inter-disciplinary and needs co-ordination of the relevant concepts in the fields of civil engineering, mechanical engineering, geology, physics, chemistry and allied fields. The present investigation on the fire resistance of concrete slabs with dolomite aggregates is based on such an effort.

The fire resistance of concrete slabs depends on various parameters like the material properties of its constituents, moisture content and mechanical effects. The thermal properties of concrete depends on the thermal properties of both the cement and the aggregates. Investigations show that the thermal properties of cement paste are not subject to large variations [16]; the thermal properties of aggregates, however, can vary over wide ranges and have therefore substantial influence on the temperature distribution within a slab subjected to fire. Quartz, among the siliceous aggregates and Dolomite, among the calcareous aggregates are expected to provide the lower and upper bounds of values for fire resistance, based on their chemical behaviour at elevated temperatures. The studies at the Portland Cement Association and the National Research Council of Canada, on small slab specimens provide the necessary information on the thermal properties of quartz and the thermal behaviour of concrete with quartz aggregates. The lack of published evidence on (i) the representative thermal properties of dolomite and dolomite concrete

in fire environments and (ii) the fire resistance and the thermal behaviour, during the growth and decay period of fire, in dolomite concrete slabs (concrete slabs with dolomite aggregates) necessitates the present investigation.

The objectives of the thesis are:

- A. To study the temperature distribution, during the growth and decay period of fire and determine (a) the thermal fire resistance and (b) the concrete cover requirements for reinforcing and prestressing steels in dolomite concrete slabs subjected to fire.
- B. To compare the fire resistance capacities and thermal behaviour, of dolomite concrete slabs and quartz concrete slabs (concrete slabs with quartz aggregates).
- C. To perform a three-dimensional non-linear transient heat flow analysis with a finite element model of the slab to (a) compare the theoretical and experimental results for the temperature distribution and (b) establish the data that represent the dolomite concretes, that will enable the determination of temperature distribution in any concrete structural component that can be modelled within the capacity of the finite element program used.

1.2 REVIEW OF CONCEPTS

The concepts relevant to the thermal response of concrete materials and concrete slabs exposed to fire are briefly elucidated in the following sub-sections.

1.2.1 BEHAVIOUR OF CONCRETE MATERIALS AT FIRE TEMPERATURES

For the study of behaviour of structures in fire, the following

properties of the building materials and their changes due to high temperatures are of importance:

- a. Thermal expansion
- b. Thermal conductivity and specific heat
- c. Modulus of elasticity
- d. Strength, yield point, elongation at fracture and creep behaviour.

The changes in composition and the structure of some building materials can also affect the behaviour of the construction in fire.

We shall now review the important changes that are encountered in concrete at fire temperatures.

a. Thermal expansion

The high temperature behaviour of concrete varies considerably, depending on the mix, materials employed and especially the aggregates. At room temperatures the mechanical properties of solid concrete are determined primarily by the cement paste. However, at high temperatures the mechanical properties, especially the coefficient of thermal expansion, is greatly influenced by the aggregates as well, since they make up the greater part of the volume of concrete.

The effect of the aggregates on the behaviour of concrete at high temperatures depends primarily on its coefficient of thermal expansion. The texture of concrete specimen can remain intact in the presence of increasing temperatures only if the resulting changes of the separate components are mutually compatible and the internal stresses can be absorbed by the cement paste [35]. Hence, the aggregates with a low coefficient of thermal expansion and temperature-expansion curve

that is as smooth as possible, behave best.

When concrete specimens are heated it is not only the aggregates that expand. The cement paste also changes in volume. Since the aggregates expand and the cement paste begins to shrink at high temperatures, the thermal expansion occurring in concrete is less than the aggregate itself. Under otherwise similar conditions the co-efficient of thermal expansion decreases with increasing cement content.

b. Thermal conductivity and Specific heat

The thermal conductivity of concrete is determined primarily by the bulk density and the moisture content. The greater the bulk density and moisture content, the greater the conductivity. The influence of moisture on the thermal conductivity of concrete presents special difficulties that are relevant for temperatures within the range up to 200°C. Well defined measurement of thermal conductivity for moist material in this temperature range is difficult to undertake due to the complicated interaction between moisture and heat flow.

The thermal conductivity of the cement paste is not subject to large variations and hence it is the thermal conductivity of the aggregates that determines the insulating quality of concrete [16].

Most concrete aggregates can be regarded as mixtures of crystalline and amorphous formations. Highly crystalline rocks exhibit relatively high conductivities at room temperature and gradually decreasing conductivities at increasing temperatures. The conductivity of amorphous rock formations, on the other hand, is low at room temperatures, relatively insensitive to the chemical composition and increases slightly with an increase in the temperature. It is probable that the amount of material in the aggregate that undergoes endothermic reactions upon

5

heating, such as dehydration, decomposition and transformation also has a great influence on thermal conductivity and specific heat characteristics of the aggregate. In siliceous aggregates, for example, the presence of quartz, which transforms from α -quartz to β -quartz at about 550°C will cause an increase in specific heat. In calcareous aggregates the presence of magnesite and dolomite, which dissociate at temperatures of approximately 350°C and 750°C respectively, will affect the thermal properties of the aggregate. During the dissociation heat is absorbed, so that the presence of magnesite and dolomite should be beneficial for the fire resistance of concrete elements. Its effect on the thermal properties of concrete, however, is not known precisely [25]. For normal weight concretes, generally, the thermal conductivity decreases and specific heat increases with increasing temperature.

c. Modulus of elasticity

When concrete is exposed to elevated temperatures, a decrease in the modulus of elasticity occurs. According to Cruz [11], the test results on 75 mm x 150 mm cylinders made of normal weight concrete revealed that at 200°C , the modulus of elasticity is about 70% of the room-temperature value, at 425°C it is slightly less than 50% and at 650°C , only 30%. This means that the stiffness of concrete structural members diminishes at high temperatures and plastic hinges are capable of large rotational capacities.

d. Strength

Earlier results [35] showed an increase in compressive strength of concrete up to about 300°C and a drop only on further heating. The

initial increase in strength on heating of certain concretes can be explained by the fact that heating brings about a 'steam hardening', leading to the additional hydration of cement. With many types of aggregates, moreover, a reaction between cement and aggregates is by no means impossible. The water-cement ratio is found to have no appreciable effect on the relative change of thermal compressive strength. Of greater influence, however, is the ratio of cement to aggregates [26]. The investigations showed that after exposures to temperatures up to about 300°C for several weeks no further decrease in strength could be expected.

1.2.2 PERFORMANCE OF CONCRETE SLABS EXPOSED TO FIRE

To carry out a fire test, the structural component is installed in a fire test chamber with partially or fully automatic control. The test member is installed in the fire test chamber in a manner that simulates as closely as possible the incorporation of the member in practice. Earlier researches involved testing of full-scale structural members in fire. Such type of tests were not only expensive but they provided information which were specific and had a little scope. Recent researchers recognised the testing of smaller scale members that yielded fairly accurate and necessary informations [13,15,25].

In a fire, a slab above the burning area is rapidly heated on the underside. Owing to the relatively poor heat conduction of concrete the steel reinforcement situated close to the underside in the tensile zone is heated more rapidly to critical temperatures of steel than is the concrete on the upperside of the floor structure heated to its critical temperature. Hence, the heating of the steel reinforcement

plays a decisive role in the resistance of steel reinforced concrete slabs to fire.

The fire resistance of a concrete slab is influenced by the following factors:

- a. Steel covering
- b. Quality of concrete
- c. Thickness of the slab
- d. Moisture content

By increasing the covering of the steel, the heating rate of the steel reinforcement is reduced and thus the resistance of steel reinforced concrete slab to fire is increased. Plaster in earlier tests showed greater protective effect than that given by steel covering. An essential condition, however, is that ~~the~~ plaster adheres well. The explanation may be sought in the fact that plaster has a lower bulk density than concrete and thus shows greater thermal insulating properties. The favourable effects cannot be over appreciated since they often get detached from the concrete at an early stage in the fire. For a number of years, special coatings like that of asbestos, vermiculite and perlite bases have been used to increase the fire protection. With these coatings, even comparatively thin ones, the heat insulation can be so greatly improved that the fire resistance time is increased to many times that of the uncoated floors. However, it is necessary that adequate protection be given to steel so that it is not allowed to reach the critical temperatures that will reduce its strength.

The effect of aggregates on the fire resistance has been discussed already. In addition, the concrete grade has significant influence, especially when it is of poor or medium quality, since modulus of elasticity increases with the grade of concrete. Given equal thickness and reinforcement, higher the modulus of elasticity of concrete means a lower steel stress and hence an increase in the length of the time of fire-

resistance [35].

Moisture content has great influence on the fire resistance of concrete slabs. Approximately, an increase of about 5% in fire resistance can be expected for every 1% (by volume) of moisture. Since the reproducibility of fire test results is seldom better than 5%, it may be expected that the effect of moisture contents of the order of 1% (by volume) will not show up clearly in fire resistance tests. Of the commonly used inorganic building materials, only hydrated Portland cement can, under normal atmospheric conditions, hold significantly more than 1% (by volume) of moisture [18,26]. Consequently, determining the effect of moisture on fire resistance is important only in constructions where significant amount of hydrated Portland cement, for instance more than 5% by volume, is used.

1.3 REVIEW OF FIRE TEST STANDARDS

As the building fires are a major hazard to life and property, building codes require that resistance to the fire be considered in building design. Codes provide the means by which structural fire resistance is integrated into the design and construction of buildings. Most of the building codes specify the fire endurance requirements for the numerous elements of building construction. The required fire ratings are dependent upon the intended occupancy, type of construction and building size that combine to provide safety factors against potential fire hazards.

Fire test standards thus form the basis for testing building materials and assemblies in order to determine if they conform to the structural fire protection requirements for safeguarding lives and property from fire.

The fire resistive property of an assembly of building components is determined in compliance with the test methods of Underwriters' Laboratories of Canada known as ULC-S101, "Standard methods of fire endurance tests of building construction and materials"[33]. Other standards, essentially alike, include the National Fire Protection Association, Standard method no. 251; Underwriters' Laboratories, UL263; American National Standards Institute, no. A2-1; and American Society for Testing and Materials, ASTM E119 [34].

ULC-S101 is a standard for fire testing assemblies like walls, floors, beams and columns. The standard provides a common and uniform test method for the comparison of performance of assemblies for specific constructional uses.

The standard fire test is based on exposing the test specimen to a fire having a standard relationship governed by a time-temperature curve. Floor and roof specimens are exposed to fire from beneath, beams from the bottom and sides, walls from one side and columns from all sides. The temperature is raised in the furnace over a given period of time in accordance with the ULC-S101 curve shown in Fig. 1.1. The specified time-temperature relationship provides for a furnace temperature of 538°C at five minutes of the test, 704°C at ten minutes, 927°C at one hour and 1093°C at four hours. The end point of the test is reached and the fire endurance of the specimen is established when any one of the following occurs:

- a. the test assembly structurally fails to sustain the applied load and physically collapses (structural end point)
- b. cotton waste placed on the unexposed side of a floor or roof system is ignited through cracks or fissures in the specimen (flame passage end point)

Fig.1.1 ULC-S101 standard Fire Curve

- c. the temperature of the unexposed surface rises an average of ~~120~~¹²⁰° C above its initial temperature or 181° C at any location (heat transmission end point)

In addition, walls must sustain hose-stream test.

In 1970, additional criteria on steel temperatures were added and accordingly, the critical temperatures for heat transmission end point corresponds to an average temperature rise of 139° C above the initial temperature at the unexposed surface of the concrete component, an average temperature of 427° C for prestressing steel and a temperature of 593° C for reinforcing steel.

For fire tests on floor slabs ULC-S101 also requires the temperatures of the unexposed surface to be measured under a felted amosite asbestos pad of prescribed dimensions and properties. The standard describes a procedure for deriving the fire resistance for one moisture condition from that of other moisture conditions. The standard moisture content of a test specimen is that corresponding to the equilibrium state of drying in air of 50% relative humidity at 23° C.

Some fire test standards, for example, International Standard 834 of the International Organisation for Standardization, permit separation of end-point criteria based on the three principal conditions of acceptance: 1. Flame or gas passage 2. Heat transmission 3. Load-carrying capacity.

Each of these criteria is given equal weight in North America. The first end point reached terminates the test. The fire-endurance of the assembly is established from this single result regardless of how long it would take to reach the other end points. Fire-ratings

achieved by concrete assemblies are practically always based on the heat transmission end point [32]. This means that the structural integrity of the building is maintained during the test well beyond the time indicated by the fire-rating. In an actual fire, maintenance of structural integrity affords safety and protection to fire-fighting personnel and equipment. Frequently the concrete suffer little more than the superficial damage in a fire and can be readily restored to use.

In attempting to analyse the standard fire curves it must first be realised that in the first half hour, after the start of the fire; the temperatures in the fire compartment rise very rapidly and then increase gradually. The rapid changes of temperature at the beginning of a fire, in general, result in large temperature differences in the structural member. As the fire continues, there is a continuously progressive, but more even heating of the construction, which, unless a temperature equilibrium sets in beforehand, can result in a failure. The uniform time-temperature curves correspond approximately to the course followed by a fire of medium severity.

However, these curves do not account for the structural and heat transmission effects and the continuance of the risk due to fire that exists in the decay period. The future revision of the standards may include this into account appropriately, based on research results.

There is less agreement in the result of the various studies for the decay period, due partly to the complexity of the processes that determine the temperature in that period. So far, rates of decay of temperature could only be established empirically or by making conservative or highly idealized assumptions. According to Kawagoe [26] the rate of decrease of a fire with a fully developed period of more than one hour

is 7°C per minute. The Swedish code assumes a rate of decrease of 10°C per minute irrespective of the duration of the fully developed period of the fire. According to Harmathy [21] who studied several experimental fires of relatively short duration, the rate of decrease of temperature for such fires is in the order of 15°C to 20°C per minute. In general, the longer the duration of the fully developed period the lower the rate of decrease of temperature. Bruce Ellingwood and James Shaver [10] have published a set of curves representative of fire in concrete members. The expressions are being developed by the researchers to convert the fire resistances for standard fire conditions to those for any other fire severity.

The duration of the fire test also depends on the type of structure in which the test member is to be used. In Germany, for buildings threatened with fire, "fire-resistant" and in exceptional cases "highly fire-resistant" construction is required. "Fire-resistant" members according to DIN 4102, must continue to perform their functions in the fire tests for 1.5 hours and "highly fire-resistant" members must do so for 3 hours [35]. In other countries, for certain buildings such as warehouses, which are particularly exposed to fire hazards, still longer fire resistance times are prescribed.

Increasing the demands ~~for~~ duration of resistance against fire beyond a certain time does not always require substantial changes in the construction. This is because, for many structural members there is a certain time at which, during the standard fire test, heat equilibrium is more or less attained. In this state, the heat losses on the side away from fire are approximately equal to the input of heat on the side towards the fire. If the structure has not collapsed by this time, its fire-resistance can be greatly increased by reaching this threshold.

1.4 REVIEW OF PAST EXPERIMENTAL WORK

Harmathy and Allen [20] studied the thermal characteristics of sixteen concretes made of various aggregates, with the aid of thermogravimetry, dilatometry and thermal diffusivity tests. The tests were done on samples taken from the masonry units supplied by several manufacturers.

Gustaferro, Abrams and Litvin [15] studied the performance of 900 mm x 900 mm slab specimens of 50 mm to 125 mm thickness that were made of cellular, perlite and vermiculite concretes having oven dry weights between 500 to 1600 kg/m³, subjected to the ASTM standard fire. Their results showed a decrease in fire endurance with concretes of higher unit weights. They have also produced design charts to estimate the fire endurance, based on the unexposed surface temperature rise, for two-course floors or roofs made of these type of concretes combined with structural concrete base slabs.

Gustaferro, Abrams and Salse [3,14] compared the fire endurance results, from the heat transmission end-point criteria, obtained from eight full-scale pan joist floor specimens and five double-tee specimens made of limestone, siliceous and shale aggregates with the results from 900 mm x 900 mm slab specimens. The results correlated very well.

Lie [25] performed tests on plain concrete slab specimens made of quartz aggregates and determined the fire endurance behaviour in these slabs.

The following relevant observations were made based on the past experimental works:

- a. The information on the representative thermal properties and fire response of dolomite concretes is lacking.
- b. The studies did not include the performance of slabs during

the decay period of fire.

1.5 REVIEW OF ANALYTICAL AND NUMERICAL METHODS

Methods have been developed in recent years to solve fire performance problems by calculation. In order to calculate the fire performance of a building element, it is necessary to know the temperature of the element during exposure to fire. If the relevant representative thermal properties are known, prediction of the temperatures in these elements, with reasonable accuracy, during fire exposures is possible.

Although analytical methods for the determination of temperatures in structural elements during exposure to fire are often less accurate than numerical or experimental methods, they nevertheless have advantages. An important advantage is that it is possible to estimate the fire resistance of structural elements or determine a conservative value of it by means of simple formulae or graphs. For practical purposes, estimations of temperatures and fire resistances with the aid of analytical solutions are often sufficiently accurate and they have been proven of great value [26]. Available methods for a calculation of the transient heat flow within a fire exposed structure are based on the Fourier equation of heat conduction in non-transparent, non-porous materials. In application to concrete structures, this equation constitutes an approximation of the problem. Concrete is classed as a porous material which implies that a heat transfer occurs also by convection and radiation in the pores of the material [5]. Furthermore, the heat transfer is connected to a simultaneous moisture transport and from a strict thermodynamical point of view, these two transport mechanisms have to be analysed in parallel over a system of partial differential equa-

tions.

Lie and Williams-Leir [24,25,36] have developed approximate formulae for fire resistance, influence of moisture content and cover thickness requirements in slabs that provide an easier means for fire-resistant design of the floor and roof components. Abrams and Lin [2] have developed analytical procedures and computer programs by which fire response of reinforced concrete slabs could be predicted.

For a practical determination of the time-temperature fields in the exposed structures, numerical methods have been developed and arranged for computer calculations. Such numerical methods are based either on finite difference or finite element approximations. The methods are opening the possibilities for systematic determinations of the time-temperature fields for various conditions of fire exposure and varying structural characteristics, giving a basis in the form of diagrams and tables for facilitating a differentiated fire engineering design in practice.

Finite difference method of analysis has been used in developing programs for the fire resistance of composite concrete floor and roof slabs and temperature distributions in slabs and columns subjected to fire [24,25].

Many finite element programs have been developed in the past six years, that can be used to determine the temperature distribution in structural components exposed to fire. The advantage of finite element method are numerous. The method is very general with respect to geometry and material properties; complex shapes composed of different materials can be easily represented. Non-linearity of materials and boundary conditions can be treated by this method quite conveniently. Most numerical

methods convert the continuous governing or integral equations of heat transfer to a set of linear algebraic equations. However, in the finite element method, the linear equations produce a symmetric positive definite matrix in banded form which can be readily solved with a reasonably minimum computer storage and time. A brief description of a few efficient finite element programs that are currently in use is given in the following paragraphs:

Program FIRES-T: [6,23]

The solution technique used in FIRES-T is a finite element method coupled with time-step integration. This general approach has been presented in the work of Zienkewicz and extended to the fire situation by Bizri. A nonlinear heat flow analysis is used to account for the temperature dependence of thermal properties and the thermal boundary conditions associated with the fire. These non-linearities require the use of an iterative procedure within any given time-step. Thus the problem is linearized about the current temperature distribution within any given iteration.

Programs DOT and DETECT: [29]

DOT (Determination Of Temperatures) is a finite-element heat transfer analysis program for both linear and non-linear two-dimensional planar and axisymmetric heat conduction problems. Material non-linearities such as temperature-dependent conductivity and specific heat are considered as well as non-linear radiation boundary conditions for the case of structures exposed to a fire environment.

DETECT (DEtermination of TEMperatures in ConstRuction) is a linear heat transfer analysis program for the analysis of planar

and axisymmetric structures of arbitrary geometry constructed incrementally, with particular application to mass concrete dams.

Program FIRES-T3: [22,28]

FIRES-T3 (Fire Response of Structures - Thermal -3 dimensional) evaluates the temperature distribution in the structures subjected to fire environments. The program provides options for a nonlinear transient heat flow analysis with three dimensional solids, two dimensional cross sections and structures in which heat flow is one dimensional. The structures may consist of one material or may be composites such as reinforced concrete. The temperature distributions generated by FIRES-T3 can be used with the stress analysis program FIRES-SL that is being updated at the University of California at Berkeley, to provide the overall behaviour of the structural systems subjected to fires.

The heat flow problem is modelled in FIRES-T3 by the heat conduction boundary value problem. The equations are non-linear because of the temperature dependence of the thermal properties of structural materials and heat transfer mechanisms associated with the fire environments. The solution technique used in FIRES-T3 is a finite element method coupled with time-step integration. Fire environments are represented by a linear or a non-linear model that includes both convective and radiative mechanisms.

1.6 SCOPE OF THE INVESTIGATION

An experimental investigation was performed to determine the thermal response of concrete slabs made of dolomite aggregates, subjected to fire. Initially, tests were done on appropriate aggregate and concrete

specimens to determine the essential thermal properties viz., thermal conductivity, specific heat, thermal expansion and mass loss as a function of temperature, that will provide information of their influence on the thermal behaviour of slabs.

Fire endurance tests were carried out with two different sets of slabs, approximately 800 mm x 850 mm size. The first set consisted of slabs of three different thicknesses and was made with dolomite coarse and dolomite fine aggregates. The second set also consisted of slabs of three different thicknesses, but made with dolomite coarse and commercially sold calcareous fines that contained significant percentage of silica. The second set of slabs was made to study the possible fire performance variation with the presence of silica in fines. The fire endurance tests were conducted in a furnace at the Fire research laboratory of the National Research Council of Canada, built mainly from insulating fire brick. During the tests, the temperatures in the slabs were measured with thermocouples inserted at various depths. The unexposed surface temperatures were measured under felt amosite asbestos pads as specified in the ULC-S101 standards. For various thickness of slabs it was possible to obtain the temperature distribution in the slab as a function of time at various depths.

The temperature history in the slab was also determined, with the use of the program FIRES-T3. The thermal properties obtained through the experiments were input in the program and a non-linear transient three-dimensional thermal analysis was carried out, with the slab being modelled of eight node brick elements and subjected to ULC-S101 standard fire. The thermal data that represent dolomite concretes in the theoretical analysis was established.

CHAPTER 2

EXPERIMENTAL STUDY

This chapter describes the experiments performed to study the thermal properties and fire endurance characteristics of dolomite concrete specimens. The test specimens, the test procedures involved in the study and the test results are described in the following sections.

2.1 TEST SPECIMENS

The subsequent sub-sections describe the test specimens, materials used and the fabrication and conditioning methods in detail.

2.1.1 DESCRIPTION OF SPECIMENS

A. Fire endurance test specimens

The specimens measured 800 mm x 850 mm in plan.

Set I (DF/DC type) consisted of slabs of three different thicknesses, 60 mm, 100 mm, and 150 mm. The slabs were made with dolomite coarse aggregates (DC), dolomite fine aggregates (DF) and Type 10 Portland cement.

Set II (CF/DC type) consisted of slabs of three different thicknesses, 60 mm, 100 mm, and 150 mm. The slabs were made with dolomite coarse aggregates (DC), calcareous fines (CF) and Type 10 Portland cement.

Thermocouple wires were introduced at various depths in the slabs to measure the temperatures. The details are shown in Figs.2.1 and 2.2.

Fig. 2.1a Sectional plan of a slab specimen
(All dimensions are in mm)

Fig.2.1b Sectional view of the slabs indicating the location of thermocouples along the depth
(All dimensions are in mm)

Fig. 2.2 Forms for slab specimens

Two steel rods were provided along the width of the slabs for shrinkage and handling purposes.

Slab designations indicate the fine and coarse aggregates used in the slab and its thickness, e.g., DF/DC(100) denotes a 100 mm thick slab that contained dolomite fine aggregates and dolomite coarse aggregates.

B. Associated test specimens for thermal property tests

Specific heat tests

The tests required finely ground samples of fine aggregates and concrete.

Thermal conductivity tests

Two sets of specimens were made alongwith the two sets of fire endurance test specimens. A third set of specimens were cut from the dolomite rock (DR) itself. Each set consisted of two 200 mm x 100 mm x 50 mm and one 200 mm x 100 mm x 12 mm specimens.

Thermal expansion tests

The specimens of 100 mm x 12 mm x 12 mm were cut from the cylinders made alongwith the fire endurance test specimens. A specimen of same dimensions was also cut from the dolomite rock.

Mass loss tests

The tests required finely ground samples of fine aggregates and concrete.

Typical slab and the associated specimens used in the tests are shown in Figs. 2.3, 2.4 and 2.5.

Fig. 2.3 Typical slab specimens

Fig. 2.4 A set of specimen for thermal conductivity test

Fig. 2.5 Typical specimens for thermal expansion tests

2.1.2 MATERIALS

Dolomite aggregate of maximum size 20 mm was obtained from Standard Industries, Guelph. Petrographic analysis on a sample of this aggregate revealed the presence of more than 99% pure dolomite. A part of this aggregate was crushed to fine size, to meet the grading requirements of fine aggregates, and was used in Set I slabs. The calcareous fines for the Set II slabs was obtained from Spratt Limited, Ottawa. The aggregate was predominantly dolomitic. Petrographic analysis showed it to contain approximately 80% dolomite, 5% calcite and 12-15% silica. A sample of the cement was analysed and the main components are given in Appendix A.1. The thermocouples used were of the type Hg/Hg-24-K. The forms for the slabs and associated specimens were made of plywood.

2.1.3 FABRICATION AND CONDITIONING OF SPECIMENS

Concrete was mixed in a tilting drum mixer. Needle vibrators were used to consolidate the concrete. Slab surfaces were struck off to the desired thickness and finished with wood floats. The associated specimens for thermal property tests and the standard test cylinders were cast along with the slabs. The data on concrete mixes is given in Appendix A.2. The grading of aggregates used in the mix is given in Appendix A.3.

Slab specimens were cured in the forms under damp burlap for 4 days at room temperature. Some of the specimens were then conditioned in air at 23°C and 50% relative humidity until fire tested. Other specimens were conditioned in a dry atmosphere for several weeks before the fire endurance test. The cylinders and the specimens for thermal conductivity tests were conditioned at 100% relative humidity until they were tested.

2.2 THERMAL PROPERTY TESTS

The tests were performed using the instruments at the Division of Building Research, National Research Council of Canada. All the tests were performed on specimens dried in an oven at $105 \pm 0.5^{\circ}\text{C}$ for 24 hours and then, if necessary, kept in this 'reference condition' in a dessicator containing $\text{Mg}(\text{ClO}_4)_2 \cdot 2\text{H}_2\text{O}$ until tested.

2.2.1 SPECIFIC HEAT

A Differential Scanning Calorimeter cell, in conjunction with a plotter, has been used to determine the specific heat values for the samples as a function of temperature. The cross-section of the cell is shown in Fig.2.6. The apparatus is shown in Fig.2.7. The temperature range of operation of the cell is ambient to 600°C . The operations of the cell and the calculations involved in the determination of specific heat values are explained in Ref. [9].

The tests required finely ground samples weighing around 15 to 25 mg. The tests were done on four samples viz., dolomite aggregate, calcareous fines, DF/DC concrete and CF/DC concrete. The concrete samples were obtained by powdering the corresponding cylinder specimens. The specific heat values as a function of temperature, obtained for the four samples, are shown in Fig.2.8.

2.2.2 THERMAL CONDUCTIVITY

A special furnace built for thermal conductivity tests that can be heated from all six sides with provisions for the current to each be adjusted separately, has been used. Fig.2.9 shows the specimen assembly used for the test. The central piece, the test specimen, measured 200 mm x 100 mm x 12 mm and the reference pieces (top and bottom piece)

Fig. 2.6 Differential Scanning Calorimeter Cell cross-section [9]

Fig. 2.7 Apparatus for specific heat and mass loss tests (a) Differential Scanning Calorimeter
(b) Thermogravimetric analyser

Fig.2.8. Specific heat curves as a function of temperature

measured 200 mm x 100 mm x 50 mm. The block diagram of an experimental set-up for thermal conductivity measurements is shown in Fig.2.10. The method involved in the computation of thermal conductivity values, using the test results from the above furnace, is explained in Ref. [19].

A single test specimen was used for the entire temperature interval of interest. The first test was always performed at room temperature. Following this, the temperature was set stepwise at higher and higher temperature intervals. At each temperature the specimen was 'heat-soaked' for atleast 6 hours before the test. During this time the specimen is assumed to have acquired an equilibrium composition corresponding to the given temperature.

The tests were done on three samples viz., dolomite rock, DF/DC concrete and CF/DC concrete. The results of the tests are shown in Fig.2.12. The test results could be obtained only upto a temperature of 600°C due to the difficulty encountered in the attainment of further stable temperatures.

2.2.3 THERMAL EXPANSION

A dilatometer has been used for the determination of linear expansion of the samples, as a function of temperature. The apparatus used is shown in Fig.2.13. The operations and calculations involved are explained in Ref. [21].

The test specimens measured 100 mm x 12 mm x 12 mm. In this test, the temperature of the specimen was raised from the room temperature to 1000°C at a nominal rate of 5°C per minute. With this procedure, the reaction products are not allowed to achieve the chemical equilibrium at any one temperature.

The tests were done on three samples viz., dolomite rock, DF/DC

Fig. 2.9 Specimen assembly for thermal conductivity test [19]

- 1. measuring piece 2. top piece 3. bottom piece
- 4. Platinum foil 5. Inconel clamps 6. Alumel lead wire for foil heating 7. thermocouple wires
- 8. Fiberfrax cover 9. overall Fibrefrax wrapping

Fig. 2.10 Thermal conductivity test apparatus in the Division of Building Research at the National Research Council of Canada

Fig. 2.11 Experimental setup for thermal conductivity test.[19]
 1. Furnace and specimen 2. foil heating 3. measuring output from thermocouples (a) Dewar flask for keeping constant temperature at copper connections (b) dc amplifier (c) 1-mV recorder 4. furnace heating (d) variable transformer (e) resistor switch with globar resistors 5. furnace temperature measurement (f) temperature recorder (g) potentiometer for checking the difference of temperature at top and bottom of specimen.

Fig.2.12 Thermal conductivity curves as a function of temperature

Fig. 2.13 D - Dilatometer

Fig.2.14 Dilatometric curves as a function of temperature

concrete and CF/DC concrete. The dilatometric curves for the three samples are shown in Fig.2.14.

2.2.4 MASS LOSS

A Thermogravimetric analyser, in conjunction with a plotter, has been used to determine the loss of mass in the samples, as a function of temperature. The apparatus is shown in Fig.2.7. The calculation method for the determination of mass loss is explained in Ref. [21].

The test samples were same as that for the specific heat tests. Similar to dilatometric test, in the thermogravimetric analyser the temperature of the specimen was raised from room temperature to 1000°C at a rate of 5°C per minute.

The thermogravimetric curves for the four samples are shown in Fig.2.15.

2.3 FIRE ENDURANCE TESTS

The tests were performed in a furnace built mainly from insulating fire brick (Fig.2.16). Heat was supplied to the test specimen by a stainless steel plate heated by propane gas. The temperature of the plate was controlled in such a way that the average furnace temperature closely followed the standard fire curve specified in ULC-S101 [33].

Temperatures within the furnace were measured as the average of the temperatures indicated by 3 shielded thermocouples located on the steel plate, and 2 shielded thermocouples connected to two iron rods located 300 mm beneath the underside of the slab (Fig.2.17). Unexposed surface temperatures were measured by 3 chromel-alumel thermocouples placed under standard felted asbestos pads located as shown in Fig.2.19. The thermocouples were made of 20-gage chromel-alumel wire.

Fig.2.15 Thermogravimetric curves as a function of temperature

Fig. 2.16 Fire test furnace and the recorder
with the test set-up

Fig. 2.17 Top view of the furnace

Fig. 2.18 Hoisting arrangement to set the slab on the furnace

Fig.2.19a The unexposed surface of the slab indicating the location of asbestos pads.
 1, 2, 3 - asbestos pads 150 x 150 x 10
 Distance $aA = AB = BC = Cc = 292$
 (All the dimensions are in mm)

Fig. 2.19b A View of the Unexposed surface of the slab

Precise furnace temperature control was attained within five minutes from the start of the test. The test furnace was located in a room in which all the doors and windows were kept closed during the tests to minimize the cooling effect of drafts.

The average moisture content in the slab specimen was determined with a sample obtained by horizontally drilling on one side of the slab a hole of 10 mm diameter and extracting the material contained between 50 mm and 100 mm depths.

The specimen was placed in position on the top of the furnace perfectly, with the help of the hoisting arrangements designed for this purpose (Fig. 2.18). The thermocouples from the furnace, within the slab and on the unexposed surface of the slab were then connected to a recorder. All the four sides of the slab were then covered with fiberfrax insulation. The ULC-S101 fire curve was drawn on a time-temperature chart and attached to the recorder. The flow of gas was regulated so that the average temperature indicated by the thermocouples in the furnace adheres to the curve.

The furnace temperature was raised until such time the temperature of the unexposed surface, indicated by the thermocouple B (Fig. 2.19a), reached a temperature of approximately 232°C (450°F). Then gas supply was cut off but the test was continued, to study the behaviour during the decay period of fire, till the temperatures indicated by all the thermocouples showed a decrease.

The fire endurance tests were performed on 15 slab specimens. A minimum of two slabs of a particular thickness were tested in each set of slabs.

The following observations were made during the fire tests:

About 10 minutes after the fire tests were started, moisture

emanation was observed in all the slabs for various lengths of time, depending on the slab thickness, moisture content in the slab at the time of test and concrete type. Most of the moisture evaporated before 20 minutes in 60 mm thick slabs, 45 minutes in 100 mm thick slabs and 90 minutes in 150 mm thick slabs. No changes were noted after that time.

Differential expansion between the exposed and unexposed faces caused the slabs to bow toward the exposed side (heat sink effect). The maximum deflection measured at the centre of unexposed face of 60 mm thick slabs was around 3 mm. The effect was not significant in 100 mm and 150 mm thick slabs.

The observations made after the test include the following:

Hairline cracks, randomly distributed on the exposed side of the slab, were observed clearly in 150 mm thick slabs. Short longitudinal cracks were seen on the four insulated sides in all the slabs.

The fire endurance was determined by the duration of the fire test until the average temperature of the unexposed surface rose 139°C above room temperature. Test fire endurances were adjusted for moistureless and standard moisture condition using the method described in ULC-S101 [33]. The procedure is explained in Appendix B. The fire endurance results are given in Table 2.1.

The temperature distribution in the typical DF/DC and CF/DC type slabs conditioned in the dry atmosphere are shown in Figs. 2.20 to 2.25.

The test results were compared with that of the siliceous concrete slabs (QF/QC type) made of quartz coarse and quartz fine aggregates [25] to establish the bounds of fire resistance in concrete slabs. The test results for the behaviour of siliceous concrete slabs during the decay

period of fire is not available and hence the comparison is restricted to the growth and fully developed period of fire. The curves are shown in Figs. 2.26 to 2.28.

2.4 DISCUSSION OF RESULTS

Thermal properties (Figs. 2.8, 2.12, 2.14, 2.15)

The complex endothermic chemical reactions in dolomite aggregates involved with the vigorous dehydration of cement paste at temperatures around 350°C in the presence of carbonates and the dissociation of carbonate components at temperatures 750°C and 950°C (Appendix D) show a significant influence on the thermal properties of aggregates and concretes tested.

Thermal conductivity and specific heat of dolomite aggregate vary smoothly with increasing temperatures. As the tests were conducted only up to 600°C , due to the reasons mentioned earlier the possible appreciable changes due to the decomposition reactions at still higher temperatures, could not be presented. The curves for the dolomite aggregate show that the thermal conductivity decreases and specific heat increases with increasing temperatures. The aggregate was found to be stable up to 500°C . The decrease in mass observed at temperatures between 500°C and 700°C is attributable to significant thermal expansion and possibly to some solid transformations. The abrupt variation of mass and expansion at temperatures around 700°C is due to the decomposition of carbonates. While the aggregates expand rapidly beyond this temperature, the mass remains almost constant with a slightly decreasing trend. The presence of 12-15% silica in CF aggregate significantly reduces the specific heat values of this aggregate at any instant of temperature as compared to pure dolomite aggregate. The specific heat of CF aggregate has a sudden peak value at about 550°C , characteristic of α - β transformation in quartz:

In dolomite concrete (DF/DC) the thermal conductivity shows the decreasing trend as exhibited by other normal weight concretes. The values are consistently lower as compared to that of dolomite aggregates; owing to the presence of non-evaporable moisture and uninterrupted series of dehydration of cement paste beyond 100°C . The specific heat value attains a sudden peak near 400°C and simultaneously the reduction of mass is initiated. The mass loss indicates the progress of decomposition reactions that are accompanied by significant heat absorptions which increase the specific heat. The concrete exhibit less than 4 per cent mass loss at 500°C . The decomposition reaction accompanied by the superposition of the shrinkage of cement paste matrix may be attributed as reasons for the shrinkage of concrete beyond 750°C . The mass loss and thermal expansion of concretes are significantly less compared to the aggregates tested. The influence of presence of 12 - 15% silica, even though only in fine aggregates, is easily detectable in CF concrete due to the increased thermal conductivity, less mass loss and higher thermal expansion as compared to dolomite concrete.

Fire endurance tests:

The test fire endurance for the dolomite concrete slabs of thickness 60 mm, 100 mm, 150 mm can be averaged to 45 min., 122 min., 270 min. (Table 2.1) respectively. The fire endurance is approximately doubled for every 40 per cent increase in thickness. This approximation holds good also for the adjusted fire endurances shown in Table 2.1. The curves of slab temperatures (Fig. 2.20 to 2.22) show that the unexposed surface temperature increases for a significant time beyond the cut-off point. The exposed surface temperature show an increase for about 40 min., 80 min., and 120 min. beyond

the cut-off time in 60 mm, 100 mm and 150 mm slabs respectively. Only the trend can be concluded from this variation since the temperature of cut-off and the rate of decay of furnace temperature has the influence on the temperatures in the slabs beyond the cut-off point.

The exposed surface temperatures in the slabs are less than 900°C and hence the advantage of the endothermic reaction due to the dissociation of CaCO_3 in the aggregates at 950°C is not realised. Only a narrow surface layer of the slab attained temperatures in excess of 500°C . Hence, the appreciable mass loss beyond this temperature showed by the dolomite concrete has little significance in the overall thermal performance of the dolomite concrete slabs. A comparison of the performance of these slabs with the corresponding CF/DC slabs [Figs. 2.23 to 2.25] show that even with the presence of small percentage of silica, the slab temperatures in 60 mm and 100 mm thick slabs are relatively higher at any instant of time while the trend of variation is similar. The unexposed surface temperatures in CF/DC slabs reached a comparatively higher value before decrease. The behaviour of 60 mm thick slabs in either case is almost same. A comparison again with the performance of quartz (siliceous) concrete slabs [Fig. 2.26 to 2.28] indicate that the endothermic reactions in dolomite concrete has appreciably reduced the slab temperatures. The presence of silica, irrespective of its quantity, hence, increases the slab temperatures. The fire endurance of dolomite concrete slabs are observed to be approximately 40 per cent higher than that of quartz concrete slabs. The curves indicate the bounds of performance exhibited by these slabs.

Table 2.1 Data on the fire endurance of the tested specimens

Specimen type	Slab thickness (mm)	Age at test (days)	Average moisture content (m_a)	Conditioning environment	Test fire endurance (hr:min)	Adjusted fire endurance	
						Standard moisture condition # (hr:min)	Moistureless condition (hr:min)
DF/DC	60	116	0.0100	50% H *	0:46	0:51	0:43
DF/DC	60	117	0.0077	Dry	0:47	0:52	0:45
DF/DC	60	118	0.0098	Dry	0:42	0:47	0:40
DF/DC	60	147	0.0055	Dry	0:43	0:49	0:42
DF/DC	100	120	0.0126	Dry	2:10	2:21	2:02
DF/DC	100	130	0.0128	50% H	2:05	2:15	1:58
DF/DC	100	138	0.0087	Dry	1:51	2:02	1:46
DF/DC	150	131	0.0243	50% H	4:30	4:38	4:13
DF/DC	150	134	0.0151	Dry	4:30	4:45	4:18
CF/DC	60	139	0.0077	Dry	0:40	0:45	0:38
CF/DC	60	135	0.0098	50% H	0:42	0:47	0:39
CF/DC	100	136	0.0090	Dry	1:34	1:44	1:29
CF/DC	100	141	0.0141	50% H	1:36	1:45	1:30
CF/DC	150	140	0.0137	50% H	4:00	4:16	3:50
CF/DC	150	146	0.0120	Dry	3:50	4:06	3:41

* H denotes Humidity.

Adjusted for differences in moisture condition of specimens at the time of test to values that would be appropriate for specimens with mid-depth relative humidity of 50 percent.

Fig.2.20 Slab temperatures as a function of time at various depths [slab type: DF/DC(60)]

Fig.2.21 Slab temperatures as a function of time at various depths [Slab type: DF/DC(100)]

Fig.2.22 Slab temperatures as a function of time at various depths [slab type: DF/DC (150)]

Fig.2.23 Slab temperatures as a function of time at various depths [slab type: CF/DC (60)]

Fig.2.24 Slab temperatures as a function of time at various depths [slab type: CF/DC (100)]

Fig. 2.25 Slab temperatures as a function of time at various depths [slab type: CF/DC (150)]

Fig.2.26 Temperature variation as a function of time at various depths in DF/DC, CF/DC and QF/QC slabs [Slab thickness: 60 mm]

Fig.2.27 Temperature variation as a function of time at various depths in DF/DC, CF/DC, and QF/QC slabs [Slab thickness: 100 mm]

Fig.2.28 Temperature variation as a function of time at various depths in DF/DC, CF/DC and QF/QC slabs [Slab thickness: 150 mm]

CHAPTER 3

THEORETICAL STUDY

The thermal analysis to study the fire response of slabs can be considered as a heat flow problem [22,28]. The three-dimensional heat flow is governed by the following partial differential equation.

$$\begin{aligned} \rho C_p \frac{\partial T(x,y,z,t)}{\partial t} = & \frac{\partial}{\partial x} \left\{ K \frac{\partial T(x,y,z,t)}{\partial x} \right\} + \frac{\partial}{\partial y} \left\{ K \frac{\partial T(x,y,z,t)}{\partial y} \right\} \\ & + \frac{\partial}{\partial z} \left\{ K \frac{\partial T(x,y,z,t)}{\partial z} \right\} + Q_{\text{exo}}(x,y,z,t) \end{aligned} \quad (3.1)$$

where

x, y, z - spatial co-ordinates

t - time

$T(x,y,z,t)$ - temperature history

C_p - specific heat (temperature and space dependent)

K - isotropic conductivity (temperature and space dependent)

Q_{exo} - internal heat generation rate (time and space dependent)

ρ - density (temperature and space dependent)

An integral part of this equation is its boundary conditions and initial conditions. The initial conditions comprise of the temperature of every point in the structure at the start of the analysis, i.e.,

$$T(x,y,z,t_0) = T_0(x,y,z) \quad (3.2)$$

where T_0 is specified. The boundary conditions shall be a specified temperature history or a specified heat flow history. The solution to the heat flow problem is the internal temperature history that

satisfies the field equations (3.1), the initial conditions (3.2) and the prescribed boundary conditions.

3.1 FINITE ELEMENT EQUATIONS

In the finite element method of analysis, the continuum over which the Eq.(3.1) is defined is discretized into a finite number of elements connected at nodal points. The partial differential equation is transformed into a system of simultaneous first order differential equations, one at each node.

The finite element equations can be visualized as nodal heat balance equations, i.e., at each node in the discretization,

$$Q^s + Q^i = Q^e$$

where

- Q^s - rate at which heat is stored within the elements adjacent to the node
- Q^i - rate of internal heat transfer by conduction in the elements adjacent to the node
- Q^e - rate at which heat enters the node from an external source

In the matrix form the equation can be represented as

$$[C] \{\dot{T}\} + [K] \{T\} = \{Q\} \quad (3.3)$$

where

- $[C]$ - capacity matrix (temperature dependent)
- $[K]$ - conductivity matrix (temperature dependent)
- $\{Q\}$ - external heat flow vector (dependent on exothermic reactions and fire boundary conditions)
- $\{T\}$ - temperature vector (time-dependent)
- $\{\dot{T}\}$ - temperature rate of change vector (time dependent)

The external heat flow vector term in the matrix equations (3.3)

can be separated as follows:

$$Q = Q_F + Q_p + Q_E$$

where

Q_F - heat flow due to the exposure of the system to an external fire source on the boundary

Q_p - heat flow prescribed on the boundary

Q_E - heat flow from an exothermic reaction within the system

The term Q_F is considered a function of both convective and radiative mechanisms. If the boundary of the system exposed to fire, represented by $T_f(t)$, is assumed to be composed of surfaces bounding adjacent nodes, the external heat flow for a node can be represented by:

$$Q_F = A_F \cdot q(T_s, T_f)$$

where

A_F - tributary area for the node

q - rate of heat flow per unit area

T_s - surface temperature

T_f - temperature of pseudo-fire

The rate of heat flow q on the surface exposed to fire is given by:

$$q = A(T_f - T_s)^N + V \cdot \sigma (a \epsilon_f \theta_f^4 - \epsilon_s \theta_s^4)$$

where

A - convection coefficient

N - convection power factor

V - radiation view factor

σ - Stefan-Boltzmann constant

a - absorption of surface

ϵ_f - emissivity of flame associated with fire

θ_f - absolute temperature of fire

ϵ_s - surface emissivity

θ_s - absolute temperature of surface

The unknown nodal temperature vector, $\{T\}$, in the matrix equation (3.3) is a function of time, $\{T(t)\}$, and can be solved by step-by-step integration over the time domain.

3.2 FINITE ELEMENT ANALYSIS RESULTS FOR THE TEMPERATURE DISTRIBUTION IN DOLOMITE CONCRETE SLABS

The temperature distribution history in the dolomite concrete slabs was calculated by using the program FIRES-T3. The program was developed in the Department of Civil Engineering, University of California, Berkeley for the CDC 6400 computer [22,28]. The authors have provided evidence on the reliability of the results of the program by using it to solve a variety of problems for which analytical and experimental results are available [22,28,29].

The program had to be modified in order to run it in the Honeywell CP-6 computer of Carleton University.

The finite element mesh chosen for the three dimensional non linear transient analysis of a dolomite concrete slab with a standard asbestos pad at the center of the unexposed surface is shown in Fig.3.1. Only one-quarter of the system was analysed since both the slab and the heated area were symmetrical. The thermal properties determined experimentally were input as a function of temperature. The thermal conductivity, specific heat and density values for the dolomite concrete were assumed constant beyond 600°C. The change in mass of the concrete at any temperature was assumed to be the same as change in density, for calculation purposes. Other data used for the analysis are shown in Table 3.1. In modelling the thermal boundary conditions it was assumed

Fig. 3.1a Sectional plan of the slab system analysed

Fig. 3.1b Sectional elevation of the slab system analysed
(All dimensions are in mm)

Fig. 3.1c Finite element mesh for the three-dimensional analysis

Table 3.1 Additional data used in the thermal analysis

Item	Value assumed
Thermal conductivity of the asbestos pad	$0.001 \text{ Wm}^{-1} \text{ }^{\circ}\text{K}^{-1}$ ($0.0316 \text{ Btu ft}^{-1} \text{ h}^{-1} \text{ }^{\circ}\text{R}^{-1}$)
Specific heat of the asbestos pad	$323 \text{ J Kg}^{-1} \text{ }^{\circ}\text{K}^{-1}$ ($0.25 \text{ Btu lb}^{-1} \text{ }^{\circ}\text{R}^{-1}$)
Density of the asbestos pad	500 Kg m^{-3} (31.2 lb ft^{-3})
Convection power, N	1.25
Convection Factor, A, for the slab [22]	$3.735 \text{ Wm}^{-2} \text{ }^{\circ}\text{K}^{-1.25}$ ($0.27 \text{ Btu ft}^{-2} \text{ h}^{-1} \text{ }^{\circ}\text{R}^{-1.25}$)
Convection Factor, A, for the asbestos pad [24]	$2.49 \text{ Wm}^{-2} \text{ }^{\circ}\text{K}^{-1.25}$ ($0.18 \text{ Btu ft}^{-2} \text{ h}^{-1} \text{ }^{\circ}\text{R}^{-1.25}$)
Stefan-Boltzmann constant	$5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ }^{\circ}\text{K}^{-4}$ ($0.1713 \times 10^{-8} \text{ Btu h}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{R}^{-4}$)

that the ULC-S101 standard fire would act on the bottom surface of the slab with the fire emissivity of 0.6, that corresponds to the fire emissivity attained in the furnace used in the experimental study. A value of 0.9 was used for concrete emissivity. The ambient air at the boundaries on the unexposed surface was modelled as a pseudo fire at a constant temperature of 20°C with an effective emissivity of 1.0.

The choice of mesh was based on past recommendations [22,28, 29,37]. The mesh size and the time-step size during the time integration had to be so chosen that acceptable results can be obtained with minimum computer storage and run time. Time-step size was kept quite small in order to ensure convergence of an iterative solution and avoid the numeric instability in the region of fire surface at high temperatures. For the ULC-S101 fire, 120 time steps were needed for a two hour analysis. The three dimensional analysis consumed a maximum of 36 minutes of central processing time.

The temperature distribution across the centroidal cross-section of 60 mm, 100 mm, and 150 mm dolomite concrete slabs were obtained from the analyses and the results are shown in Figs. 3.2 to 3.4. The exposed, mid-depth and the unexposed surface temperatures as a function of time for the above three slabs obtained from the finite element analysis are compared with that from experiments, in Figs. 3.5 to 3.7.

A 100 mm thick dolomite concrete slab was chosen to study the influence of fire emissivity on the temperature distribution in slabs. The analysis was carried out for three fire emissivities viz. 0.4, 0.6, 0.8. The temperature distribution as a function of time at various depths in the slab for the different emissivities are shown in Fig. 3.8.

A two-dimensional analysis was done for a 150 mm thick slab with a finer mesh across the depth (Fig. 3.9) for comparing the temperature distribution results across the centroidal cross-section obtained with a three-dimensional analysis. In this case the asbestos pad was assumed to spread along the entire width. The results were fairly close as shown in Fig. 3.10. The analysis consumed 3.2 minutes of central processing time.

3.3 DISCUSSION OF RESULTS

The temperature distribution in slabs, shown in Figs. 3.2 to 3.4 indicate that the temperature variation near the exposed surface is steep and gradually decrease at higher depths. Further, for the same interval of time, the area under two successive temperature distribution curves decrease with the increase in time.

From the temperature distribution results, the depth at which critical steel temperatures (593°C for reinforcing steel and 427°C for prestressing steel) are attained when the surface temperature increases by 139°C are determined. By providing the steel with a concrete cover that is at least equal in thickness to this depth, the attainment of steel temperatures in excess of the critical temperatures can be prevented. The minimum clear cover thickness for reinforcing and prestressing steels required in dolomite concrete slabs thus calculated are shown in Fig. 3.11.

The theoretical results of time-temperature variation in dolomite concrete slabs compared well, as revealed from Figs. 3.5 to 3.7. Hence, the thermal data used in the thermal analysis can be considered to represent the dolomite concrete in the theoretical analyses. The assumption of constant diffusivity for the concrete, beyond 600°C has little

influence on the fire endurance characteristics of these slabs. The influence of the fire emissivity value on the fire endurance behaviour is small provided it is not exceptionally low, as can be seen in Fig. 3.8.

Fig. 3.2 Temperature distribution across the centroidal cross-section of a DF/DC (60) slab

Fig. 3.3 Temperature distribution across the centroidal cross-section of a DF/DC (100) slab

Fig. 3.4 Temperature distribution across the centroidal cross-section of a DF/DC (150) slab

Fig. 3.5 Exposed surface temperatures as a function of time in DF/DC slabs

Fig. 3.6 Mid-depth temperatures as a function of time in DF/DC slabs

Fig. 3.7 Unexposed surface temperatures as a function of time in DF/DC slabs

Fig. 3.8 Influence of emissivity on slab temperatures as a function of time at various depths [slab type: DF/DC (100)]

Fig. 3.9 Finite element mesh for the two-dimensional analysis (All dimensions are in mm)

Fig. 3.10 Comparison of slab temperatures obtained from three-dimensional and two-dimensional analysis [slab type: DF/DC (150)]

Fig. 3.11 Minimum clear cover thickness to reinforcing and prestressing steels in DF/DC slabs for different fire ratings

CHAPTER 4

SUMMARY AND CONCLUSIONS

The thesis presents the results of the investigation on the fire endurance behaviour of concrete slabs with dolomite aggregates. The test results are compared with those obtained from the slabs that contained 12 - 15% silica only in fine aggregates and the other that contained completely siliceous aggregates. The comparison showed the influence of siliceous content on the fire endurance characteristics of the slabs. The thermal properties were determined by tests and the results are used to theoretically obtain the time-temperature relationships and the temperature distribution in dolomite concrete slabs. The concrete cover requirements for reinforcing and prestressing steels in dolomite concrete slabs are computed with the temperature distribution results.

The following conclusions are made from the study:

- (i) The chemical behaviour of dolomite at high temperatures has significant influence on the fire endurance behaviour of the dolomite concrete slabs. The endothermic reactions up to 800°C reduce the slab temperatures and increase the fire endurance.
- (ii) Based on the heat transmission end point criteria the dolomite concrete slabs of thickness 60 mm, 100 mm and 150 mm exhibited a fire endurance of 50 min., 130 min., and 280 min. respectively, corresponding to standard moisture condition in the slab specimens. The fire endurance doubled for every 40 per cent increase in thickness.

- (iii) The unexposed surface temperatures show an increase for a considerable period beyond the time of cut off of fire.
- (iv) The concrete cover requirements for reinforcing and pre-stressing steels in the dolomite concrete slabs, from thermal criteria, is of importance only if the required fire rating is higher than 1 hour.
- (v) The dolomite concrete slabs exhibit about 40 per cent higher fire endurance than the siliceous (quartz) concrete slabs. The curves of slab temperatures provide the information on the bounds of thermal performance of the concrete slabs exposed for fire.
- (vi) The presence of even a small percentage of silica in the midst of dolomite aggregates show a decrease in the fire endurance. It also influences the thermal properties of concrete. The presence of silica increase the thermal conductivity, decrease the specific heat, lessen the mass loss and increase the expansion, as compared to the performance by dolomite concrete.
- (vii) The fire endurance of dolomite concrete slabs can be predicted within 5 per cent deviation using the theoretical analysis. The distribution of temperature across the depth of the slab obtained with the theoretical analysis correlate with the experimental results. The thermal property values as determined by the experiments, with the assumption of constant diffusivity beyond 600°C , and the related data given in the text (Table 3.1) predict very well the temperature distribution in dolomite concrete slabs, provided the

fire emissivity is not too low. The data shall be used to theoretically determine the temperature distribution in other dolomite concrete components subjected to fire..

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APPENDIX A/

Appendix A.1

Grading of aggregates in the concrete mixes

Sieve size	Percentage passing		
	Dolomite (*)		Calcareous fine (**)
	Coarse	Fine	
19 mm (3/4")	91	-	-
9.5 mm (3/8")	30	-	-
4.75 mm (No. 4)	-	100	100
2.36 mm (No. 8)	-	100	90
1.18 mm (No. 16)	-	75	52
600- μ m (No. 30)	-	30	39
300- μ m (No. 50)	-	16	16
150- μ m (No. 100)	-	2	2

(*) from Standard Industries, Guelph.

(**) from Spratt Limited, Ottawa.

Appendix A.2Composition of cement used in tests

Composition	Weight percentage
<hr/>	
Si O ₂	21.59
Al ₂ O ₃	4.27
Fe ₂ O ₃	2.25
Ca O	63.83
Mg O	2.72
S O ₃	2.96
Na ₂ O	0.34
K ₂ O	1.01
Ti O ₂	0.16
P ₂ O ₅	0.12
Sr O	0.14

Appendix A.3Concrete Mix Data

Item	Concrete type	
	DF/DC	CF/DC
Mix proportion (by volume)	1:2.36:3.54	1:2.36:3.54
Water-cement ratio	0.55	0.52
Average slump (mm)	80	105
Average comp- ressive strength at 28 days (MPa)	23.6	30.7
Average oven- dry unit weight (kg/m ³)	2140	2240

APPENDIX B

Description of the method to determine
the fire endurance for different moisture
conditions in fire test specimens

The adjusted fire endurance of the test specimens for the standard moisture condition and moistureless condition are determined as follows. The DF/DC (60) slab that exhibited a fire endurance of 47 minutes in the test is chosen as an example. The average moisture content in the test specimen at the time of test (m_a) was 0.01 or 1.0%. The standard moisture content is given by $m_s = vA(m_e)_{50}$, where v = volume fraction of the cement paste in the mix, A = Drying correction constant for the conditioning environment and $(m_e)_{50}$ = moisture content in the sample for an equilibrium relative humidity of 50 per cent at the mid depth of the slab. The values of A and $(m_e)_{50}$ are obtained from the Tables B.1 and B.3. For the slab considered; $v = 0.231$, $A = 1$ and $(m_e)_{50} = 0.175$. Hence, $m_s = 0.231 \times 1 \times 0.175 = 0.0405$.

Correction procedure

An empirical factor b , for the material is obtained from Table B-2, and bm_a and bm_s are calculated. On the nomogram (Fig.B-1) lines are drawn from point R to the right-hand ordinate values of bm_a and bm_s (points A and S respectively). From the test fire endurance value of the specimen, a line is drawn parallel to RA to intersect the curve. From this point on the curve, a line is drawn parallel to RS to obtain the adjusted fire endurance for the standard moisture condition, on the left-hand ordinate. From the same point on the curve a horizontal line is drawn and the adjusted fire endurance corresponding to moistureless condition can be read on the left-hand ordinate.

For the slab considered $bm_a = 5.5 \times 0.01 = 0.055$ and $bm_s = 5.5 \times 0.0405 = 0.222$. Using the above procedure the fire endurance corresponding to standard moisture condition is 51 min and corresponding to moistureless condition is 43 min. The method is 11-

illustrated in the nomogram (Fig. B.1), where T is the test fire endurance, S is the fire endurance corresponding to the standard moisture condition and M is the fire endurance corresponding to the moistureless condition.

TABLE B-1. Drying Correction Constants [33,34]

Conditioning environment	Specimen RH at test, percent	A for portland cement in	
		normal-weight concrete	lightweight concrete
60 to 80°F atmospheric conditions	any	1.0	1.0
120 to 160°F 20 to 35% RH	70-75	0.7	0.7
190 to 200°F 0 to 5% RH	70-75	0.45	0
120 to 200°F 5 to 35% RH	less than 70	0	0

TABLE B-2. Permeability Correction Factors [33,34]

Material	b
Normal-weight and gun-applied concrete	5.5
Structural lightweight concrete	8.0
Lightweight insulating concrete	10.0

TABLE B-3. Moisture Content at Given Relative Humidity of Sample [33,34]

Equilibrium RH at middepth, percent	m_e
90	0.30
85	0.275
80	0.255
75	0.24
70	0.225
65	0.21
60	0.195
55	0.185
50	0.175
45	0.16
40	0.15

Fig. B.1 Nomogram for calculating the effect of moisture on fire endurance [18, 33, 34]

APPENDIX C

Flow charts for Programs FIRES-T3 [22]

Fig. C.1 Flow chart for Program FIRES-T3 [22]
(Titles in paranthesis are names of subroutines)

Fig. C.2 Flow chart for subroutine HEATFLO [22]
(Titles in paranthesis are names of subroutines)

APPENDIX D
FACTS ABOUT DOLOMITE

DOLOMITE

Colour: Colourless or white, tinged with yellow or brown;
colourless in thin section.

Metamorphic paragenesis: The molecular percentage ratio of the components in the mineral dolomite is shown along with quartz, calcite and magnesite in the table below.

Mineral	Formula	Molecular percentage ratio		
		SiO ₂	CaO	MgO
Quartz	SiO ₂	100	0	0
Calcite (limestone)	CaCO ₃ = CaO.CO ₂	0	100	0
Magnesite	MgCO ₃ = MgO.CO ₂	0	0	100
Dolomite	CaMg(CO ₃) ₂ = CaO.MgO.(CO ₂) ₂	0	50	50

Chemistry: The thermal dissociation takes place in two steps, firstly, $\text{Ca Mg}(\text{CO}_3)_2 \rightarrow \text{CaCO}_3 + \text{MgO} + \text{CO}_2$ at around 750°C, followed by the breakdown of calcite component, $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ at around 950°C. Both these reactions are endothermic. Complex endothermic reactions also occur at temperatures around 350°C due to the vigorous dehydration of cement paste in the presence of dolomite aggregates.

APPENDIX E

CONVERSION TABLE

(The units according to Systeme International d'Unites are marked (SI))

QUANTITY	MULTIPLY	BY	TO OBTAIN
Area	m^2 (SI)	10.8	ft^2
	cm^2	0.155	in^2
Coefficient of expansion (linear)	m/mK (SI)	0.556	$in/in^\circ F$
	$m/m^\circ C$	0.556	$in/in^\circ F$
Coefficient of expansion (cubic)	$m^3/m^3 K$ (SI)	0.556	$in^3/in^3^\circ F$
	$m^3/m^3^\circ C$	0.556	$in^3/in^3^\circ F$
Coefficient of heat transfer	$W/m^2 K$ (SI)	0.176	$Btu/ft^2 h^\circ F$
Density	kg/m^3 (SI)	6.24×10^{-2}	lb/ft^3
	g/cm^3	62.4	lb/ft^3
Flux	W (SI)	0.948	Btu/s
Force	N (SI)	0.225	lbf
	N (SI)	0.102	kgf
	kgf	2.205	lbf
Intensity (heat)	W/m^2 (SI)	0.317	$Btu/ft^2 h$
Length	m (SI)	3.281	ft
	cm	0.394	in
Mass	kg (SI)	2.205	lb
Rate of burning	kg/s (SI)	7.938×10^3	lb/h

QUANTITY	MULTIPLY	BY	TO OBTAIN
Specific heat	J/kgK(SI)	2.39×10^{-4}	Btu/lb°F
Specific heat (volumetric)	J/m ³ K(SI)	1.49×10^{-5}	Btu/ft ³ °F
Stress	MPa (SI)	145.03	lbf/in ²
Temperature	K(SI)	°C = K - 273.15	°C
	K(SI)	°F = 1.8K - 459.67	°F
	K(SI)	°R = 1.8 K	°R
	°C	°F = 1.8 °C + 32	°F
Thermal capacity	J/K(SI)	5.267×10^{-4}	Btu/°F
Thermal conductivity	W/mK(SI)	0.578	Btu/ft h °F
Thermal diffusivity	m ² /s (SI)	3.875×10^{-4}	ft ² /h
Volume	m ³ (SI)	35.3	ft ³
Weight	N(SI)	0.225	lbf
	N(SI)	0.102	kgf
	kgf	2.205	lbf

APPENDIX - F

GLOSSARY OF TERMS

ABSORPTIVITY - the fraction of the incident radiation that is absorbed by an object on which it falls.

CARBONATE AGGREGATE CONCRETE - concrete made with aggregates consisting mainly of calcium and/or magnesium carbonate, e.g., limestone, dolomite.

COEFFICIENT OF HEAT TRANSFER - amount of heat transferred to an object per unit area of the object, unit time and unit temperature difference between the exposing medium and object.

COEFFICIENT OF THERMAL EXPANSION (LINEAR) - the expansion of length per unit length per degree rise of temperature.

COEFFICIENT OF THERMAL EXPANSION (CUBIC) - the expansion of volume per unit volume per degree rise of temperature.

CONDUCTION (OF HEAT) - transfer of heat through a solid material from warmer to colder regions.

CONVECTION (OF HEAT) - transfer of heat by movement of a gas or liquid.

EMISSIVITY - the ratio of the intensity of radiation emitted by a surface to that by a black body of the same temperature.

FIRE ENDURANCE - a measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings it shall be measured by the methods and to the criteria defined in ULC-S101.

FIRE RESISTANCE - the property of a material or assembly to withstand fire or to give protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a given structural function or both.

FIRE RESISTANCE RATING - a legal term defined in building codes, usually based on fire endurances.

HEAT FLUX - amount of heat passing through an area per unit time.

HEAT TRANSFER COEFFICIENT - see coefficient of heat transfer.

LIGHTWEIGHT AGGREGATE CONCRETE - concrete made with aggregates of expanded clay, shale, slag, or slate or sintered fly ash, and weighing about 1300 kg/m³ to 1800 kg/m³.

MODULUS OF ELASTICITY - measure of elastic deformation, defined as the stress which would produce a unit strain.

NORMAL WEIGHT CONCRETE - any concrete made with natural aggregates, cement and water having a unit weight of about 2200 kg/m^3 to 2500 kg/m^3 .

SILICEOUS AGGREGATE CONCRETE - concrete made with aggregates consisting mainly of silica.

SPECIFIC HEAT (MASS) - the heat necessary to raise the temperature of unit mass one degree.

SPECIFIC HEAT (VOLUMETRIC) - the heat necessary to raise the temperature of unit volume one degree.

STANDARD FIRE CURVE - a standard time-temperature relation, usually used as heating curve for investigating the behaviour of structural elements in fire.

THERMAL CAPACITY - the heat necessary to raise the temperature of a given mass one degree.

THERMAL CONDUCTIVITY - the ability of a material to conduct heat.

THERMAL DIFFUSIVITY - a quantity that determines the rate of rise of temperature in a material at points away from the exposed surface. It is equal to the thermal conductivity divided by the product of the specific heat and density.

END

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