ALEXANDRIA UNIVERSITY
FACULTY OF ENGINEERING

THERMAL PERFORMANCE OF RC COLUMNS STRENTGHNED WITH CFRP AT ELEVATED TEMPRATURE

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ABSTRACT

One of the main problems that inhibit the widespread of using FRP in constructions fields is the problem concerning the elevated temperature and fire resistance for FRP strengthening system, if FRP strengthening system isn't properly protected it will be totally lost when exposed to temperature above the glass transition temperature of the epoxy resin (*T*g) which for most commercially available epoxy resins varies from 60^{o}c to 100^{o}c. Accordingly special thermal and fire protection consideration must be included as an essential and integral part of the design of FRP strengthening works.

This research addresses the structural effectiveness and thermal endurance of R.C. columns confined by CFRP and subjected to elevated temperature; nine different insulating materials have been tested to protect CFRP sheets and its epoxy resin. An experimental program has been conducted to investigate the effect of different temperature levels "below100^{o}c, 100^{o}c, 200^{o}c, 250^{o}c, 300^{o}c, and at 350^{o}c" and durations "4, 8, 12, and 24 hours" on the structural performance of R.C. square columns. Subsequently, evaluate the effectiveness of different thermal protection materials in increasing the thermal endurance and decrease the heat transfer rate to reach CFRP surface. A total of 19 R.C. square columns were tested thermally using an electric furnace which constructed to serve this experimental program, it has special specifications for this specific purpose, and it is designed to have ultimate temperature equal 1000^{o}c, subsequently, tested after being cold under a monotonic axial compression load to measure its residual capacity.

Based on experimental evidence, the use of thermal insulating material improves the thermal endurance effectiveness for the insulated columns but to different extents depend on the used insulating material thermal properties and their moisture content. This beneficial effect was tremendous with respect to granular insulating material rather than fibrous insulating materials. According to the structural effectiveness, no significance deterioration in the CFRP confinement effectiveness occurs for exposure to constant temperature 100^{o}c until 24 hours. While at 200^{o}c the CFRP confinement effectiveness depended mainly on the exposure duration, it lost only 13 % for exposure for 4 hours, and 20 %, 24.6 %, and 33.3 % for 8, 12, and 24 hours respectively. On the other hand, no significant loss of column ductility has been measured at this temperature level. Results also indicate that, there is a large difference between the loss in CFRP effectiveness when exposed to 300^{o}c for 4 hours and 8hours, as it lose 42 % of its load capacity while it loss all of the confinement effectiveness at 8 hours. All columns tested at 350^{o}c lose all of the CFRP confinement

effectives and their failure mode govern by de-bonding between the CFRP sheets and concrete surface. This finding may seriously be considered for columns confined by CFRP and subjected to fire temperature.

The research developed a finite element thermal model conducted on insulated square R.C. columns confined by CFRP sheets and subjected to elevated temperature. The model simulates the transient heat transfer through different insulating material in accordance to the furnace heating rate. The ultimate goal of the research is to provide design recommendations and guidelines that can be suggested for protecting R.C. confined by CFRP using different insulating materials according to the standard fire. Moreover, model predicts the temperature distribution at different interfaces of the insulating material and concrete specimen accurately. The thermal endurance for each insulating material has been validated with the experimental program. On the other hand, the model have been developed to simulate the rate of heat transfer through insulating material in accordance with the standard fire curve, this leads us to compute the fire endurance and the critical time that the insulated CFRP confining system can be affected by fire exposures. For further validation of the model, it was compared to results reported in other research studies. Comparing with all available published test results to date the correlation between the predicted and measured temperature is fairly accurate for the entire time-temperature history. Finally, employing the validated FEM approach, a parametric study is carried out to predict the effect of insulation thickness on their fire endurance.

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TABLE OF CONTENTS

CHAPTER 3

EXPERIMENTAL PROGRAM

CHAPTER 4

EXPERMENTAL RESULTS

CHAPTER 5

ANALYTICAL APPROACH

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIOS

LIST OF ILLUSTRATIONS

Figure **Page**

Chapter 1

Chapter 2

Chapter3

Chapter4

CHAPTER 5

LIST OF TABLES

NOTATIONS

Tg	Glass transition temperature
k	Thermal Conductivity W/m.k
t_f	Thickness of one layer of FRP
f	Strength of FRP,
ε_f	Maximum strain at failure for FRP
E_f	Modulus of elasticity of FRP
q	Heat transfer rate
$\frac{\partial T}{\partial x}$	Temperature gradient in the direction of heat flow
c_p	Specific Heat
α	Thermal Diffusivity
erf	Gauss error function
x	Insulation thickness
T_i	Initial temperature
T	Temperature beneath the insulation material
t	Time in hours
T_f	Fire temperature in °c
f	Reinforced Concrete Column Strength
f_{cu}	Concrete Characteristics Compressive Strength
$\varepsilon_{t,cu}$	The maximum transverse strain measured at failure
$\varepsilon_{t,co}$	The maximum strain for the control specimen

ACRONYMS AND ABBREVIATONS

ACI	American Concrete Institution
AFRP	Aramid Fiber Reinforced Polymer
ASTM	American Standard for Testing and Material
CFRP	Carbon Fiber Reinforced Polymer
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
RC	Reinforced Concrete
PC	Plain Concrete
ASTM E 119	Standard Fire Curve
CAN/ULC	Underwriters Laboratories of Canada / Inspection and Testing of Fire Alarm Systems

CHAPTER 1
INTRODUCTION

1 - 1 GENERAL

The effect of elevated temperature on the properties of reinforced concrete elements was investigated many years ago[1-9]. It was found that the concrete strength and its modulus of elasticity were badly affected by the rise in temperature. The concrete may loose the bond stress with the reinforcement steel due to the difference in the coefficient of steel and concrete. Some physical changes occur inside the concrete, such as the pressure induced by the moisture inside the concrete core may cause the concrete crushing or the aggregate to spall out.

The repair and strengthening of concrete structures is a challenging and growing segment of the concrete repair industry for both engineers and contractors. Several studies have been conducted to investigate the axial behavior of concrete columns confined with CFRP jackets[10-21]. These studies have all indicated that CFRP jackets enhance the compressive strength and axial strain of confined concrete by providing adequate lateral confining pressure to the column. On the other hand, the most commonly asked question about the use of FRP for strengthening is, quite rightly, "*How does it perform at elevated temperature and fire?*"

One of the main problems that inhibit the widespread of using FRP in constructions fields is the problem concerning the elevated temperature and fire resistance for FRP strengthening system, if FRP strengthening system isn't properly protected it will be totally lost when exposed to temperature above the glass transition temperature of the epoxy resin (Tg) which for most commercially available epoxy resins varies from 60^{o}c to 100^{o}c, Accordingly special thermal and fire protection consideration must be included as an essential and integral part of the design of FRP strengthening works[22]. Many types of fire protective insulating materials are available either granular material like Gypsum, Thermal concrete, and Perlite, etc. or fibrous material like Rock wool and Ceramic fibers. Also, other chemical bases of fire protective coating are available in some chemical companies.

1 - 2 FRP MATERIALS UNDER ELEVATED TEMPERATURES

Widespread deterioration of infrastructure resulting from corrosion of reinforcing steel in concrete has led recently to the use of fiber reinforced polymer (FRP) in a number of infrastructure applications. However, the performance of FRP materials in fire remains a serious concern, which needs to be addressed before these materials can be used with confidence in applications where fire endurance is a design criterion (i.e. buildings, parking garages, etc.)[23].

FRP materials are sensitive at elevated temperatures. As the temperature of the polymer matrix approaches its glass transition temperature "*T*g", it transforms to a soft material with reduced strength and stiffness, common room-temperature cures thermoset polymer matrices used in FRP strengthening of concrete structures, exhibit glass transition temperatures below 100°c. Under extreme heat, the polymer matrix may ignite, spread flames and produce toxic smoke

Figure (1.1) shows the approximate variation of ultimate tensile strength with temperature for aramid, glass and carbon FRPs, For FRP-strengthened RC members, where the FRP materials are typically bonded to the exterior of the RC structural members, no concrete cover is available for protection of the FRP reinforcement, and thus unprotected wraps can be expected to experience rapid degradation of structural effectiveness almost immediately under exposure to a fire. However, because FRP materials are not usually used as primary reinforcement, loss of FRP effectiveness during a fire may or may not be critical to ensure structural fire safety [24].

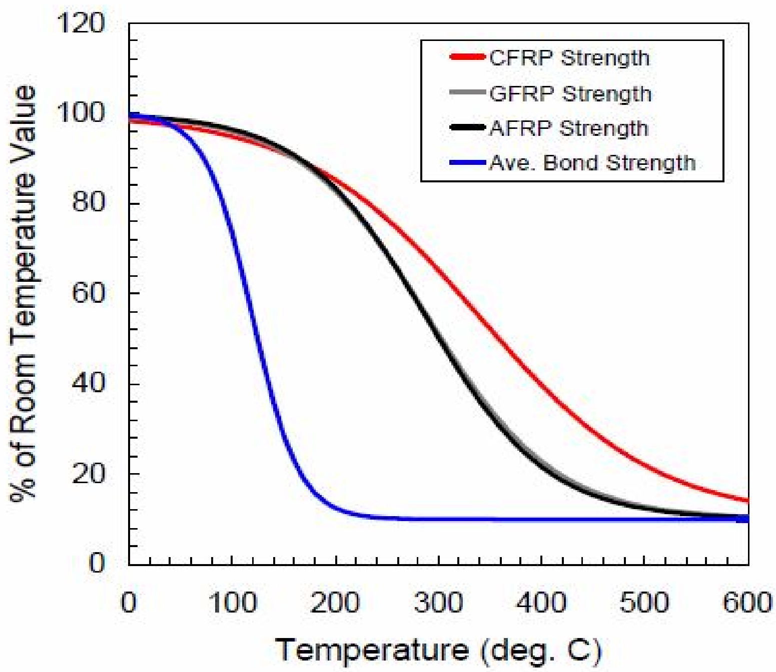

Fig. 1.1 FRP (Carbon, Glass and Aramid) properties at high temperature - FRP strength and bond strength to concrete

Structural fire endurance modeling requires a detailed understanding of material behavior at high temperatures. However, information on the deterioration of mechanical properties of FRP is extremely scarce, and a great deal of further research is required to fill all the gaps in knowledge. The properties that are of interest for structural and insulating materials can be divided into two broad categories: thermal and mechanical. Important thermal properties include: thermal conductivity, specific heat, emmissivity, and density; while mechanical properties include: thermal expansion, creep, and stress-strain behavior. It should be noted that conventional infrastructure materials such as steel and concrete do not combust, and hence will not contribute fuel to a fire, evolve toxic gases, or generate smoke. This is not typically true in the case of FRP, most of which are combustible. Figure (1.2) shows the rapid deterioration in FRP materials strength with increasing the temperature compared to steel, concrete[24].

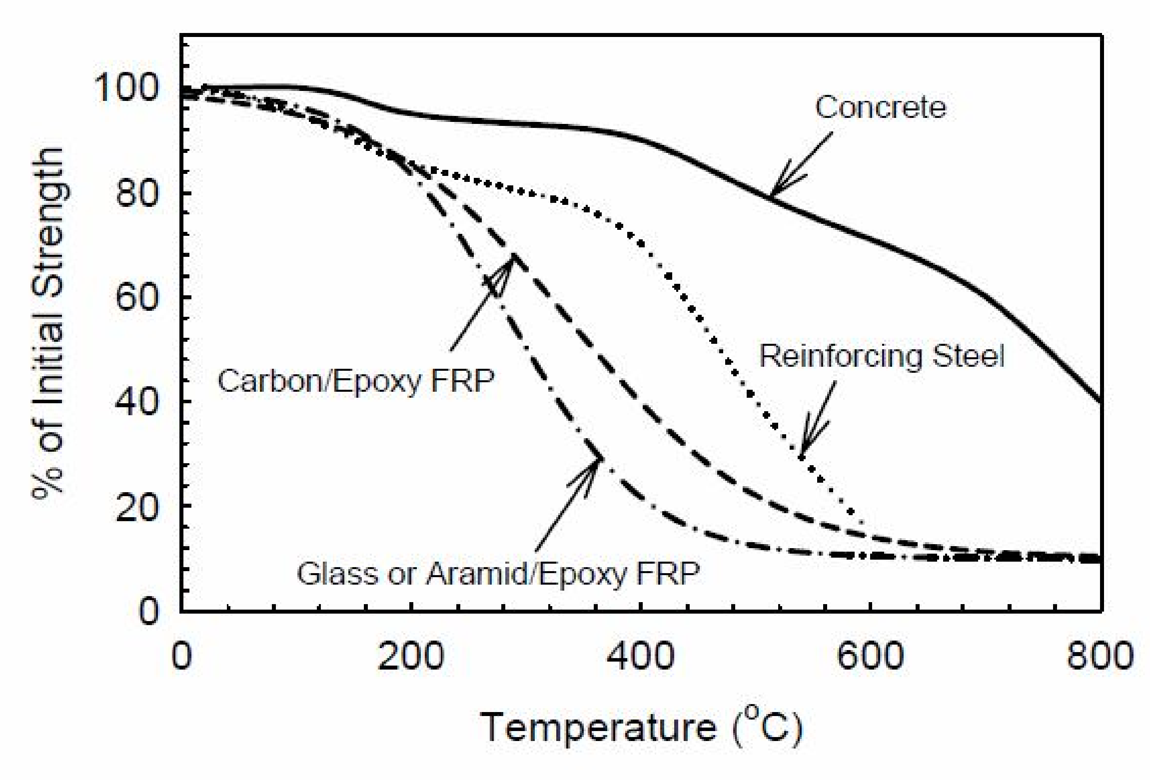

Fig. 1.2 Variation of strength with temperature for CFRP, GFRP, concrete, and steel

1-3 FIRE ENDURANCE

In considering the fire performance of FRP-wrapped RC columns, it is important to first outline what is implied by "fire endurance". The fire endurance (fire resistance) of structural members is defined by ASTM E119[25] or CAN/ULC S101[26]. For reinforced concrete columns, the only structural requirement to achieve satisfactory fire endurance is that they must be able to carry their full service load for the required duration during fire. The required duration (fire rating) is generally between 2 and 4 hours and depends on a variety of factors such as the building size and occupancy, applied load, member type, dimensions, fire intensity, and the materials involved.. Under current fire testing and design guidelines there is no explicit requirement that the FRP temperature to remain below some specified value (e.g. the matrix glass transition temperature (GTT)) [27]

The fire endurance of RC columns has traditionally been defined in terms of their load-carrying capacity during exposure to a standard fire. The standard fire is defined by ASTM E119[25] as shown in figure (1.3). This curve can be approximately expressed using the following equation:

$$T_f = 20 + 750\left(1 - e^{-3.79533\sqrt{t}}\right) + 170.41\sqrt{t}$$

Where: t = time in hours
T_f = Fire temperature in °C

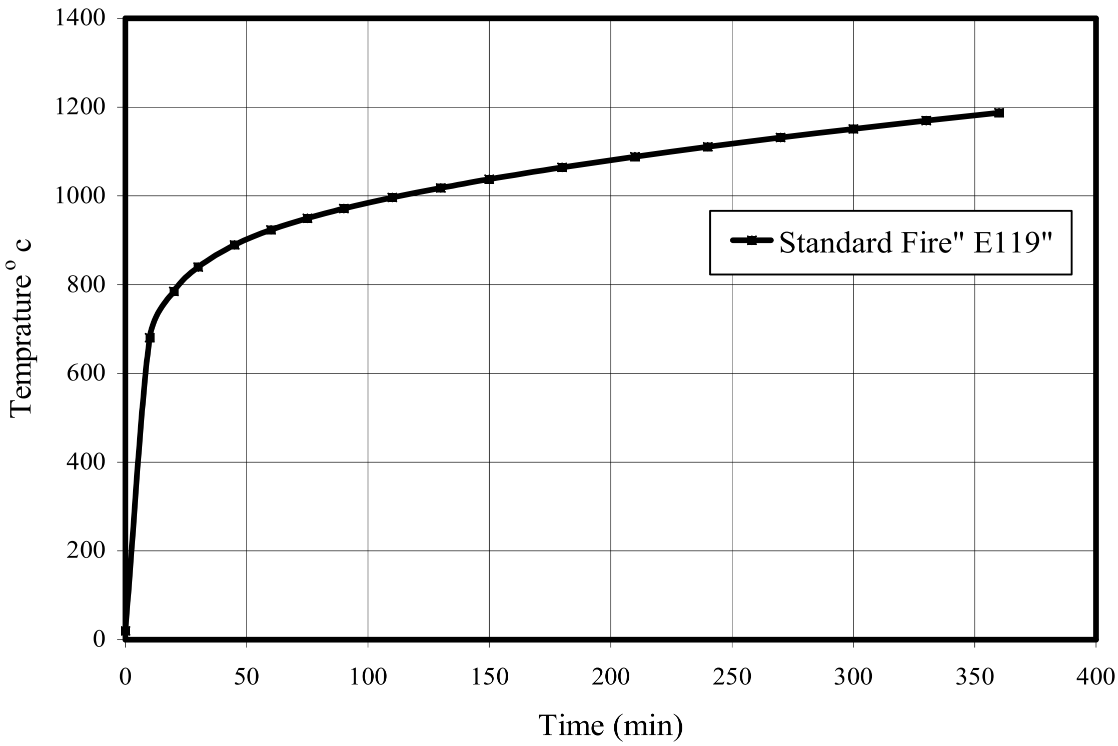

Fig. 1.3 Standard Fire Curve according to ASTM E119

1-4 PROBLEM DEFINITION

FRP materials are very sensitive to elevated temperature and experience severe deterioration in strength, stiffness, and bond properties at elevated temperature. Very little information is currently available in this area, and concern associated with elevated temperature must be studied before FRP wrapped columns can be used with confidence in most buildings. This gap of knowledge is primary factor preventing the widespread application of FRP.

ACI 440 2R-02[28] states that no information is currently available on the specific behavior of the bond between unprotected externally FRP materials and concrete at high temperatures. The bond will likely be lost very quickly under fire exposure. For insulated FRP systems, it is not clear exactly how long the bond between the externally bonded FRP and substrate can be maintained during fire (Fire Endurance), the thermal effectiveness and thickness of the insulation, and various other factors in the thermal properties for the insulating material, in addition, post-fire residual behavior of these systems is unknown and need further research.

Full-scale fire tests are relatively time consuming and costly to perform, and while other current study includes experimental tests on insulated FRP-wrapped RC columns, it was desired to develop analytical models that could be verified based on the test results and subsequently used to conduct parametric studies to investigate the effects of a number of column parameters on column behavior in fire. Once validated, the models can also be used to provide design guidance to engineers wishing to implement FRP strengthening applications in buildings.

1-5 OBJECTIVES AND SCOPE OF INVESTIGATION

The main objective of this investigation is to determine the effect of various experimental parameters on the performance of square R.C. columns confined by one layer of carbon fiber-reinforced polymer (CFRP) under elevated temperature and what level of heat exposure and time duration requires replacing the system, and how effective are the available fire proofing system to prevent heat damage.. Special attention was given to find a proper treatment for the elevated temperature problem associated with CFRP confined R.C. column; using varies kinds of insulating materials, measure of their thermal endurance at different temperature levels and for what extent the used insulating can decrease the rate of heat transfer to the CFRP surface.

Transient thermal finite element analyses are used to determine the temperature distribution on the column cross section, thermal gradient across the insulation material thickness, heat flow through insulating material and concrete, and other such thermal quantities in the columns. Moreover, the model has provided a wealth of useful information on the important factors to consider in designing fire protection material and their proper thickness for fire insulating the FRP strengthened columns. The validity of the model was first verified by comparing the FEM prediction for time- temperature curves to the measured values obtained in the experimental study and other studies according to the furnace heating rate and the standard fire curve for heating.

1-6 THESIS ORGANIZATION

The thesis consists of six Chapters outlined as follows:

Chapter 1 an introductory chapter.
Chapter 2 summarizes existing literature on the following tittles:

- Effect of elevated temperature on reinforced concrete.
- Fire endurance test on R.C. members.
- FRP properties at elevated temperature.
- Fire endurance tests on R.C. structures strengthened by FRP bars or external sheets
- Effect of elevated temperature on R.C. columns confined by FRP
- Thermal insulation

Chapter 3 describes in detail the experimental program undertaken in this study, including a description of the specimens and the manner in which they were constructed, instrumented and tested.

Chapter 4 presents the structural and thermal results of the testing program.

Chapter 5 includes the analytical model to simulate the transient heat transfer through different insulating material in accordance to the furnace heating rate and predicts the temperature distribution at different interfaces of the insulating material and concrete specimen accurately. Lastly, a parametric study is carried out to predict the effect of insulation thickness on their fire endurance.

Chapter 6 presents the main conclusions and recommendation developed through this study.

CHAPTER 2
LITERATURE REVIEW

2-1 GENERAL

In recent years, the construction industry has shown significant interest in the use of fiber reinforced polymer (FRP) materials for reinforcement and strengthening of concrete structures. This interest can be attributed to the numerous advantages that FRP materials offer over conventional materials such as concrete and steel. One particularly successful use of FRPs in structural engineering applications involves repair and rehabilitation of existing reinforced concrete structures by bonding carbon/epoxy or glass/epoxy FRP strengthening systems to the exterior of reinforced concrete members. Moreover, effective application of FRP materials is circumferential wrapping (confinement) of R.C. columns, which have been shown to increase strength and ductility of this members[10-21]. Design recommendation are now available for repair and upgrade of concrete columns with FRP wraps, and this technique has been used in hundreds of field application around the world[28].

Despite the numerous advantages of the FRP wrapping technique, it has not yet widely implemented in building, due to uncertainties associated with the performance of FRP repair materials and FRP repaired concrete members during fire or elevated temperature. Most building structures are subject to strict building codes requirements for maintenance of structure safety during fire and high temperature arising from fire. However there is currently insufficient information on FRP strengthening systems under these conditions. Indeed, several studies have recently placed effect of elevated temperature among the most critical research needs to promote further application of FRPs in structural application. Moreover, the accumulated annual loss of life and property due to fires is comparable to the loss caused by earthquakes and cyclones. This necessitates development of fire-resisting structural design, particularly of columns as these are primary load bearing members of any structure.

All structural material, including concrete and steel, experience some degradation in its mechanical properties at elevated temperature, and this is true also with FRPs. At elevated temperature beyond the glass transition temperature (GTT) of the FRP's polymer matrix component (Epoxy); its mechanical properties deteriorate rapidly. The resulting loss of load transfer between fibers and concrete, in conjunction with a severe deterioration in the mechanical properties in the fibers themselves, results in a reduction in the strength and stiffness of the FRP. Also, in externally bonded FRP application, it is likely that exposure to elevated temperature would lead to rapid and severe deterioration of the FRP/concrete bond, resulting in de-bonding of the FRP and loss of its effectiveness as tensile or confining reinforcement[22-24]

The effect of fire and elevated temperature on FRP strengthened concrete members are well recognized in this literature, although relatively few studies have been conducted investigating this issue[22-24]. All these studies have demonstrated the sensitivity of FRP materials to elevated temperature and confirmed the need for thermal insulation of FRP materials during fire or structures expose to high temperature to prevent rapid loss of the FRP's structural effectiveness. However, no complete information is currently available on the performance in elevated temperature and fire of FRP wrapped RC columns, and it is this knowledge gap that this thesis addresses

2-2 EFFECT OF ELEVATED TEMPRATURE ON REINFORCED CONCRETE

2.2.1 Performance of Concrete

Concrete is non-combustible and emits no toxic fumes. As concrete is a good insulator (k=1.28 W/m.k), the concrete temperature will usually be much less than the flame temperature. As the concrete temperature rises, it progressively loses moisture and gradually loses strength. The loss of strength is greatest at concrete temperatures levels above 450-600 ^{o}c (the exact temperature depends on the aggregate type) as shown in figure (2.1). Curve designated "Unstressed" is for specimens heated to test temperature without any applied load then tested hot. Curve designated "Stressed" is for specimens heated while stressed to 0.4 f'_c and then tested hot. The third curve designated "Unstressed residual" is for specimens heated to test temperature then cooled to room temperature and then tested in compression[29].

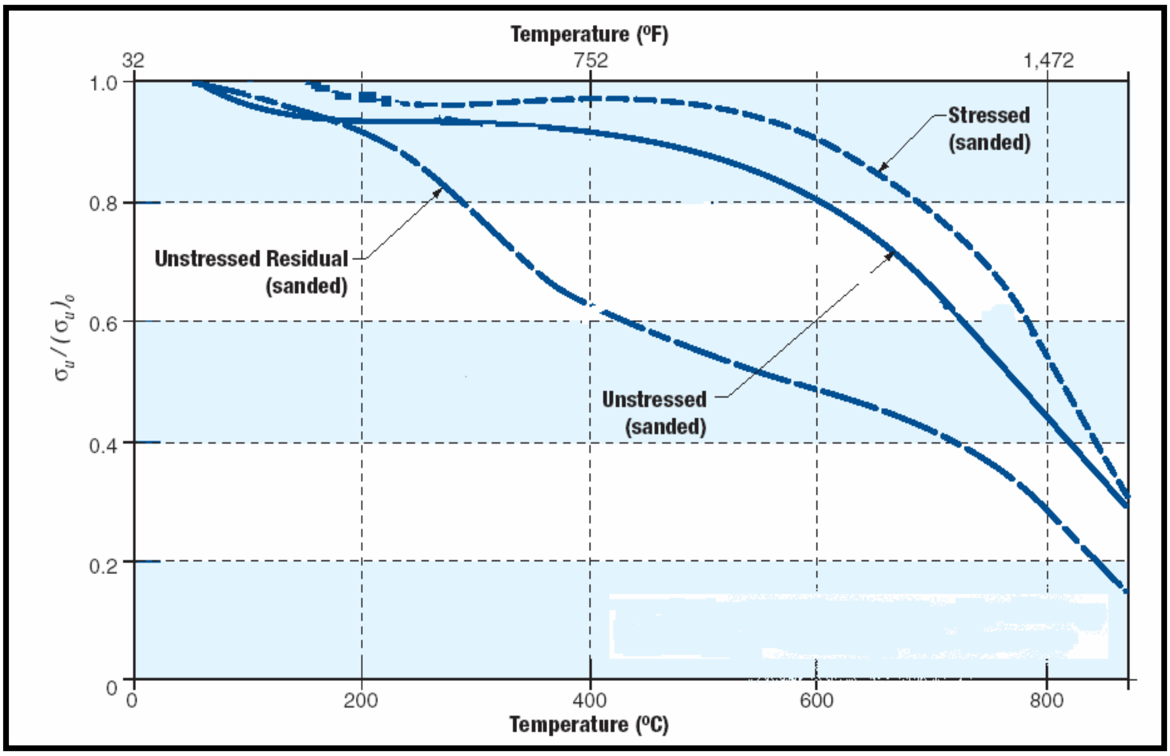

Fig.2.1 Reduction of the compressive strength of Concrete at elevated temperature

Wet or moist concrete can spall in a fire, due to the build up of steam pressure within the concrete, leading to separation and loss of the surface layer. In most fires, concrete will retain its structural integrity and the structure can be successfully repaired.

When subjected to heat, concrete responds not just in instantaneous physical changes, such as expansion, but by undergoing various chemical changes. This response is especially complex due to the non-uniformity of the material. Concrete contains both cement and aggregate elements, and these may react to heating in a variety of ways. First of all, there are a number of physical and chemical changes which occur in the cement subjected to heat. Some of these are reversible upon cooling, but others are nonreversible and may significantly weaken the concrete structure after a fire.

Most porous concretes contain a certain amount of liquid water in them. This will obviously vaporize if the temperature significantly exceeds the moisture plateau range of 100-140°c or so, normally causing a build-up of pressure within the concrete. If the temperature reaches about 400°c, the calcium hydroxide in the cement will begin to dehydrate, generating further water vapor and also bringing about a significant reduction in the physical strength of the material. Other changes may occur in the aggregate at higher temperatures, for example quartz-based aggregates increase in volume, due to a mineral transformation, at about 575°C and limestone aggregates will decompose at about 800°C.

These physical and chemical changes in concrete will have the effect of reducing the modulus of elasticity of concrete as shown in figure (2.2)

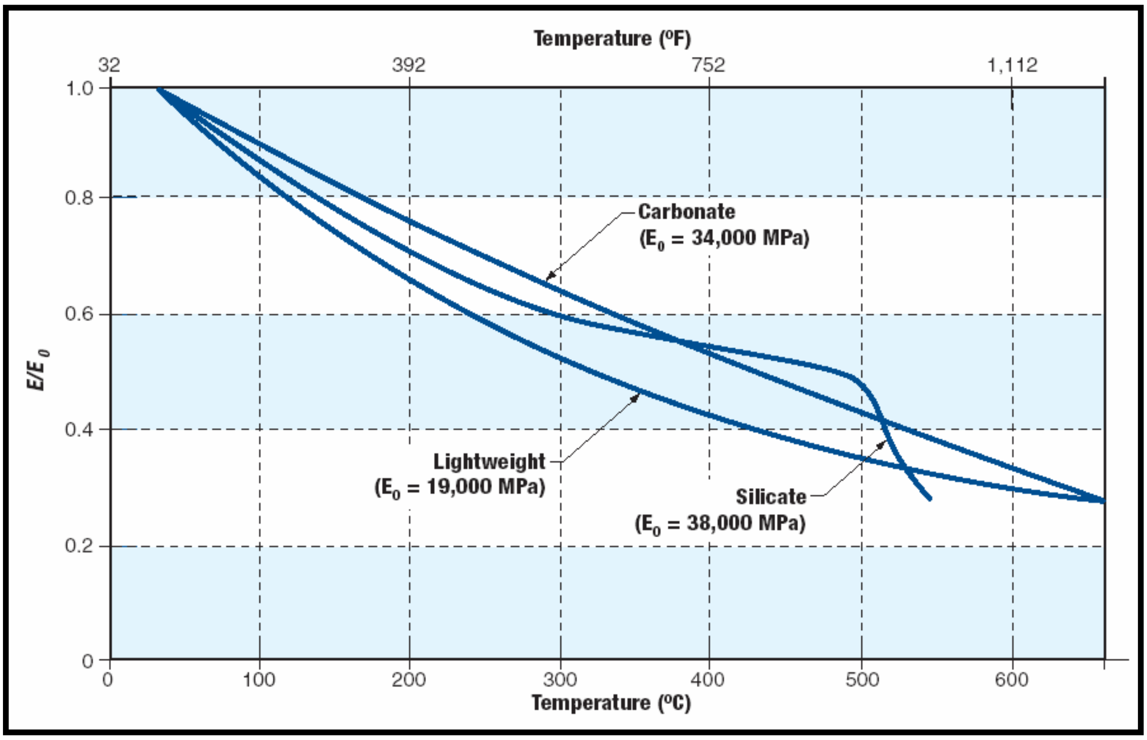

Fig.2.2 Effect of temperature on the Modulus of Elasticity for different types of concretes

2.2.2 Performance of Reinforcing Steel Bars

The principal thermal properties that influence the temperature rise and distribution in a member are its thermal conductivity, specific heat, and density[30]. The temperature dependence of the thermal conductivity and specific heat for steel are depicted in Figure (2-3)

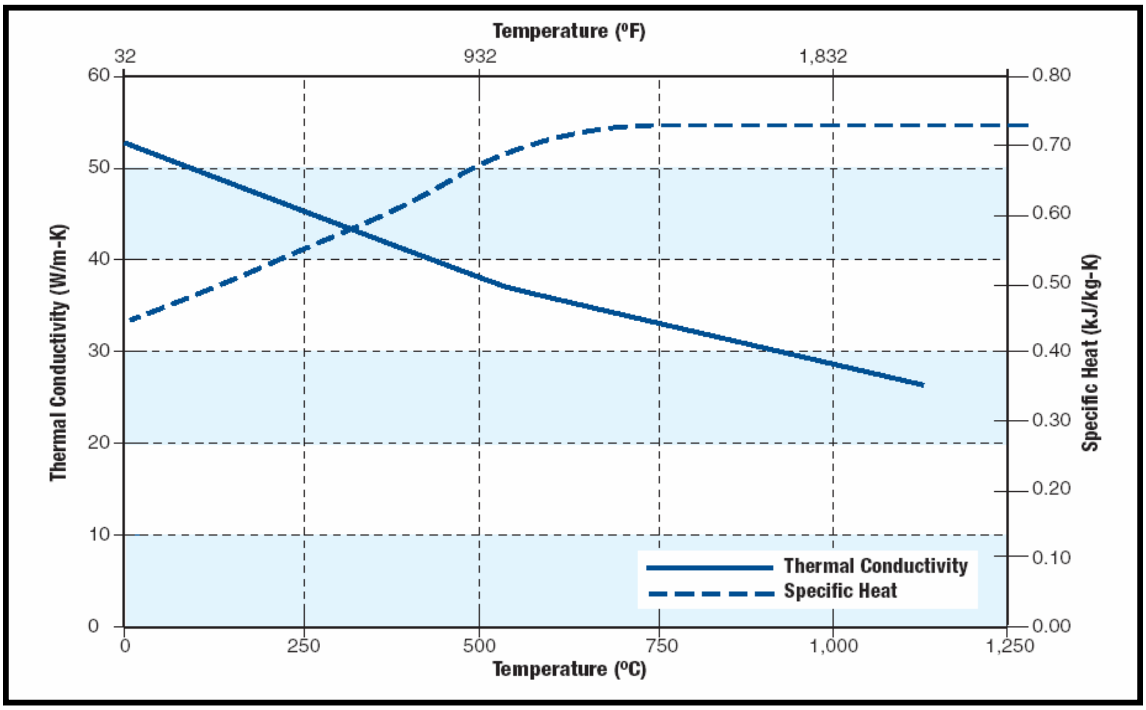

Fig.2.3 Thermal properties of steel at elevated temperatures

References to the tensile or compressive strength of steel relate either to the yield strength or ultimate strength. Figure (2-4) shows the stress-strain curves for a structural steel (ASTM A36) at room temperature and elevated temperatures.

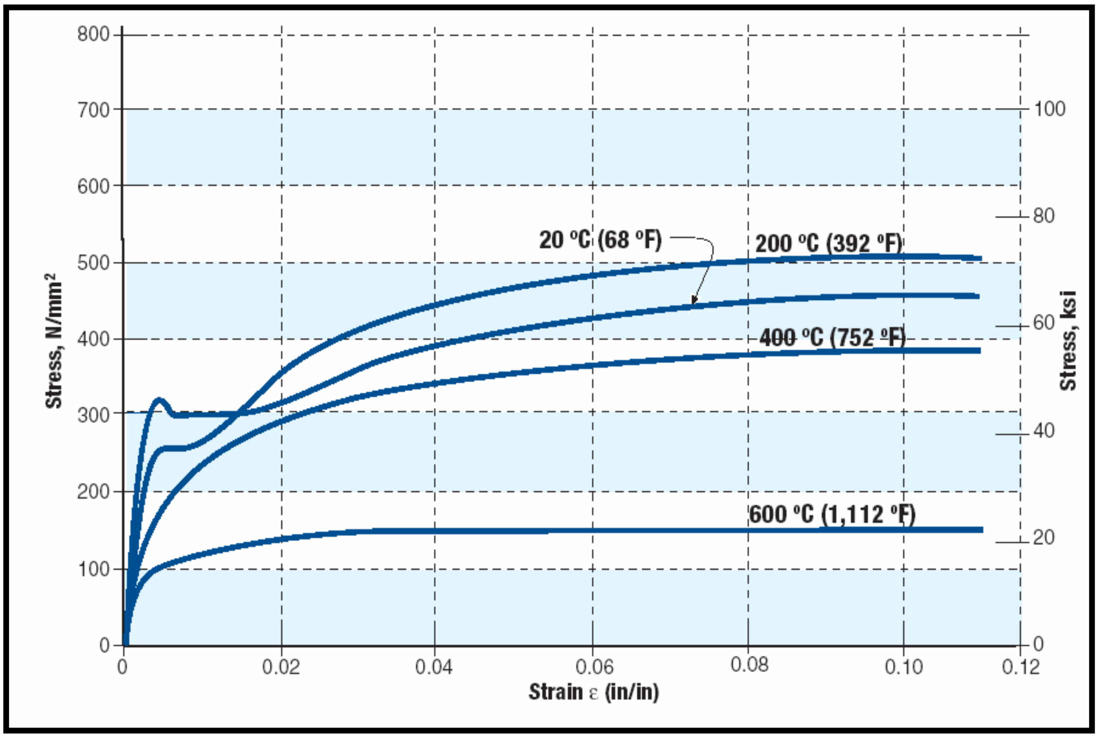

Fig.2.4 Stress-strain curves for structural steel (ASTM A36) at range temperatures

As indicated in the figure, the yield and ultimate strength decrease with temperature as does the modulus of elasticity. Figure (2-5) shows the variation of strength with temperature (ratio of strength at elevated temperature to that at room temperature) for hot rolled steel such as A36. As indicated in the figure, if the steel attains a temperature of 550 °C (1,022 °F), the remaining strength is approximately half of the value at ambient temperature.

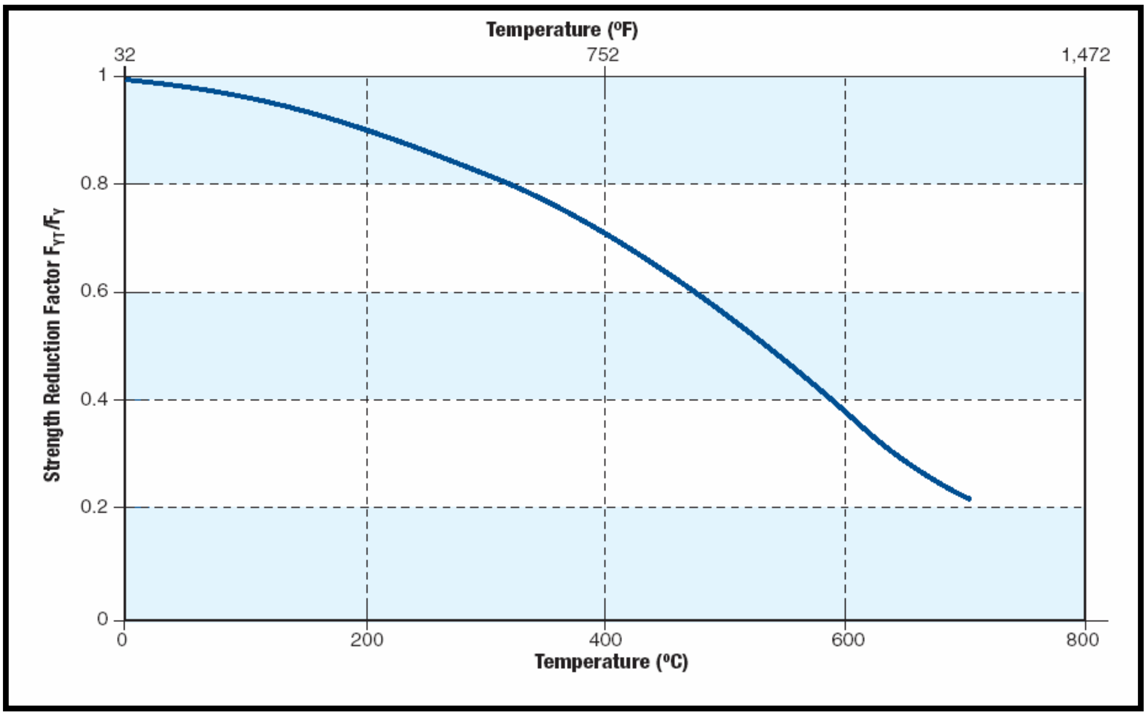

Fig.2.5 Strength of steel at elevated temperatures

The modulus of elasticity, E_0, is about 210 x 10^3 MPa for a variety of common steels at room temperature. The variation of the modulus of elasticity with temperature for structural steels and steel reinforcing bars is presented in Figure (2-6). As in the case of strength, if the steel attains a temperature of 550 °C (1,022 °F), the modulus of elasticity is reduced to approximately half of the value at ambient temperature.

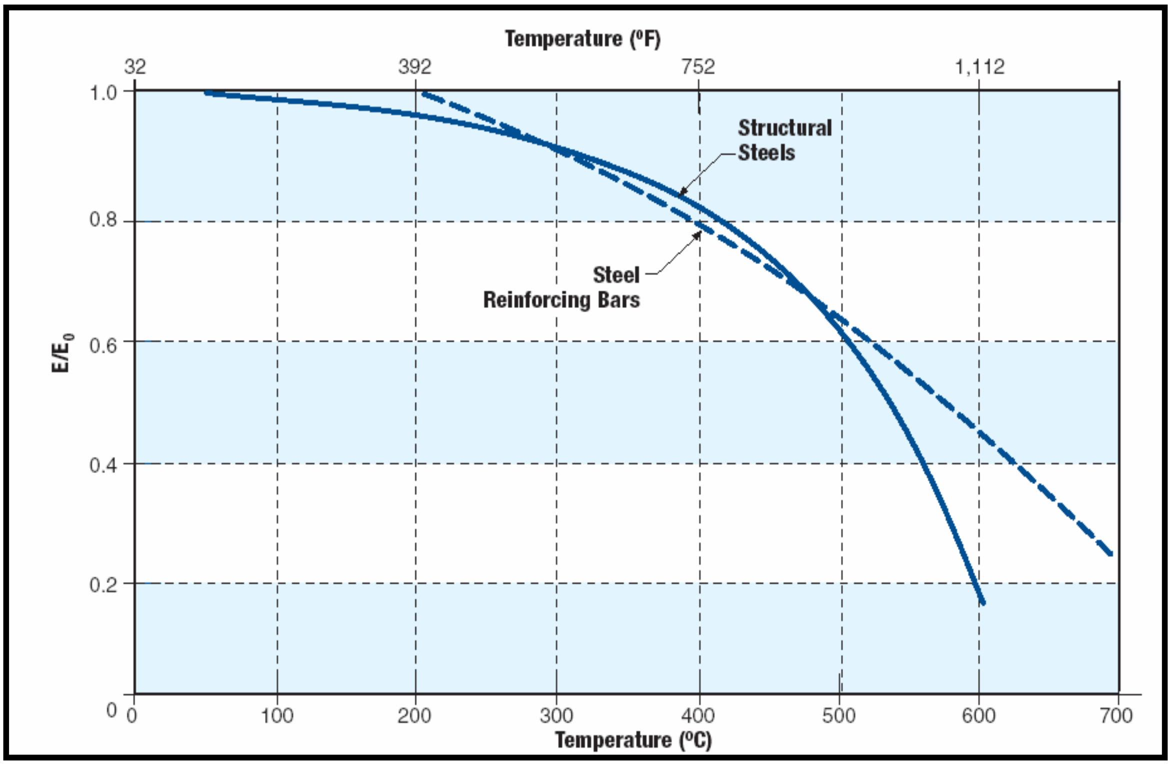

Fig.2.6 Modulus of elasticity at elevated temperatures for structural steel and steel Reinforcing bars

2-3 FIRE ENDURANCE TESTS ON REINFORCED CONCRETE MEMBERS

Columns are very important elements in transferring both gravity and lateral loads to the ground. Therefore, a good understanding of the behavior of the reinforced concrete columns exposed to fire is very important as a first step to save human lives and protect the structure from damage.

The effect of elevated temperature on the properties of reinforced concrete elements was investigated many years ago[31-37]. It was found that the concrete strength and its modulus of elasticity were badly affected by the rise in temperature. The concrete may lose the bond stress with the steel reinforcement due to the difference in the coefficient of expansion of the steel and concrete. Some physical changes occur inside the concrete, such as the pressure induced by the moisture inside the concrete core may cause the concrete crushing or the aggregate spall out. To understand the behavior of structural elements under the exposure of elevated temperature, many researchers performed experimental programs[31-37] these programs were performed either on full scale models of the structural elements or smaller scales. Also, the exposure temperature rates were according to standard time- temperature curves like that of ASTM E119 [25] or a proposed curve according to the available facilities.

2-4 FRP PROPERTIES AT ELEVATED TEMPERATURE

An understanding of material behavior at high temperature is essential to experimentally or analytically investigate the fire endurance of structural members. The properties that are of interest for structural materials can be divided into two broad categories: thermal and mechanical. Important thermal properties include: thermal conductivity, specific heat, emmissivity, and density; while mechanical properties include: thermal expansion, creep, and stress-strain behavior.

As early as 1982, it was recognized that fire posed a significant risk to FRP-reinforced concrete members. In their pioneering work on FRP-wrapped concrete columns, Fardis and Khalili[38] included a section that discussed various concerns associated with the flammability of the polymer matrix and the consequences for reinforced concrete structures. At that time, they suggested the use of flame retardant additives and fillers to improve the fire performance of polymer matrices, but did not attempt to improve or test fire performance themselves. It is interesting to note that relatively few studies have been conducted to investigate the fire resistance of FRPs for structural applications in the twenty-two years since.

Two types of performance against fire are extremely important [39]; performance against initial fire and performance in the post-flashover stage. Performance against initial fire includes: flammability, which affects the spread of fire (non-combustibility and flame retardency), and smoke and gas-generating properties, which affect the ability to safely evacuate a building. The performance against fire in the post-flashover stage includes: heat-insulating, flame resisting, and smoke barrier properties of separating members, such as floors or walls, and structural safety (or load-bearing capability) of framing members, such as columns and beams.

Fibre-reinforced polymers display a high temperature performance that is drastically different than steel. All polymer matrix composites will burn if subjected to a sufficiently high heat flux. In addition, commonly used matrix materials such as polyester, vinyl ester, and epoxy not only support combustion, but evolve large quantities of dense black smoke[40]. Compared to non-filled plastics however, thick FRP have two advantages with regard to their involvement in fire. First, the non-combustible fibers (with contents as high as 70% by weight) displace polymer resin, making less fuel available for the fire. Second, when the outermost layers of a composite lose their resin due to combustion, the remaining fibers act as an insulating layer for the underlying composite, significantly reducing heat penetration to the interior[41].

2-4-1 Matrix Behavior

As far as the fire endurance of FRP-reinforced or strengthened concrete is concerned, some of the more important matrix properties are the thermal conductivity, the glass transition temperature (T_g), the coefficient of thermal expansion (CTE), and the flame resistance

The burning characteristics of thermoplastics and thermosets differ significantly. Sorathia et al. (1992)[40] offer a review of the fire behavior of different resin types used for FRPs in marine applications. They state that thermosets will degrade, thermally decompose, or char when exposed to fire, but will not soften or melt like thermoplastics. In general, thermosets burn for a shorter duration than thermoplastics, and have much higher heat release rates. Thermoplastics, on the other hand, tend to soften when exposed to high temperature due to their primarily linear chain molecular structure. Thermoplastics burn longer and release less heat than thermosets. Currently, thermosets are most often used in civil engineering applications.

With respect to thermosets, Bakis (1993)[42] states that polyesters can be made quite resistant to fire, and that their upper use temperatures are about 100°C to 140°c. Vinyl esters have advantages over polyesters in terms of high temperature resistance, with upper use temperatures in the range of 220 to 320° c. Epoxy resins, the most versatile FRP resins and subsequently the most widely used in structural applications, can have upper use temperatures anywhere from 50° c to 260° c depending on the particular formulation and resin additives. Polyamide resins, which can be either thermoplastic or thermosetting, have maximum use temperatures as high as 316° c. Thermoplastics can have upper use temperatures anywhere from 85° c to 277° c, but have rarely been used in structural applications to date.

Probably the most important property of the matrix material, as far as fire behavior in reinforced concrete applications is concerned, is the glass transition temperature, T_g. The T_g for a particular FRP is the temperature at which the amorphous polymeric regions of a material undergo a reversible change from hard and brittle to viscous and rubbery (Bank, 1993)[43].These changes are due to changes in the molecular structure of the material. T_g for resins used in commonly available FRPs are relatively low, typically less than 200°c, while the fibers can withstand comparatively high temperatures (more than 1000°c in the case of carbon). Because the GTT of a polymer is specific to that material, it is virtually impossible to make generalizations with regard to safe temperature ranges for the enormous variety of FRPs currently available for structural applications.

2-4-2 Fiber behavior

The three commonly used fiber types have significantly different thermo-mechanical properties at high temperature. Aside from a tendency to oxidize at temperatures above 400°c, some carbon fibers have shown negligible strength loss up to temperatures of 2000°c. Aramid fibers have a high thermal stability, but oxidation limits their use above 150°c. Glass fibers will not oxidize, but tend to soften at temperatures in the range of 800°c to 1000°c as shown in figure (2.7)[42]

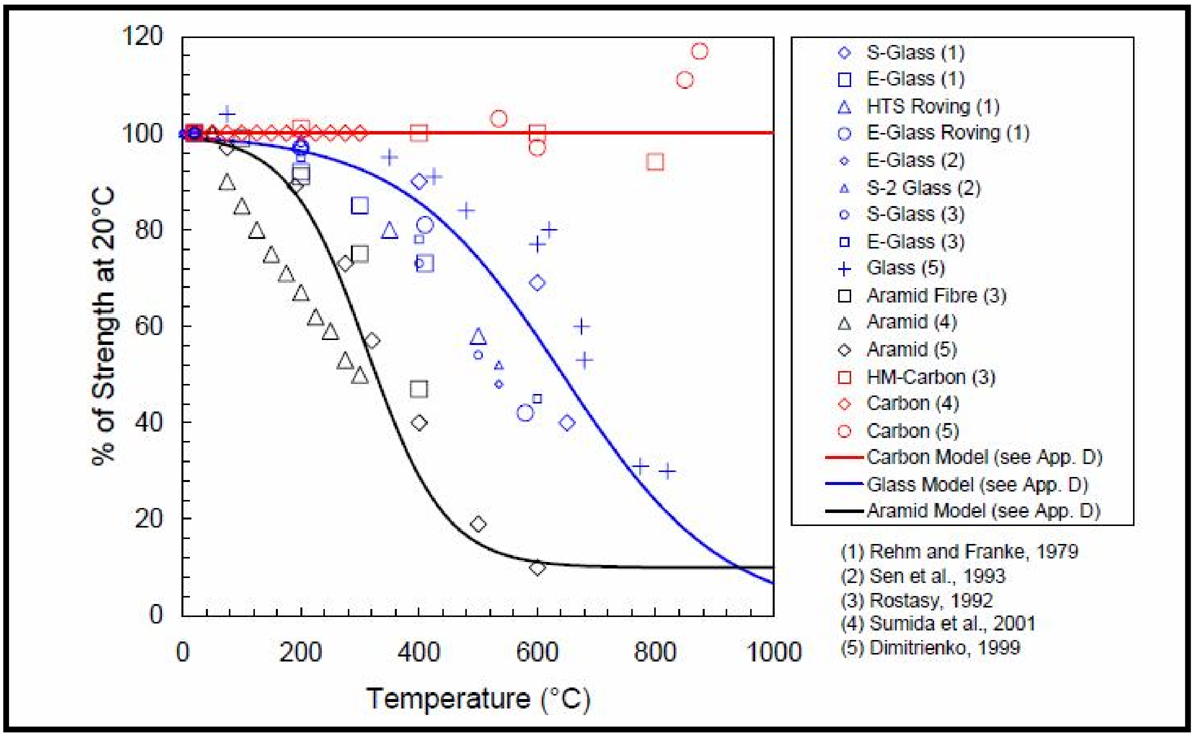

Fig.2.7 Variation in tensile strength of various fibers with elevated temperature.

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Rostasy (1992)[44] conducted a series of tests to examine the effect of temperature on the tensile strength of carbon, glass, and aramid fibers. The tests indicated that the tensile strength of aramid fibers was more dependent on temperature than glass fibers, but the tensile strength of carbon fibers seemed to be affected only slightly by temperatures up to 1000°c. Sumida et al. (2001)[45] tested the tensile strength of both carbon and aramid fibers at high temperature and determined that, while carbon fibers are unaffected by temperatures up to 300°c, aramid fibers experience an almost linear decrease in strength at temperatures above 50°c with a strength reduction of 50% at 300°c.

Dimitrienko (1999)[46] provides experimental data from tests on a variety of fibers at temperatures up to 1400°c. Tests were performed on carbon, glass, and aramid fibers in pure tension under exposure to elevated temperature. It was determined that carbon fibers were relatively insensitive to high temperature, with strength and stiffness actually increasing at temperatures above 600°c up to 1400°c. Glass fibers were found to weaken and soften at temperatures above 400°c, with a reduction of 20% in both strength and stiffness at 600°c and of 70% at 800°c. Glass fibers showed negligible strength and stiffness at temperatures above 1200°c. Aramid fibers performed very poorly, with significant reductions in strength and stiffness at temperatures above 100°c. Aramid fibers demonstrated a 20% decrease in strength and stiffness at 250°c, and a 70% decrease at 450°c.

It is evident that, while all fibers seem to be affected by elevated temperatures, aramid is the most severely affected with reductions of over 50% at 500°c, and carbon is the least with reductions of less than 5% at the same temperature. Sorathia et al. (1992) [40] states that the type and quantity of the fiber will significantly influence the fire performance of the FRP composite. Glass and carbon FRPs generally smoke less, and give off less heat than those with organic fibers such as aramid. The fiber type also significantly influences the thermal conductivity of FRP, with carbon FRPs having higher thermal conductivities than glass (particularly in the fiber direction).

2-4-3 Bond Properties at Elevated Temperature

The bond between FRP and concrete is essential to transfer loads, through shear stresses that develop in the polymer matrix or adhesive layer, from the FRP to the concrete and vise-versa. In the event of fire, changes in the mechanical properties of the matrix material have the potential to cause loss of bond at increasing temperatures, and result in loss of interaction between FRP and concrete. The result could be catastrophic, both for internally FRP-reinforced concrete and for externally FRP-wrapped reinforced concrete, since loss of interaction could very rapidly lead to loss of tensile or confining reinforcement, and subsequent failure of the concrete member.

Katz et al. (1998, 1999)[47,48] and Katz and Berman (2000)[49] studied the effect of elevated temperature on the bond properties of FRP bars in concrete. They investigated the pullout strength of glass FRP bars reinforcement, with six different types of surface textures, subjected to temperatures up to 250°c and found that the bond strength of FRP bars decreased as the surrounding temperature increased. Up to 100°c, the loss of bond was found to be similar to that observed in steel reinforced concrete, but at temperatures of 200°c to 220°c, the bond strength decreased dramatically to a value of about 10% of the original. The authors commented that the reduction in bond strength was likely due to changes in the properties of the polymer matrix at the surface of the rod.

Sumida et al. (2001)[45] conducted bond strength tests at high temperature on carbon and aramid/epoxy FRP rods, and found large bond strength reductions at rod temperatures above 100°c. They concluded that the surface temperature of FRP rods should be kept below 100°c when subjected to high levels of permanent stress, and that advanced resins with superior high temperature properties are required to improve the fire resistance of FRP reinforcing materials.

Essentially rare information is currently available on the specific behavior of the bond between unprotected externally bonded FRP materials and concrete at high temperature. The bond will likely be lost very quickly under fire exposure, because externally bonded systems are typically very thin (< 2 mm [0.08 in.]), and the T_g of the resin will thus be exceeded almost instantaneously during a standard fire exposure. For insulated FRP systems, however, it is not clear exactly how long the bond between externally bonded FRPs and substrate can be maintained during fire. This is due in part to the type of concrete or masonry used, the effectiveness and thickness of the insulation, and various other factors. In addition, post-fire residual behavior of these systems is unknown. This research presents a comprehensive experimental work to study the effect of several factors on the bond between FRP and concrete surface

Gamage et al (2005) [50] conducts an experimental program using shear test method to measure the bond strength with increasing epoxy temperatures. They prepare two concrete blocks, size 130x130x300 in mm, the concrete surface was prepared for bonding purpose, using a high pressure water jet. A primer layer was applied uniformly on the surface using a spatula. Then the thermocouples were fixed in the epoxy/concrete interface as illustrated in figure (2.8).

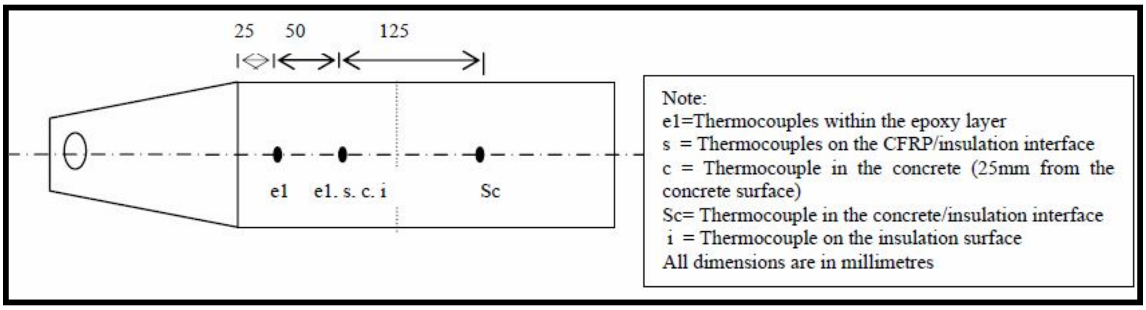


Fig.2.8 Thermocouple Locations (Plan View)

The CFRP sheet, saturated with epoxy, was pressed onto the concrete surface. Air trapped within the epoxy layer was rolled out before curing. The CFRP was bonded onto the surface of the concrete block ensuring the required bond width of 100mm and the bond length of 125mm. Then the specimen was kept to cure for 7 days. The material called 'Vermitex-TH', developed by LAF group, was used to provide passive fire protection on the strengthened member. A timber mould was used to apply Vermitex for all six sides of the specimen. The specimen was wetted before the insulation layer was applied. Mechanical reinforcements to secure whole thickness of Vermitex were installed parallel to the faces of the specimen, maintaining 15mm cover. Vermitex was mixed in the mechanical mixer following manufacturer's guidelines. Finally, Vermitex was sprayed onto the specimen as a single coat maintaining 50mm thickness, all over the surfaces.

The specimen was kept in the oven using a steel grip. Four thermocouples were installed parallel to the faces of the specimen to measure the oven temperature in accordance with AS1530/4[51]. The other ends of the thermocouples were connected to the data taker. The non-insulated sides (two edges) of the oven were covered using a ceramic fiber blanket to minimize the heat transfer with environment. The controller was programmed to increase the oven temperature by 3 steps; from ambient to 600^{o}c within the first hour, from 600^{o}c to 1000 ^{o}c within the second hour and up to 1200 ^{o}c during last hour. Temperature measurements were noted in the data-taker at 1 second intervals.

The main outcome of this series of testing was temperature distributions within the different interfaces of the specimen. Temperature versus time curves were developed using temperature readings given by the thermocouples. The failure temperature of epoxy (73.6^{o}c) was taken from the previous shear test results of the non-insulated identical specimens tested under uniformly increasing temperature (Gamage et al. 2005)[52]. Failure times under the experimental temperature conditions were finalized 73.6 min or two specimens as illustrated in Figure (2.9)

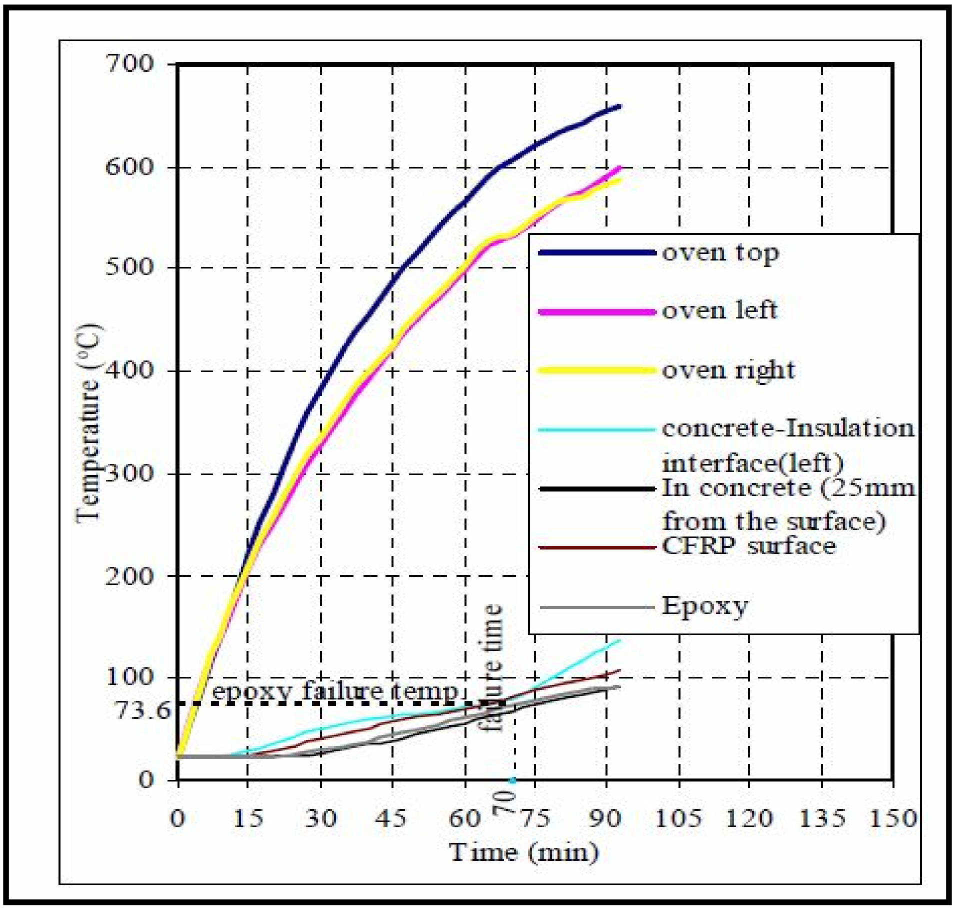


Fig.2.9 Temperature distribution for the insulated CFRP strengthened specimen

Two types of failures were observed in this experimental program, peeling off of the CFRP sheets for the specimen tested at epoxy temperature greater than 60°c. The combination of bond failure and concrete rupture was noted in low temperature range from 22°c to 36°c

They developed a finite element model to simulate the thermal behavior of the insulated composite structure. This model is capable of predicting the temperature distribution in the different interfaces of the specimen accurately. Based on this F.E. model, simulation of heat transfer process for an insulated CFRP strengthened concrete member under standard fire curves was carried out. The thickness of insulation was taken as a variable (25, 40, 50, 60, 70, 77 mm). They showed that Vermitex insulation " *thermal conductivity =0.127 W/mK* " can provide 2 hrs and 3 hrs fire resistance levels for 55mm and 77mm thickness of the insulation layer respectively as shown in figure (2.10).

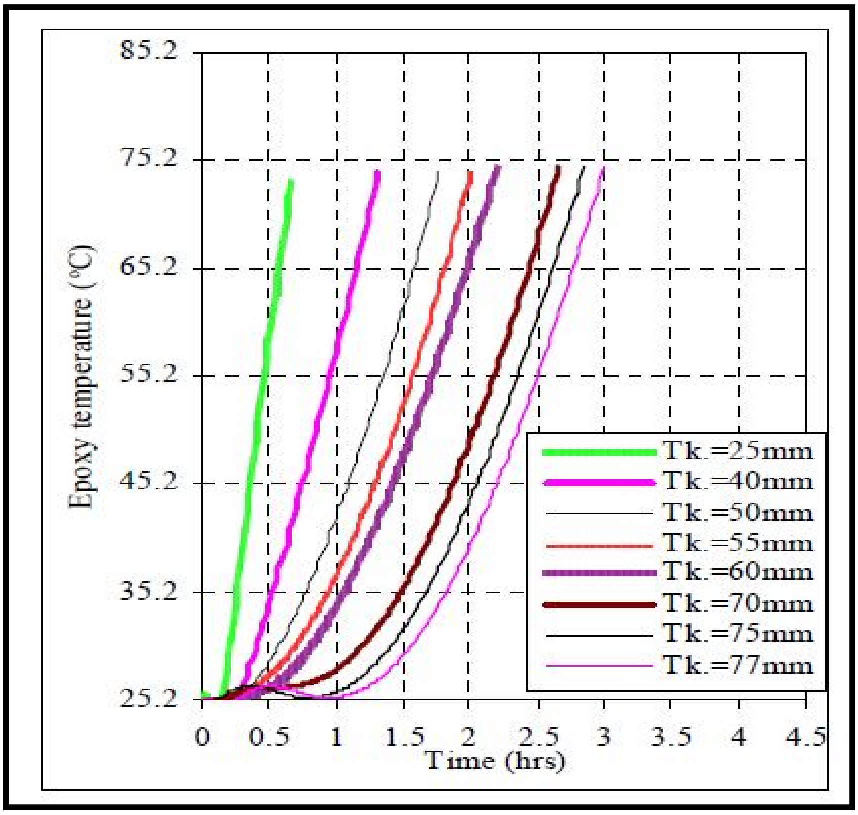


Fig.2.10 Variation of Fire Resistance Levels with the insulation thickness

2-5 FIRE ENDURANCE TESTS ON FRP-REINFORCED CONCRETE STRUCTURES

Studies investigating the thermal and structural behavior of FRP-reinforced concrete elements are extremely scarce. The few tests results that have been presented in the literature represent tests on specific FRP reinforcing systems and materials, and are not generally applicable to many different FRP-reinforced concrete elements.

2-5-1 Fire Endurance Tests on FRP Bar-Reinforced Concrete (Slabs and Beams)

Kodur and Bisby (2005)[53] &(2006)[54] present the results of an experimental and numerical study performed to investigate the performance in fire of insulated concrete slabs reinforced with steel, glass FRP rebar, or carbon FRP rebar. The slabs were strengthened and insulated with a unique, patented insulation system developed and manufactured by Fyfe Co.

LLC. Fire protection for the slabs consisted of a passive layer of Tyfo® VG insulation that was coated with an intumescent layer (Tyfo® EI). The VG layer was spray-applied at 19mm (Slab 1) and 38mm (Slab 2) thicknesses as shown in figure (2.11), followed by a trowel-application of a 0.25mm layer of EI to each slab. Twelve thermocouples were installed at various locations throughout the concrete depth and within the FRP and insulation layers.

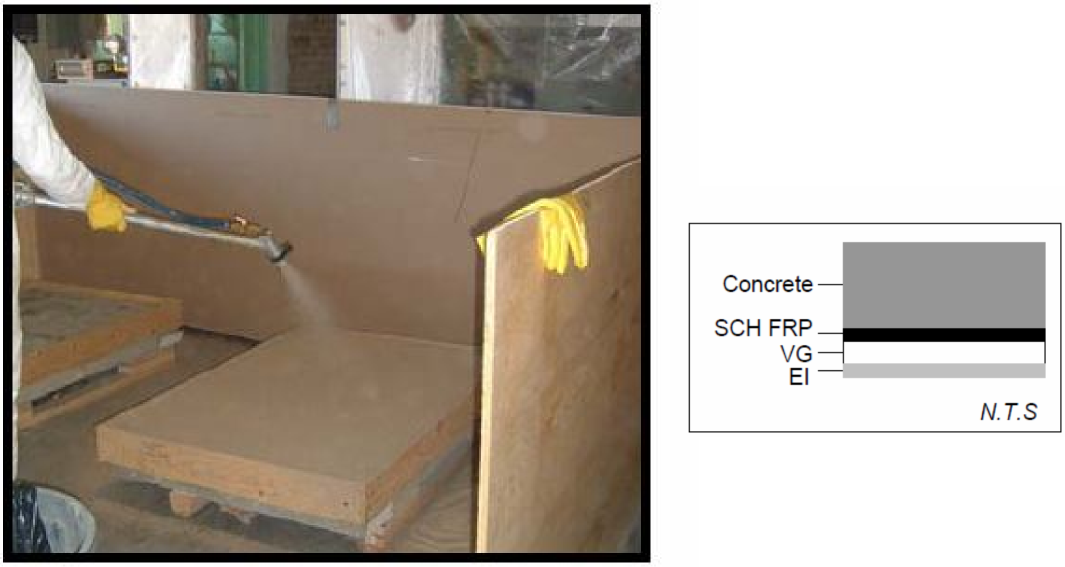


Fig.2.11 Slab Strengthening and Insulation details and spray application

Fire tests, performed in accordance with ASTM E119, were conducted on two intermediate scale reinforced concrete slabs. A number of parameters were varied among the slabs, including: the slab thickness, the rebar type, the aggregate type, and the thickness of the concrete cover to the reinforcement. In addition, a finite difference numerical heat transfer model was developed and verified against the test data, and was shown to agree satisfactorily with the results.

The slabs were exposed to fire for four hours. The test furnace allowed for limited viewing of the exposed surface of the slabs through two small view ports. Within the first five minutes, the intumescent layer (EI) of the fire protection system activated, formed a char layer and evolved smoke, then de-bonded within 15 minutes. At 2h12min, the 19mm thick insulation layer on Slab (1) de-bonded from the FRP, which was followed approximately 2 minutes later by de-lamination of the FRP layer. This was followed by spalling of the concrete cover layer, and the formation of cracks at the unexposed face. No exterior damage was observed on Slab (2) and the insulation remained intact for the entire duration of the test. The temperature within the EI/VG/FRP (exterior) layers and the concrete depth were monitored at one minute intervals. Figure (2.12) shows the temperatures recorded throughout the exterior layers for both slabs.

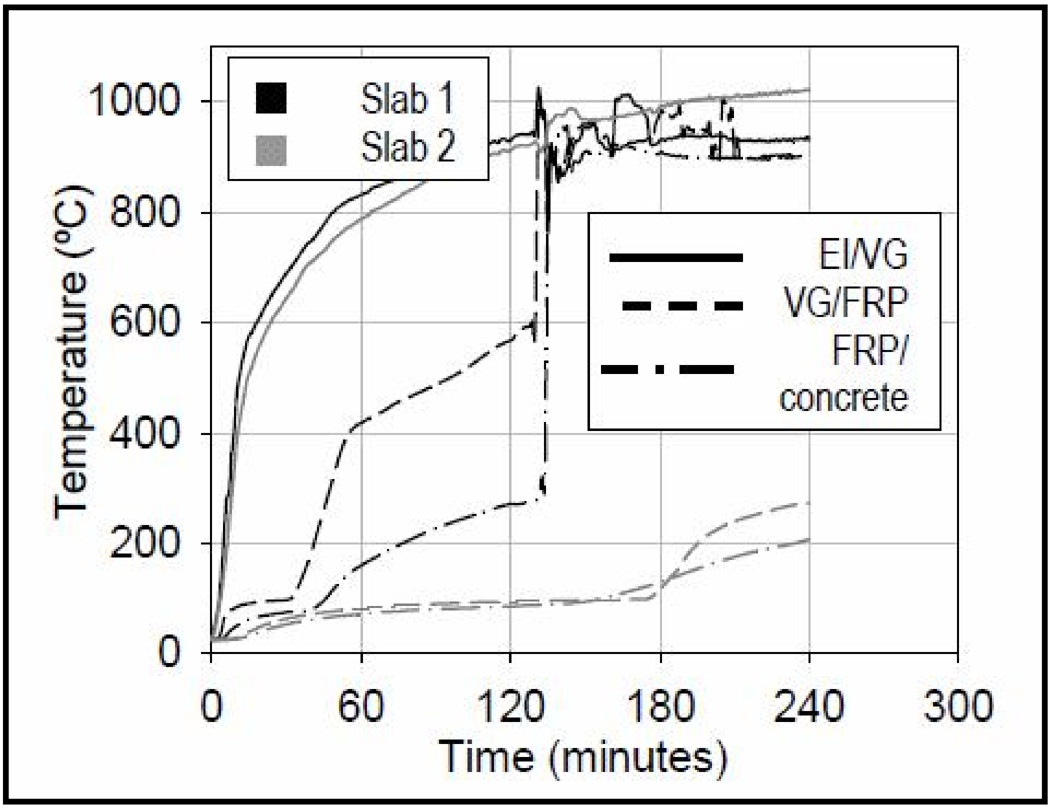


Fig.2.12 Slab 1&2 Temperature in EI/VG/FRP

The primary conclusions reached in the Kodur and Bisby (2005)[53] study were that: the qualitative fire performance and heat transfer behavior of FRP-RC slabs appears similar to slabs reinforced with steel bars; the reinforcement type has a significant effect on the predicted fire resistance of RC slabs, with FRP-RC slabs having much lower fire resistance as compared to those reinforced with steel; slab thickness does not have a significant effect on the fire resistance of the concrete slabs; concrete cover thickness has a significant influence on the fire resistance of RC slabs; and aggregate type has a moderate influence on the fire resistance of FRP-RC slabs.

The authors note that higher fire resistance for FRP-RC slabs can be obtained by using larger concrete cover thickness or through the use of carbonate aggregate concrete. Full-scale tests on loaded FRP-RC slabs are thus required to determine whether bond degradation, which can be expected to be severe at only mildly increased temperatures, might cause premature structural failure during fire.

NEFCOM Corporation (1998)[55] conducted fire endurance tests on concrete slabs that were internally reinforced with either glass or carbon FRP grids produced under the trade name NEFMACTM. A total of ten 3500mm by 500mm, 120mm thick, slabs were exposed to fire on one side for a maximum duration of 2 hours. Parameters that were varied in the experimental program included the load intensity, the type of reinforcement (GFRP, CFRP, GFRP/CFRP in combination, or conventional reinforcing steel), the type of polymer matrix used (vinyl ester or unsaturated polyester), the bar size of the grids, the thickness of concrete cover, the presence of a construction joint, and the presence of supplemental insulation in the form of a 25 mm thick rock wool board. Deflections, cross-sectional temperatures, and reinforcement temperatures were all monitored during the tests.

It was observed that the deflection of all slabs increased dramatically when the temperature at the bottom of the reinforcement reached 600°c. This was due to a severe drop in the stiffness of the FRP grid at these elevated temperatures. The performance in fire of the FRP-reinforced slabs did not appear to be affected by the type of resin used in the fabrication of the FRP grid. The rise in temperature in the FRP grid, for the same concrete cover thickness, did not appear to be affected by the type of fiber used. However, the temperature rise at the level of the reinforcement for the steel-reinforced slab was slower than for the slabs reinforced with NEFMAC™, the slower temperature rise in the reinforcement observed for the steel reinforced slab was likely due to the higher thermal conductivity and heat capacity of steel, such that it acted as a thermal sink to draw heat further into the slab, and thus reducing the observed temperature at that location.

Slabs with construction joints failed, before the bottom surface of the reinforcement reached 600°c, because of rapid thermal degradation of the epoxy joint filling agent, resulting in very high temperatures at the location of the joint. The insulated slabs showed substantially higher fire endurance than those without insulation. After two hours of the test, the temperature in the reinforcement in the insulated slab was only 170°c and the deflection only 25mm, as opposed to 600°c and 73mm in the un-insulated slabs. Specimens with higher applied loads showed lower fire endurance based on the time to reach a limiting deflection of 73 mm.

The authors concluded that there was no recognizable difference in the fire deflection behavior of slabs reinforced with NEFMAC™ or with steel. The most interesting information presented in the above paper is that the NEFMAC™ grid reinforcement was apparently able to maintain strength and stiffness until it reached a temperature of 600°c. Most FRP materials should have lost a significant portion of their strength and stiffness at temperatures well below 600°c. While these results seem contradictory, it is possible that special chemical additives were incorporated in the FRP matrix to improve the fire behavior, although the authors do not comment in this regard.

Tanano et al. (1995)[56] performed a study on the fire behavior of FRP-reinforced concrete beams in Japan. Their study focused on the residual strength of beams after exposure to fire. In this study, 3m long beams with a 200 mm by 300 mm cross-section, and reinforced with either carbon, glass, or aramid FRPs, were heated in a furnace according to a modified version of the Japan Industrial Standard heating curve, such that their temperature reached some specified value in one hour, and was then maintained at a constant level for one and a half hours until the temperature at the level of the internal tensile reinforcement reached 250°c, 350°c, or 450°c.

The authors observed several explosive failures during the heating. It was noted that, because these failures were only observed in beams with an epoxy matrix FRP, the explosive failures were not thought to be associated with generation of steam within the specimens, but with the use of epoxy matrix FRP with a spiral configuration. The specific cause of the explosive failures remains unknown.

After heating, the beams were returned to room temperature and tested in four-point bending. It was observed that bond strength and stiffness decreased for epoxy matrix FRP-reinforced concrete beams as the heating temperature increased, but that the rate of decrease was different depending on the type of FRP used. The rates of decrease in both strength and stiffness were greater for epoxy matrix FRP-reinforced beams than for those reinforced with conventional reinforcing steel. Beams reinforced with an inorganic matrix FRP showed only a small reduction in residual strength after exposure to temperatures of 250°c and above. The residual tensile strength of the FRP reinforcement decreased as exposure temperature increased for all materials, as evidenced by a change in failure mode of the beams from compression failure in the concrete to tensile failure of the internal reinforcement.

Sakashita (1997)[57] investigated the effect of fire on concrete beams reinforced with carbon, glass, and aramid FRP rods with different surface textures and fiber orientations (braided, spiral, or straight). The behavior of these beams was compared to that of a conventionally reinforced concrete beam in a fire test. All specimens were heated to 100ºc for three hours prior to testing and then heated to 1000ºc under load in 180 minutes. It was found that, at a furnace temperature of 350ºc, specimens containing aramid FRP experienced a sudden increase in vertical deflection.

These beams failed at a furnace temperature of 500ºc. However, specimens containing glass or carbon FRPs, or conventional steel, completed the 180-minute test without failure. At the end of the tests, it was observed that the average mid-span deflections and temperature at the bottom face of the beams were 160 mm and 680ºc for GFRP, 30 mm and 700ºc for CFRP, and 100 mm and 680ºc for conventional reinforcing steel.

2-5-2 Effect of Elevated Temperature on R.C. Members Strengthened by Externally FRP

In concrete members externally reinforced with FRP, unless an insulating or intumescing protective layer (or both) is applied, the FRP would be immediately exposed to the heat of the fire, likely resulting in rapid loss of composite action. In these cases, it is required that the reserve strength of the member, which would revert to a conventional steel-reinforced concrete member, would be relied on to carry the necessary loads for the duration of the fire. Few tests on externally FRP-reinforced concrete have been reported in the literature.

2-5-2-1 Effect of Elevated Temperature on R.C. strengthened by externally FRP(Beams and Slabs)

In terms of tests on beams and slabs, Deuring (1994)[58] studied flexural strengthening with externally bonded FRP materials on six concrete beams during exposure to fire. One beam was un-strengthened, one was strengthened with an adhesive bonded steel plate, and four were strengthened with CFRP plates. Two of the FRP plated beams were tested without insulation and two were protected with insulating plates of a different thickness. The results of this initial test program demonstrated the need for thermal insulation of the FRP plates. Bond between the FRP and concrete was lost very rapidly (within minutes) for the unprotected specimens but occurred after about an hour for those with supplemental insulation.

In an effort to gain further insight into the behavior of FRP-plated reinforced concrete beams during fire, a second study was conducted by Blontrock et al. (2000). The focus of this test program was to investigate a number of different thermal protection materials and layouts. The program included tests on a total of ten beams. An un-strengthened reference beam and a strengthened reference beam were statically tested to failure in four point bending, two unprotected and un-strengthened beams were loaded to full service load and tested under fire exposure, and six strengthened and protected beams were loaded to full service load and tested under fire exposure. The protection schemes were different for all six protected beams and consisted of gypsum board/rock wool combinations. All strengthened beams were strengthened using the SikaCarboDur ™ carbon/epoxy FRP strengthening system.

The fire endurance tests were conducted in accordance with the International Standards Organization (ISO) test method 834 for fire testing of concrete members, which is essentially the same as the Canadian CAN/ULC S101 fire testing procedure.

The U-shaped protection scheme shown in Figure (2.13) was most effective at prolonging the time before loss of interaction between the plate and the concrete. This scheme had the additional advantage of lowering the temperature of the internal reinforcing steel, thus contributing to lower deflections throughout the tests.

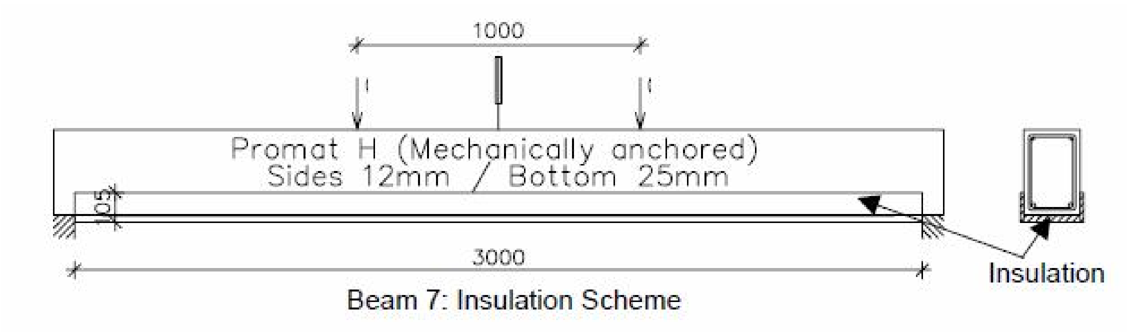


Fig.2.13 Details of selected FRP beams fire tested by Blontrock et al. (2000).

Benichou et al (2008)[60] conduct an experimental program consists of Four full-scale fire tests have been conducted on reinforced concrete T-beams that were strengthened in flexure with one layer of externally-bonded carbon FRP sheets. To provide anchorage for the flexural sheets, FRP sheets were wrapped around the web in a U-shape at the ends of the beams. Figure (2.14) shows the details of the T-beam specimens,

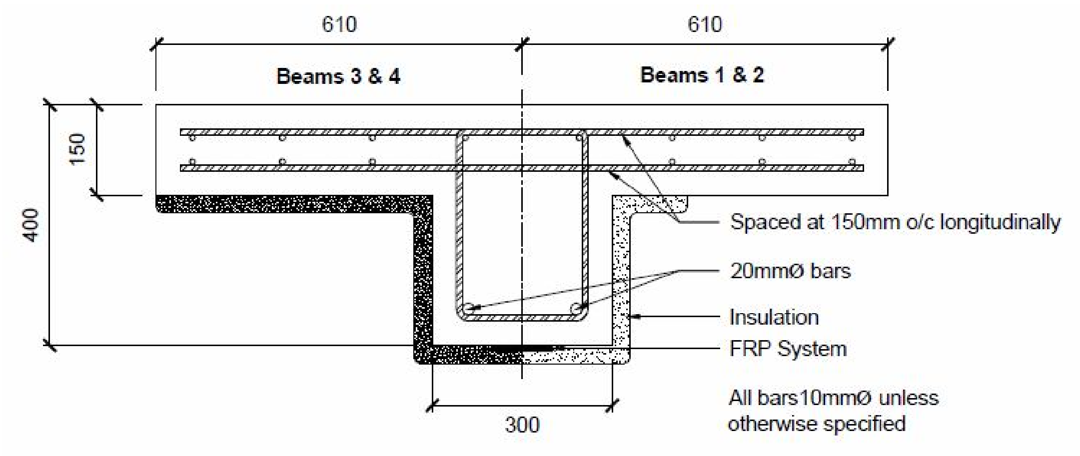


Fig.2.13 Cross-Sectional dimension of the T-beams tested by Benichou et al (2008)

Table (2.1) provides a summary of the fire tests conducted on these types of specimens. The T-beams were also protected with supplemental insulation around the web portion of the beams. The beams were tested under full-sustained service load according to ULC S101 guidelines. In this case, all four beams were insulated.

Table (2.1) Details for the beams specimens by Benichou et al (2008)

Member	Dimension	FRP	Insulation	Fire Resistance	Failure Load
T-Beam1	Length 3900 h = 400 h_s = 150 b_s = 1220 b_w = 300	1 Layer CFRP-A	VG - 25 mm	>240min	142 kN
T-Beam2		1 Layer CFRP-A	VG - 38 mm	>240min	142 kN
T-Beam3		2 Layers CFRP-B	Cem - 30 mm	>240min	146 kN
T-Beam4		2 Layer CFRP-B	Cem - 28 mm	>240min	120 kN

CFRP-A - t_f = 1.0 mm per layer, f_{max} = 745 MPa, ε_f = 0.012, E_f = 62 GPa, T_g = 93°c
CFRP-B - t_f = 0.165 mm per layer, f_{max} = 3800 MPa, ε_f = 0.0167, E_f= 227 GPa, T_g = 71°c
VG - gypsum-based insulation, thermal conductivity 0.082 W/m-ºC
Cem - cementations insulation, thermal conductivity 0.37 W/m-ºC
h = overall height of T-beam, ***hs*** = height of slab, ***bs*** = breadth of slab,

bw = breadth of web

All of these beams achieved fire resistance ratings of over 4 hours. Figure (2.14) shows the temperatures at the FRP for all beams.

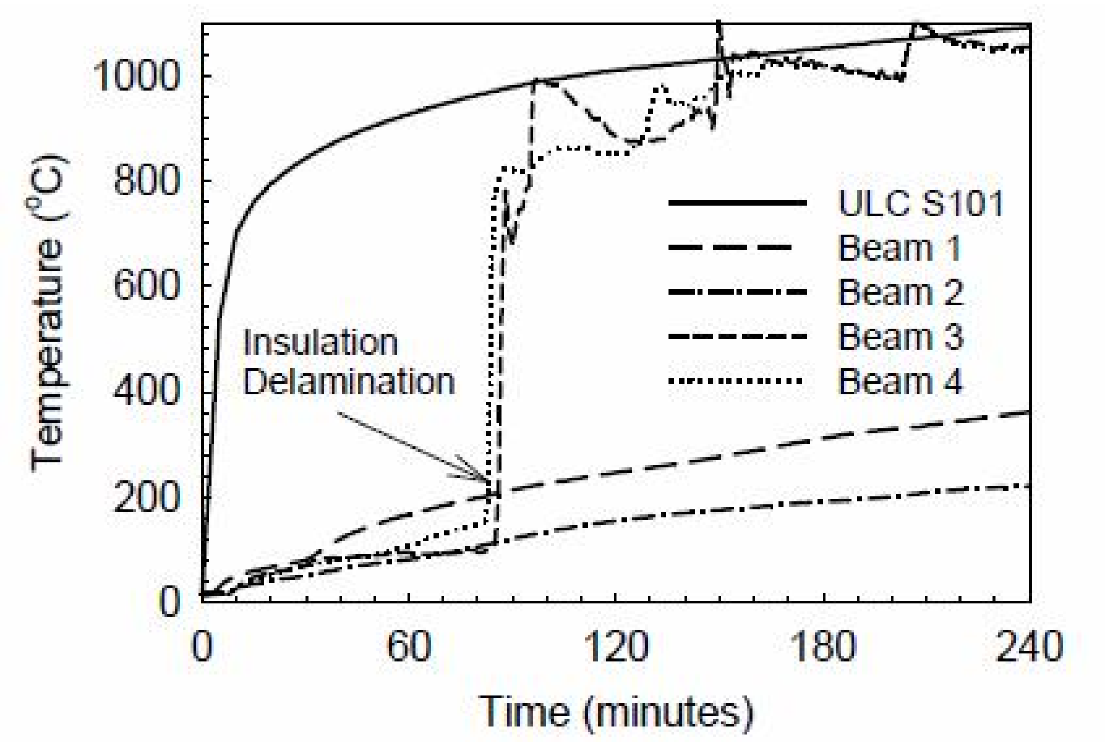


Fig.2.14 Temperatures at the level of the FRP for all beams

Owing to limitations in the capacity of the loading system in the beam-slab test furnace, it was not possible to fail the insulated FRP-strengthened beam-slab specimens during the fire tests. Thus, after the beams had cooled to room temperature, they were tested for failure under monotonic load at room temperature. It was shown in these tests that the beams retained their full pre-fire predicted flexural strength. This testing suggests that appropriately fire insulated FRP-strengthened beams can retain their full un-strengthened capacity even after 4-h fire exposure. A second interesting implication of these results is the post-fire repair ability of fire-damaged FRP-strengthened members. The results suggest that, for fire protected FRP-strengthened members; the post-fire capacity of the members is equivalent to the pre-fire capacity of the un-strengthened members. Thus, these members could be rewrapped after a severe fire and treated as essentially undamaged members.

Blontrock et al. (2001)[61] conducted a series of fire endurance tests on externally CFRP reinforced concrete slabs in an effort to evaluate their fire endurance. As was the case in the beam study discussed above, various fire insulation schemes (consisting of rock wool and/or gypsum board layers) were implemented to prevent de-bonding of the carbon FRP plating material. A total of ten slabs were tested including: un-strengthened and strengthened reference slabs tested at room temperature, un-strengthened and unprotected slabs tested under exposure to fire, and strengthened and protected slabs tested under exposure to fire.

Some of the more important conclusions reached in these studies were that: thermal protection is required in order to maintain the interaction between the FRP plates and the concrete; without protection it is impossible to achieve the same fire endurance as for the unprotected and unstrengthened beams; interaction between the externally glued composite and the concrete was lost when the temperature in the epoxy adhesive reached temperatures of 66°C to 81°C for the Sika™ CFRP product, and 47°C to 69°C for an S&P Laminates™ CFRP product; partial protection of the external strengthening system (applied to the anchorage zones only) was able to maintain interaction between the FRP and the concrete; and the fire endurance for the strengthened and protected beams was at least the same as for the unstrengthened unprotected beams.

2-5-2-2 The Effect of Elevated Temperature on R.C. columns confined by FRP

ACI Committee 440-06[61] Report identified fire or elevated temperature as another area needing further investigation. The report specifically notes concerns the effect of fire on composite material as well as on bond performance between concrete and the composite. Concern with elevated temperatures arises because of the types of epoxies often used in external composite systems. Because the external reinforcing must cover a large area, the use of heat setting epoxies is prohibitively expensive. Providing thermal blankets or other heat sources over the large areas required can be difficult and expensive. Therefore, the epoxies that bind the fabric to the concrete and provide the composite matrix are usually two-part epoxies that set at room temperature or lower. In many cases, this means the glass transition temperature of the epoxy matrix is below temperatures the materials may be exposed to during service. As the epoxies soften, there may be a temporary or permanent loss of strength either due to loss of bond in the matrix or degradation of bond between the matrix and concrete.

The National Research council in Canada had many research concerning the fire endurance on FRP strengthened RC columns. Kodur and Bisby et al (2005)[62] conduct an experimental program to investigate the behavior of FRP wrapped and insulated RC columns in fire, moreover to investigate techniques to improve their behavior in fire.

The column test program consisted of full-scale fire tests on four circular concrete columns, strengthened with carbon FRP wraps, and tested under full-sustained service load. All of the wraps were externally applied in the circumferential direction only. All columns were internally reinforced with conventional reinforcing steel. All, but one, of the columns were protected with supplemental insulation systems applied to the exterior of the FRP wrap. Details of the columns tested are given in Table (2.2).

Table (2.2) Details for the columns specimens by Kodur and Bisby et al (2005)

Member	Dimension	FRP	Insulation	Fire Resistance	Failure Load
Col 1	Ø400* 3810mm	1 Layer CFRP-A	VG - 32 mm	> 300 min	4437 kN
Col 2	Ø400* 3810mm	1 Layer CFRP-A	VG - 57 mm	> 300 min	4680 kN
Col 3	Ø400* 3810mm	2 Layers CFRP-B	None	210 min	2635 kN
Col 4	Ø400* 3810mm	2 Layer CFRP-B	Cem - 53 mm	> 300 min	4583 kN

CFRP-A - t_f = 1.0 mm per layer, f_{max} = 745 MPa, ε_f = 0.012, E_f = 62 GPa, T_g = 93°c
CFRP-B - t_f = 0.165 mm per layer, f_{max} = 3800 MPa, ε_f = 0.0167, E_f= 227 GPa, T_g = 71°c
VG - gypsum-based insulation, thermal conductivity 0.082 W/m-ºC
Cem - cementations insulation, thermal conductivity 0.37 W/m-ºC

For both columns, first circular column with VG thickness 57mm and the second, with VG thickness 38mm, the temperature at the level of the FRP is seen to increase fairly rapidly within the first 15-45 minutes of exposure, at which point the rate of temperature rise decreases and a temperature plateau is seen near 100°c. The duration of this plateau, which can be attributed to the evaporation of both free and chemically-combined moisture from the insulation at temperatures near the boiling point of water, is longer for first column, which has a greater insulation thickness, as should be expected. Indeed, the FRP temperature in the first column remains less than 100°c for more than three hours under fire exposure. Once all of the moisture has evaporated, temperatures at the level of the FRP increase more rapidly until the end of the test.

Figure (2.15) shows temperatures recorded at the level of the FRP–concrete interface in columns tested. The insulation provided good thermal protection for the columns as a whole, even though the recorded FRP temperature exceeded T_g relatively early in the fire exposure for all columns. The insulated column is visually in good condition after failure, and the fire insulation remained in-place even beyond failure. Failure of all columns appeared to be due to crushing of the core concrete, with some evidence of buckling effects. It is important to recognize that, in general, the failure modes of the columns were typically sudden and accompanied by spalling of the concrete cover.

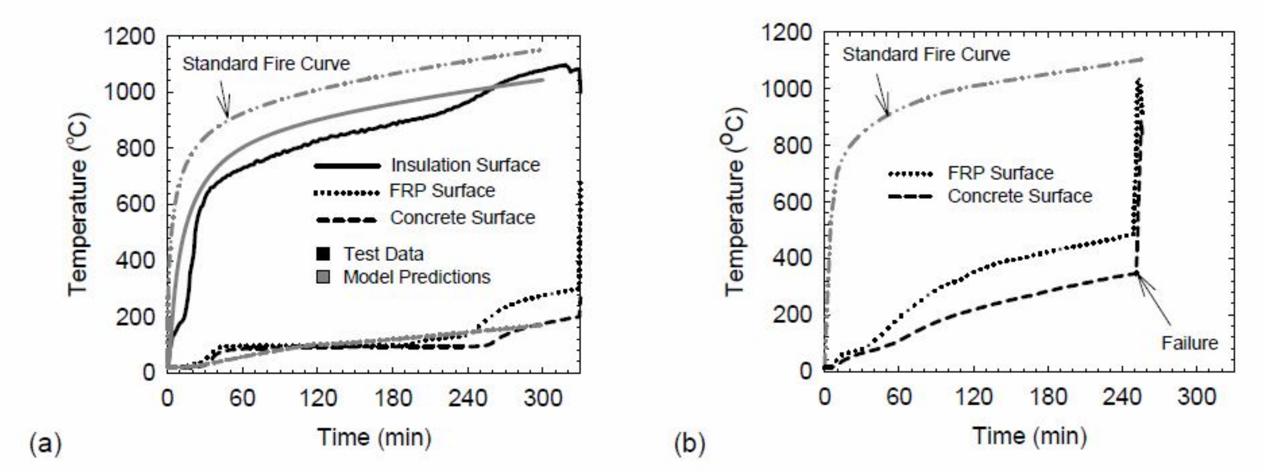


Fig.2.15 Temperatures observed (predicted) in a) Col with 57mm VG b)Col with 38mm VG

The un-insulated column also performed reasonably well during fire exposure and managed to sustain its required service load for about 3.5 h. However, the unprotected FRP-strengthening system burned within minutes of fire exposure and completely de-bonded from the column in less than 30 min. Clearly, the good performance of the column can be attributed to the fire resistance of the existing RC column, a result that demonstrates that loss of FRP effectiveness is not necessarily an appropriate failure criterion for fire resistant design of these members.

The column tests have demonstrated that the unique insulation systems used are effective fire protection systems for FRP-wrapped reinforced concrete columns. The FRP-strengthened columns protected with these systems are capable of achieving satisfactory ULC S101[26] fire resistance ratings, in excess of 5 h, even when the FRPs' Tg are exceeded early in the test. This occurs because the preexisting un-strengthened concrete column, which is designed based on ultimate loads but subjected to service loads only during fire, is protected by the supplemental insulation system and experiences only mildly increased internal temperatures that do not significantly decrease its capacity during fire.

This behavior implies that one way to significantly improve the fire performance of the columns (as insulated herein) would be to increase the GTT of the polymer matrix to even slightly above 100°c. However, as will be demonstrated below, keeping the FRP temperature below the GTT is not a necessary criterion for adequate fire endurance. The temperature at the level of the FRP remained less than the matrix ignition temperature for the full duration of fire exposure for the first column. On the other hand the second column, the ignition temperature was exceeded at about 3 hours of exposure (a factor which may have contributed to its sudden failure at slightly more than 4 hours).

This research concludes that:

- FRP materials used as externally-bonded reinforcement for concrete structures are sensitive to the effects of elevated temperatures. FRPs experience degradation in strength, stiffness, and bond at temperatures exceeding the GTT of the polymer matrix.
- Appropriately designed (and in most cases supplemental-insulated) FRP-wrapped circular RC columns can achieve satisfactory fire endurances in excess of 5 hours based on the requirements of ASTM E119 or CAN/ULC S101.
- While no explicit requirement currently exists that the temperature of an FRP wrap must remain below its matrix GTT during fire, it is not known what temperatures are allowable in the FRP such that it retains sufficient residual properties to remain effective after a severe building fire. Further work is required in this area.

Saafi and Romine (2002)[63] conducted a series of residual strength tests on FRP-wrapped reinforced concrete cylinders after exposure to elevated temperatures. A total of 40 cylinders, wrapped with two layers of a unidirectional glass/epoxy FRP, were tested in axial compression after exposures of up to three hours at 90°c, 180°c, and 360°c. The results of these tests indicated significant reductions in the overall strength and ductility of the wrapped cylinders at exposure temperatures at or above the 180°c (the GTT for this system).

Cleary et al (2003)[64], study the behavior of concrete cylinders wrapped with composite reinforcing system exposed to a range of elevated temperature. The pilot study consisted of compression tests on eight series of 200-mm diameter by 400-mm high externally reinforced concrete cylinders. All of the specimens were cast from a single batch of concrete and cured under identical conditions. A moderate strength concrete mix was used with a compressive strength of approximately 40 MPa. The cylinders were cured at 22^{o}c and 98% humidity until three days prior to wrapping. At that time they were allowed to air dry. The cylinders were reinforced in the hoop direction with two continuous layers of a reinforcing fabric applied with a two-part epoxy. The fabric primarily consisted of glass fibers running in the hoop direction. The primary glass fibers were woven around bundles of aramid and glass fibers running in the cross direction. The aramid fibers added in the cross section to improve handle ability of the saturated composite. The seam was wrapped an addition 50-mm beyond the completion of the second layer. The system is very similar to a commonly used commercial composite system but with a modified solvent-free two-component epoxy for higher temperature applications. Two sets of cylinders were treated with an epoxy based fireproofing coating and paint. The same technician following the manufacturer's recommendations applied all reinforcement and protective coatings.

Sets of four cylinders were then heated for 90 min in an electric oven to temperatures up to 185^{o}C. Oven temperatures were monitored closely because of an initial temperature drop that occurs when the mass of concrete is introduced to the oven. Direct exposure to flame was not considered because it was known that this would simply burn off the epoxy resin.

Preliminary tests with coupons of the composite indicated the particular system under consideration would degrade well below 300^{o}C. The cylinders were allowed to cool to ambient temperature, were capped, and then tested in compression to failure. Because composite wrap systems are often used as secondary reinforcement for extreme or infrequent load events, there is a low probability of elevated temperatures occurring simultaneously with an extreme loading event unless the event caused the elevated temperatures. Therefore, this study focused on whether the composite reinforcing system is still effective as secondary reinforcing after cooling and what affect the heat treatment has on the mechanism of failure.

The glass transition temperature of the epoxy used in this study was 121^{o}C. Even at a temperature of 135^{o}c, only a 4% loss of strength was observed. This loss was not statistically significant. By contrast, cylinders heated to 150^{o}C showed a 13% reduction in strength and seam de-bonding replaced hoop split as the predominant mechanism of failure. This result would seem to indicate that a heat-protection system does not need to keep the internal temperature below the glass transition temperature of the epoxy, as exceeding the glass transition temperature showed no significant impact on either strength or failure mode

2-6 THERMAL INSULATION

Plastic material like FRP composites are affected with the exposure to elevated temperature levels. This temperature mainly affects the matrix of these materials, causing it to lose its strength and may be burned and totally evaporate. Also, the resin used for sticking the wrapping layers to the structural elements is affected badly with the rise in temperature. This resin loses its strength at degree around 60-100 ^{o}c and caught fire over temperature of 300 ^{o}c.

For this reason, using of fire protective coating seems to be very essential when fiber wrapping is applied. Many types of fire protective coatings are available in the Egyptian market; the simplest one is a layer of cement mortar with or without gypsum. Also, other chemical bases of fire protective coatings are available in some companies.

The performance of fire-exposed FRP systems can be improved by the use of barrier treatments or coatings. These treatments function either by reflecting radiant heat back towards the heat source, or by delaying heat penetration to the FRP through their isolative and/or ablative properties [14].

It should be realized that insulation does not eliminate heat transfer; it merely reduce it. The thicker the insulation, the lower rate of heat transfer but also it leads to higher cost and weight of insulation. Therefore, there should be an *optimum thickness* of insulation that corresponds to a minimum combined cost of insulation, heat lost, and low own weight.

2-6-1 Classification of thermal insulation

There are several types of insulation available in the market, and some times selecting the right kind of insulation can become confusing job. Therefore, it is helpful to classify the insulations in some ways to have a better perspective of them [65]

Insulation material can be classified broadly as capacitive, reflective, and resistive materials. When we say insulation, we normally mean resistive insulation that is made of low thermal conductivity and offer effective resistance to heat flow despite of its small thickness. Insulation exhibits considerable variation in their structures and their manufactured physical forms. But they can classify into four main groups:

1-<u>Fibrous insulation</u>; as the name implies, fibrous insulation is composed of small diameter fibers that fill an air space. The fibers can be *organic*, such as wool, cotton, wood and animal hair, or *inorganic*, such as mineral wool, glass fiber, and ceramic fibers. They are well suited for high temperature applications as *Mineral wool* and can be used at temperature up to about 1100 ^{o}c while Ceramic fibers, which is alumina –silica compound, can be used at temperature as high as 1750^{o}c

2- Cellular insulation; is characterized by cellular-like structures with closed cells and made of cellular material as cork, foamed plastics, glass , Polystyrene, polyurethane, and other polymers. All these cellular insulation is impermeable and non-combustible; they have upper service temperature of 650^{o}c

3-Granular insulation; they characterized by small nodules with voids, e.g. Calcium silicate (Gypsum), vermiculate, and perlite, these material can used in temperature range of 15to 815 ^{o}c

4-Reflective insulation; they are based on reflecting the thermal radiation incident on the surface back by using highly reflective surfaces, it used to minimized the heat flow by radiation

2.7 SUMMARY AND CONCLUSIONS

It is evident from the material presented in this chapter that information on the fire and high temperature behavior of FRPs and FRP-reinforced concrete members is extremely scarce. At elevated temperatures, all FRP materials currently available for civil structural applications will experience a reduction of both strength and stiffness.

They may experience significant transverse thermal expansion leading to cracking or spalling of the concrete cover or to the development of shear stresses in their adhesive layer. They may ignite. Upon ignition, they may emit dense smoke and toxic gases. They may lose their bond with the substrate or surrounding concrete. All of these concerns have not, at present, been adequately studied or addressed by current design guidelines.

The development of standard tests for FRP materials are required both at room and high temperatures, with both static and dynamic loading and temperature regimes, The mechanical and thermal behavior of FRP materials currently available in industry must be accurately ascertained, such that experimental and parametric numerical studies can be executed with accuracy. Detailed models must be developed and continually updated in order to study the effect of varying a wide range of parameters on the fire behavior of FRP-reinforced. Finally, full-scale fire endurance tests are required in order to validate numerical procedures, and to raise awareness of and confidence in FRP reinforcing materials in the construction industry.

Eventually, it is hoped that this research will lead to the development of complete design guidelines for the use of FRP-reinforced concrete in buildings and structures concerning the elevated temperature and fire exposure and use of insulating material as an integral part in strengthening by FRP. Only when such a design code is produced and sanctioned with confidence by the engineering research community will the use of FRPs for reinforcement and strengthening of concrete gain widespread acceptance and implementation. The objective of this research is to:

a) Evaluate the effect of elevated temperature "above the glass transition temperature of FRP epoxy" on the FRP strengthened columns.
b) Evaluate the effect of different type of fire insulation on the heat transfer, column capacity, mode of failure, and ductility of FRP strengthened columns
c) Evaluate the effect of different thickness for various insulating materials.
d) Evaluate the effect of time with constant temperature on the FRP strengthened columns
e) Evaluate the effect of the elevated temperature on the bond between the FRP and concrete surface
f) Evaluate the effect second heating cycle on the FRP after subjected to elevated temperature
g) Propose an analytical finite element analysis for the heat transfer through insulating material in accordance with the standard fire curve; this leads us to compute the fire endurance and the critical time that the insulated CFRP confining system can be affected by fire exposures. Propose a parametric study to predict the effect of insulation thickness on their fire endurance.

CHAPTER 3

EXPERIMENTAL PROGRAM

3-1 GENERAL

A comprehensive experimental investigation was undertaken to study the effect of elevated temperature on square reinforced concrete (R.C.) columns confined by one layer of carbon fiber-reinforced polymer (CFRP) and insulated by supplemental insulation material applied to the exterior of the CFRP wrap. The columns were tested under axial concentric compression load after being exposed to elevated temperature up to 800^{o}c.

The investigation divided into two major portions; first, diagnose the effect of different levels of elevated temperature with several durations on the structural behavior of the CFRP confinement. Second; treatment of this elevated temperature with varies insulating materials. Furthermore, the devices and the machines used in the experiment will be described and the properties of materials used in this work will be mentioned.

3-2 SCOPE AND OBJECTIVES

The experimental program has been conducted to investigate the effect of different temperature levels "100^{o}c, 200^{o}c, 250^{o}c, 300^{o}c, and at 350^{o}c " and durations "4, 8, 12, and 24 hours" on the structural performance of R.C. square columns. Subsequently, evaluate the effectiveness of different thermal protection materials in increasing the thermal endurance and decrease the heat transfer rate to reach CFRP surface. A total of 19 R.C. square columns were tested thermally using an electric furnace which constructed to serve this experimental program, and then tested under a monotonic axial compression load

Consequently an electric furnace was constructed to serve the experimental program, so it has special specification for this specific purpose, It has rectangular shape with over-all dimension 1000*1000*1100 mm, having square opening in its movable roof with dimension 350*350 mm for column entering. It is designed to have ultimate temperature equal 1000^{o}c using six rows of electric coils.

The current experimental program considered the behavior of 1/3 scale models of RC columns, the models were fully wrapped with one layer of CFRP and subjected to elevated temperature. Furnace temperature was measured by digital control unit contain thermostat connected to a thermocouple located in the center of the furnace back wall. Moreover, the specimens were provided by thermocouples to measure the temperature inside concrete column, on to the interface between the CFRP and the insulating material and on the surface of the insulating material.

A universal testing machine was used for testing specimen after cooling the specimen to room temperature, to determine the ultimate capacity. Also the specimen fitted out with strain gauges to measure the residual strain, to measure the degradation due to exposure to elevated temperature

The main objective of this investigation is to study the effect of several experimental variables on the behavior or R.C. column wrapped with CFRP under elevated temperature. In addition to find a proper treatment for the elevated temperature problem associated with CFRP confined R.C. column; using varies kinds of insulating materials, measure of their thermal endurance at different temperature levels and for what extent the used insulating can decrease the rate of heat transfer to the CFRP surface.

3-3 EXPERMENTAL VARIABLES

As mentioned before, the main objective of this experimental study was to investigate the effect of several experimental variables on the behavior or R.C. column wrapped with CFRP under elevated temperature, the test variable were:

1. Effectiveness of different fire barriers material
    - ***Fibrous Insulation*** (Rock Wool – Ceramic Fibers)
    - ***Granular Insulation*** (Gypsum – Cement Mortar – Cement Paste - Thermal Concrete – Perlite Mix – Sikacrete 213 – and Cement + Gypsum)
2. Temperatures values (70^{o}c- 80^{o}c -90^{o}c -100^{o}c- 200^{o}c -250^{o}c- 300^{o}c- 350^{o}c)
3. Time Durations (4hrs- 8hrs- 12hrs- 24hrs)
4. Effect of heating and cooling cycles
5. Thickness for insulating material.

Two control specimens were prepared to evaluate the behavior of R.C. columns at room temperature; one specimen was unwrapped and the other was wrapped by one layer of CFRP. The rest of columns were tested with variable temperature, time, and barrier type, as shown in table (3.1).

Table (3.1) the Experimented Variables

1	2	3	4	5
Col. No.	Fire protection type	Thickness of protective layer	Heating Duration "Hours"	Tested temp. at CFRP surface
1	Control specimen Unwrapped & Not subjected to elevated temperature			
2	Control specimen Wrapped & Not subjected to elevated temperature			
3	T.C.	40mm	24	70 ^{o}c
4	G	40mm	24	80 ^{o}c
5	C.F.	40mm	24	90 ^{o}c
6	R.W.	40mm	24	100 ^{o}c
7	C.F.	40mm	4	200 ^{o}c
8	R.W.	40mm	8	200 ^{o}c
9	S	40mm	12	200 ^{o}c
10	G	40mm	24	200 ^{o}c
11	U	N.A.	4 hrs	250 ^{o}c
12	U	N.A.	8 hrs	250 ^{o}c
13	S	40mm	12 hrs	250 ^{o}c
14	C+G	40mm	24 hrs	250 ^{o}c
15	C.M.	40mm	4 hrs	300^{o}c
16	C.P.	40mm	8 hrs	300 ^{o}c
17	U	N.A.	4 hrs	350^{o}c
18	T.C.	40mm	8 hrs	350 ^{o}c
19	P	40mm	8 hrs	200 ^{o}c
		20mm		350 ^{o}c

G ***:Gypsum*** ***C.M.*** ***:Cement Mortar*** ***C.P.*** ***:Cement Paste***
C+G ***:Cement + Gypsum*** ***T.C.*** ***:Thermal Concrete*** ***S*** ***:Sikacrete***
P ***:Perlite*** ***C.F.*** ***:Ceramic Fiber*** ***R.W.*** ***:Rock Wool***

Each column is designated by a code name. The key to this code is given in figure (3.1).

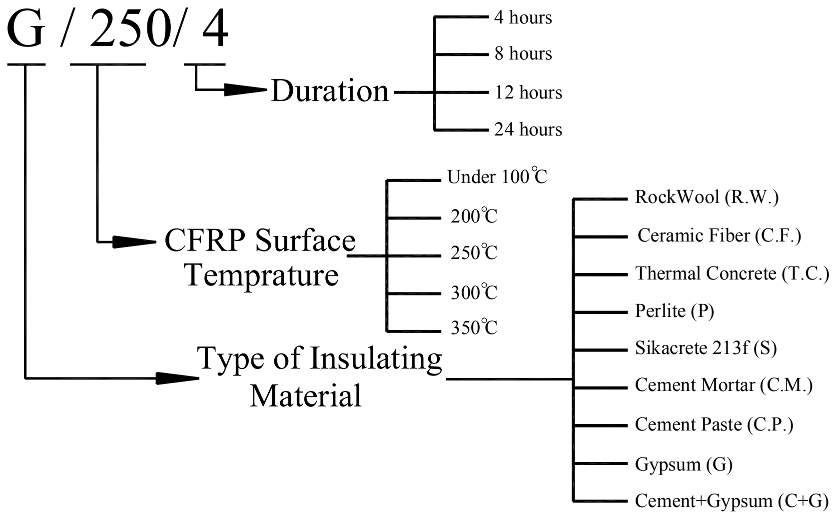


Fig. 3.1 Columns codification

3-4 SPECIMEN CHARACTERISTICS

3-4-1 Specimen Preparation

The casting molds made of 6 mm steel were constructed and used for casting the specimens vertically; they were designed to be stiff enough to prevent any significant movement during placing of the concrete. Moreover the molds construct to have circular corner with 20 mm radius to avoid any kink damage of CFRP jacket due to stress concentration at sharp edges.

Specimens were cast immediately after mixing in the molds, and then compacted using vibrating table. All specimens were exposed to identical curing conditions. After casting, specimens were stored in the laboratory for 24 hr., then de-molded and covered by wet burlap at room temperature for 7 days then allowed to air-dry until testing. It is believed that such curing regime may represent the concrete behavior in actual structures where the concrete is cured for a limited time.

The concrete cover was kept constant at 20 mm in all-RC columns. As an attempt to prevent the occurrence of premature failure at the ends of columns, the 100 mm top and bottom of each column had extra lateral steel reinforcement spaced at 25 mm. Both ends were also capped with external steel cap of 5 mm thickness as shown in Figure (3.2). This configuration forced general failure to occur within the test region. Also the steel cap served to stabilize the column during testing.

Preparation of the concrete substrate and application of CFRP materials were carried out in accordance with the guidelines for application to concrete that was provided by the material manufacturers. Only one Layer of CFRP sheet was used with 100-mm overlap is performed to provide sufficient anchorage in order to achieve the full tensile strength of the fiber sheet and prevent slip between layers. In all cases, the principal fibers were oriented perpendicular to the column axis.

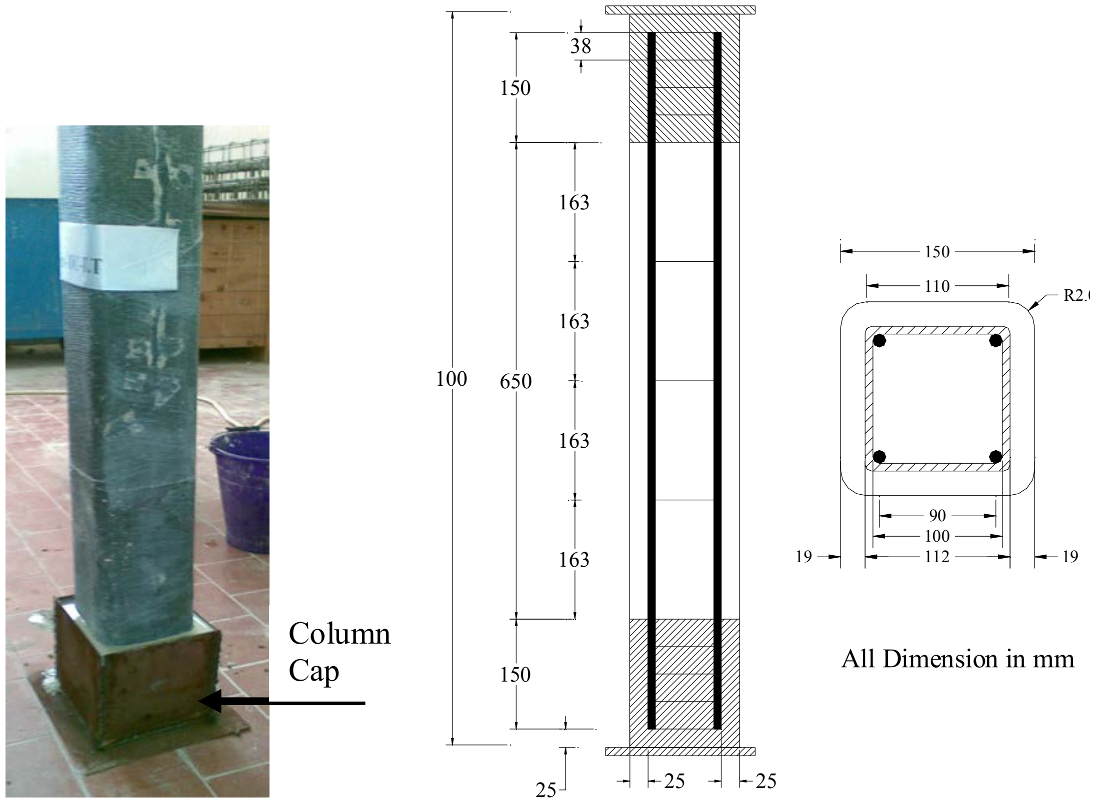


Fig. 3.2 Longitudinal and transverse reinforcing steel arrangement and column capping.

3-4-2 Test Instrumentation and Loading Device

The current experimental program considered the behavior of 1/3 scale models of RC columns, the models were fully wrapped with one layer of CFRP and subjected to elevated temperature. Furnace temperature was measured by digital control unit contain thermostat connected to a thermocouple located in the center of the furnace back wall. Moreover, the specimens were provided by thermocouples to measure the temperature inside concrete column, on to the interface between the CFRP and the insulating material and on the surface of the insulating material.

A universal testing machine with capacity 3000kN was used for testing specimen after cooling the specimen to room temperature, to determine the ultimate capacity. Also the specimen fitted out with strain gauges to measure the residual strain, to measure the degradation due to exposure to elevated temperature, as shown in figure (3.3).

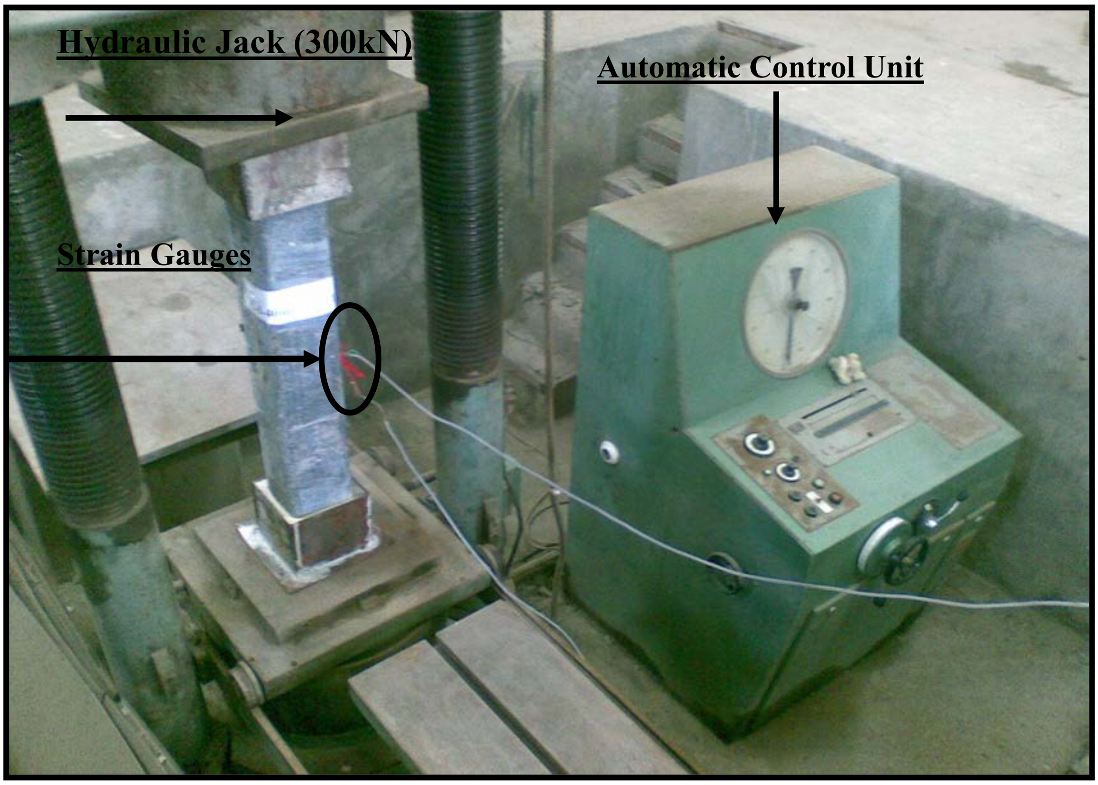


Fig. 3.3 Universal Testing Machine and the Specimen while testing

In the thermal treatment using insulating material, all specimens were heavily instrumented by eight chromel- Alumel (Type J) thermo-couples for measuring temperature at each column side, four of them on the surface of the insulating material and the other on the CFRP surface, as shown in figure (3.4). The results recorded for each test was the average of these four thermocouples as the temperature on each column side was difference due to the vertical and horizontal air flow inside the furnace. On the other hand, in the structural diagnosis, the results recorded for each test included measurements of strains in both longitudinal and transverse directions for CFRP at various load stages.

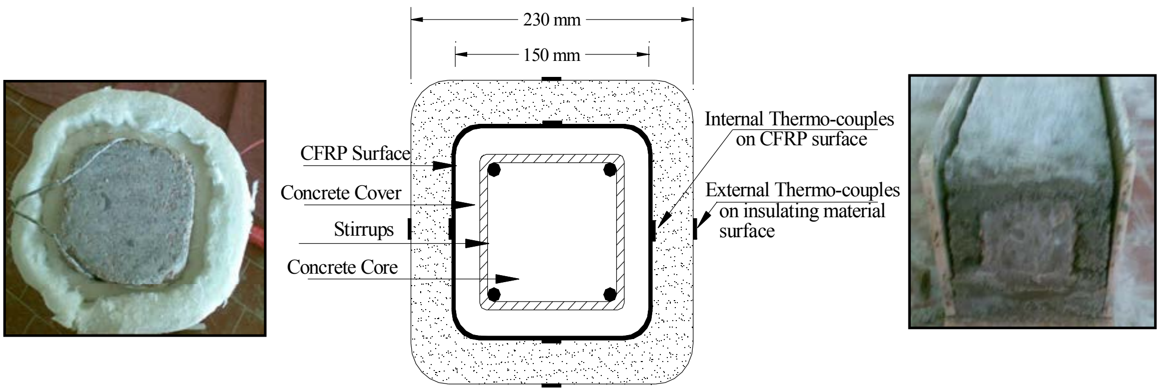


Fig. 3.4 Test specimens / FRP Wrapping / Insulation layer/Thermo-couples

3-5 MATERIAL PROPORTIES

A group of laboratory experiments were carried out to determine the physical and mechanical properties of the concrete column components. The results of these tests were recorded and compared with the covering standard specifications.

3-5-1 Concrete Materials

3-5-1-1 Cement

Ordinary Portland cements (ASTM type I) were used throughout the program for making concrete.

Tests carried out on the cement were:

- Fineness
- Initial and final setting times
- Compression test on cement paste

These tests were carried out according to the Egyptian Code of Practice[66] and results are given in table (3.2)

Table 3.2 Cement Properties

Test Result	Fineness%	Setting time				Compressive strength of cement mortar cubes	
		Initial		Final			
		Hours	Min.	Hours	Min.	3 days	7 days
Value	11.1	1	35	5	10	187kg/cm^2	285kg/cm^2

3-5-1-2 Water

The water used in mixing and curing was clean portable fresh water free from impurities.

3-5-1-3 Aggregate

3-5-1-3-1 Gravel

The Coarse aggregate used, was siliceous gravel. The particles shapes are smooth uniform gravel with nominal size is 19 mm.

Tests were carried out on the gravel and the results are compared to the values listed in the Egyptian Specifications (ESS 1109/71)[66] and listed in table (3.3).

Table 3.3 Coarse Aggregate Properties

Property	Test results	Requirements of E.S.S.
Specific gravity	2.5	2.5-2.7
Unit Weight	1.7 t/cm^3	1.4-1.7 t/cm^3
Voids ratio	25.6%	-------

The sieve analysis test was carried out on the coarse aggregate. The results are listed in table (3-4) and grading curve is shown in figure 3.5.

Table 3.4 Coarse Aggregate Sieve Analysis

Sieve Opening size mm	38.1	25	19	9.5	4.75	2.38
% Passing	100	100	97.7	43.8	1.33	0.05
Limits of E.S.S.	100-100	100-100	90-100	20-55	0-5	0-5

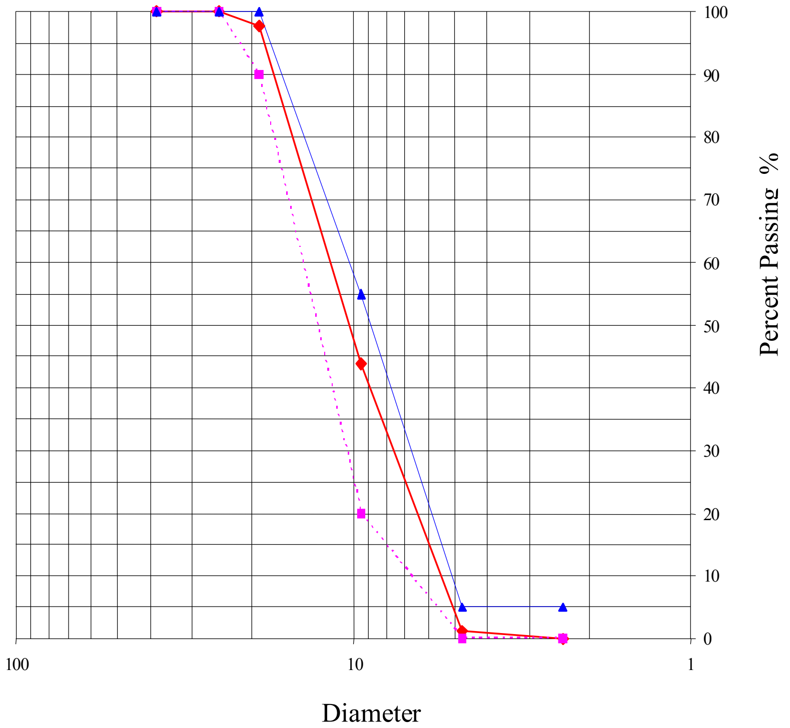


Fig. 3.5 Grading curves of coarse aggregate

3-5-1-3-2 Sand

The fine aggregate used was natural siliceous sand, clean and free from impurities, silt and clay. Table (3.5) shows the results of tests carried out on the used sand and the corresponding values, which are listed in the Egyptian Specification ESS (1109/71)[66]

Table 3.5 Fine Aggregate Properties

Property	*Test Results*	*Requirements of E.S.S.*
Specific weight	2.65	2.5-2.7
Unit weight	1.74 t/cm^3	1.6-1.8 t/cm^3
Percentage of fines	3%	Not more than 3%
Fines Modulus	2.85	1.5-3.75
Organic impurities	*****	Not allowed

The sieve analysis test was carried out. Results are listed in table (3.6) and grading curve is shown in figure (3.6)

Table 3.6 Fine Aggregate Sieve Analysis

Sieve Opening size mm	4.75	2.8	1.4	0.7	0.35	0.15
% Passing	100	95	76	67	18	1
Limits of E.S.S.	100	100-85	100-75	80-60	30-10	10

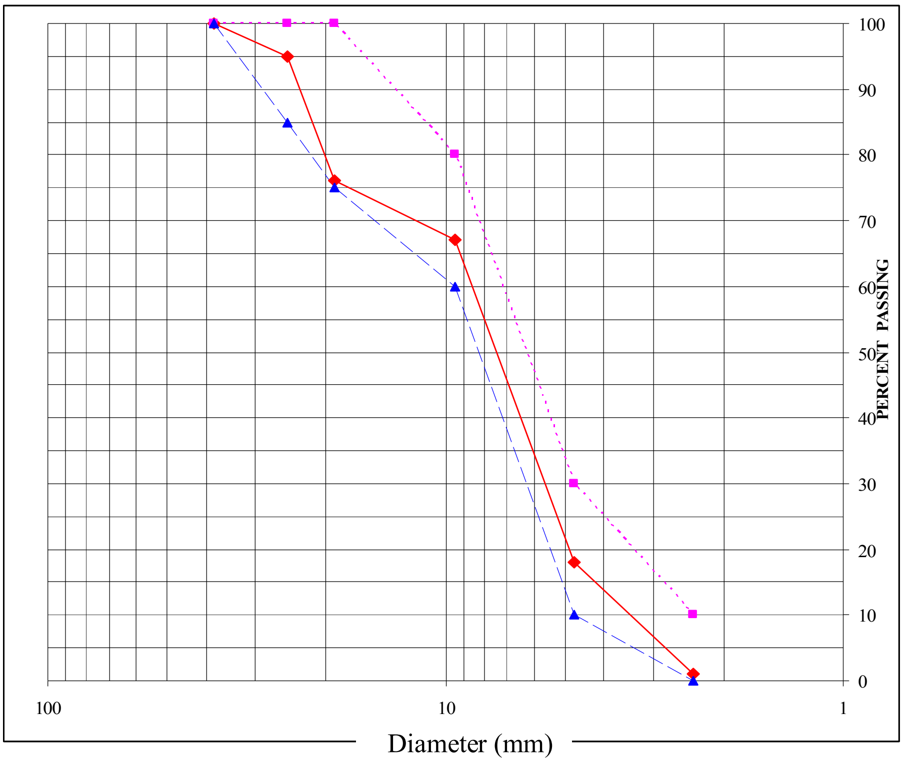


Fig. 3.6 Grading curves of fine aggregate

3-5-1-4 Concrete Mix Design

The absolute volume method (recommended by the ACI committee) was used to compute the quantities of material required for a test batch. Knowing that the cement contain 350 kg/m^3, water - cement ratio was 0.55 based on free water, and fine aggregate to the coarse aggregate ratio was 1: 1.8. No additives were incorporated in concrete. Table (3.8) shows the weight of concrete constituents for mixing 1m^3

Table 3.7 Concrete Mix Composition, kg/m^3

Cement (Kg/m^3)	Water (Litre/m^3)	Coarse aggregate (Kg/m^3)	Fine aggregate (Kg/m^3)
350	200	1200	650

3-5-1-5 Concrete Mixing & Testing

Dry materials required for each batch were weighed and then mixed dry for minute to ensure the uniformity of the mix, then water added to the dry materials and the contents were thoroughly mechanically mixed for a period of two minutes.

3-5-1-5-1 slump test

Slump test was carried out to control the plastic consistency of the fresh mix. This test was carried out according to the Egyptian standard specification and the slump = 120 mm.

3-5-1-5-2 Testing of hardened concrete

Hardened cubes and cylinders specimens were tested to determine compressive strength and modulus of elasticity for concrete. The target concrete cube compressive strength was 25 MPa after 28 days

3-5-2 Reinforcing Steel Bars

The two types of steel are used high tensile steel for the longitudinal reinforcement of diameter 10 mm and grade 360/520, and mild steel for the transverse reinforcement (stirrups) of diameter 6 mm and grade240/360.

Four longitudinal steel bars are used for each column, and distributed at the corners of the column, the spacing between the stirrups are 150 mm in the middle part of column and equal 25 mm at 100mm at the both end of column to make extra confinement to help in preventing premature failure at the end of the column as shown in Figure (3.7)

Fig. 3.7 Reinforcing steel cage

3-5-3 Carbon Fiber Reinforced Polymer Sheets (CFRP) Characteristics

The composite strengthening system used in this research study was provided by Sika for Construction, Inc. The system is comprised of two basic components namely: Sikadur 330 "2 part epoxy impregnation resin" and SikaWrap 230 C "Woven carbon fiber fabric for structural strengthening" . The combination of these two components forms a high-strength CFRP wraps.

3-5-3-1 Epoxy Resin

The fiber sheets were bonded to the concrete surface using two parts, solvent free; trixotropic based impregnating resin/adhesive. It consists of mixture of two parts; Resin part A "white color" + Hardener part B "grey color", their mixing ratio Part A: Part B = 4:1.

The epoxy resin gives the concrete bonding adhesive for the use of carbon fiber fabric "Sika Wrap 230C"; also it gives high tensile bond strength to the composite system. The properties of the resins in tension are listed in Table (3.8). The values listed were obtained from manufacturer.

Table 3.8 Resin Properties

Density (Mixed Resin)	1.3 Kg/lt
Thermal expansion coefficient	$45*10^{-6}$ /^{0}c
Thermal resistance	Continuous exposure +50^{0}c
Chemical resistance	Not suitable for chemical exposure
Tensile strength	30 N/mm^2
Modulus of Elasticity	4500N/mm^2
Elongation at break	0.9%

3-5-3-2Carbon Fiber Sheets (Sikawrap 230C):

The carbon fibers used in this research were in the form of dry unidirectional flexible sheets, the sheets had a paper backing and were supplied in a roll of 300mm width. The carbon fibers were manufactured by pyrolizing polyacrylonitrile (PAN) based precursor fibers at temperature of approximately 1500 ^{o}C. The result of the pyrolization process was a highly aligned carbon fiber chain. The carbon fiber filaments were assembled into untwisted tows that were then used to create a continues unidirectional sheet

According to the manufacturer's information, the tensile strength of CFRP 230 sheets (230 gm/m^2) is 4300 MPa, the modulus of elasticity is 238 GPa, the design thickness is 0.131mm, elongation at break 1.8%, the density is 1.76g/cm^3 and the total weight of the sheets is 230gm/m^2. Note that, the tensile strength and elastic modulus of the resin is neglected in computing the strength of the system. Therefore, stresses are calculated using the net area of the fiber only.

3-5-3-3Installation Procedure:

CFRP sheets were attached to the concrete surface by manual lay-up. Preparation of the concrete substrate and application of CFRP materials were carried out in accordance with the guidelines for application to concrete that was provided by the material manufacturers, which may be summarized as follows:

- The substrate must be sound and of sufficient tensile strength to provide minimum pull off strength of 1.0 N/mm^2 , the surface must be dry and free of contaminates such as oil, grease, and coatings.
- The surface to be bonded must be level, and high spots can be removed by abrasive blasting or grinding, to make the epoxy primer penetrates through the concrete and make strong bond between the concrete and FRP sheets.
- Wrapped corner must be rounded to minimum radius 20 mm (this achieved already before casting concrete through the rounded corner steel forms.
- The prepared concrete surface was coated with a layer of epoxy –based primer using a short nap roller. The function of the primer is to penetrate the concrete pores to provide an improved bond.
- The fiber sheets were measured and pre-cut prior to installing on the surface. Each sheet was then placed on the concrete surface and gently pressed into the epoxy . Prior to removing the backing paper, a trowel was used to remove any air bubbles. After the

backing paper was removed, a ribbed roller was rolled in the fiber orientation to facilitate impregnation by separating the fibers.

3-5-4 Fire barrier materials

This experiment program contains nine types of fire insulating material, with different chemical compositions, thermal, and mechanical properties.

3-5-4-1 Sikacrete 213 F

This material is cement based, dry mix fire protective mortar for wet sprayed applications especially in tunnel constructions, it contains phyllosilicate aggregates, which are highly effective in resisting the heat of hydrocarbon fires.

The properties of the mortar are listed in Table (3.9). The values listed were obtained from manufacturer.

Table 3.9 Mortar Properties

Density (plastered) Density(sprayed)	550.1 Kg/m^3 711.4 Kg/m^3
pH value	12-12.5
Compressive strength	4.0 N/mm^2
Thermal conductivity(plastered) Thermal conductivity(sprayed)	*0.149* W/mK at 20 ^{o}c *0.227* W/mK at 20 ^{o}c
Consumption	6 Kg/m^2 for a layer 10 mm thickness

3-5-4-2 Thermal Concrete (ACR-fire-proof 40)

Varieties of lightweight alumino-silicate castables with Al_2O_3 content of 38-52% and bulk density of 0.9 – 1.4 g/cm^3 are produced as insulating types, using different lightweight aggregates as well as hydraulic, chemical and ceramic binding materials. After mixing these castables with the proper amount of water, casting hydrating and drying, they accepted physical and thermo-mechanical values as shown in the table (3.10).

Table 3.10 Mortar Properties

BRAND NAME	**ACR-FIRE-PROOF 40**
Chemical Composition (wt %):-	
Silica,(SiO_2)	39-44%
Alumina,(Al_2 O_3)	35-40%
Iron,(Fe $_2O_3$)	*5-6%*
Lime,(Cao)	10-12%
Physical and thermo-mechanical Properties	
Max. Service temperature,(^{o}c)	1200
Grain Size,(mm)	0-6
Water Required, (%)	20-30%
Bulk Density,(gm/cm^3)	1.0-1.4
Modulus of Rupture,(kg/cm^2)	30
Thermal Conductivity ,(W/m.K)	0.25

3-5-4-3 Structural Perlite

The perlite paste consist of structure perlite and Ordinary Portland Cement, this paste have the ability for fire resisting and fire endurance up to 1280 ^{o}c. It has many uses in the internal and external plastering to protect the concrete columns and steel section from fire dangerous so it can resist direct fire up to 4 hours.

The usage theory of perlite to protect the structural member depends on:

1- When the perlite mortar facing fire the hydrated water particulars dissipate to emerge out as water vapor to save the surface temperature to 100 ^{o}c

2- Since the perlite is an insulating material for temperature the perlite mortar resist the heat flow from the fire place to the structure member and prevent reaching the critical heat temperature o the structure member

3- The low coefficient of longitudinal thermal temperature prevent initiate crakes in the protecting layer

4- The storage heat capacity for the structure member depend on its density and the perlite mortar density is less than the ordinary mortar by 50-60%, which help the structure member to return to its original temperature very fast after extinguishing the fire

The properties of the Perlite mortar are listed in Table (3.11). The values listed were obtained from manufacturer.

Table 3.11 Perlite Mortar Properties

Density	125- 196 Kg/m^3
Dry Density	1200 Kg/m^3
Thermal conductivity(dry perlite)	*0.04-0.06* W/m °c
Thermal conductivity(perlite mortar)	*0.12* W/m °c
Compressive strength	2.5-3 N/mm^2
Maximum service temperature	1280 °c

The guidelines for the perlite mortar mix use in many countries to protect the structures from the fire dangers in the shown table (3.12).

Table 3.12 Perlite Mortar Mix Guidelines

Mix Proportions			***Mix Physical Properties***	
Cement (kg)	***Perlite (lt)***	***Water(lt)***	***Dry Density(kg/m^3)***	***Compressive strength(N/mm^2)***
60	100	33	1200	13-14

<u>3-5-4-4 Rock wool (LAPINUS Wired Mats 159)</u>

Lapinus Wired Mats Rock wool 159 is a lightly bonded stone wool mat stitched on galvanized wire; they are particularly suited to meeting the specification requirements of thermal insulation, fire protection and sound attenuation of large process pipe-work, tanks, vessels, boilers and ducts

Lapinus Wired Mats 159 is especially suitable where high temperature combine with vibration or a high fire resistance is required, the wired mats conform to ASTM C 592 Class II "Standard Specification for Mineral Fiber Blanket Installation (Metal Mesh Covered), Industrial Type"

Lapinus Wired Mats 159 is light, easy to handle, Non combustible, low chloride content, cost effective, and high water repellent. The used mats have 1000 mm width and 50 mm thickness. Table (3.13) shows some thermal properties and its related standards

Table 3.13 Physical and Thermo-mechanical Properties for Rock wool

Physical and Thermo-mechanical Properties	**Performance**								**Standard**
Thermal Conductivity	T(^{o}c)	50	100	150	200	250	300	350	EN 12667
	K(W/mk)	0.040	0.046	0.052	0.060	0.069	0.081	0.097	
Maximum Service Temperature	750 ^{o}c								ASTM C411
Water Absorption	1 Kg/m^2								ASTM C1104M
Reaction with fire	Non- Combustible								ASTM E84
Normal density	100 kg/m^3								
Specific heat	840 J/kg.^{o}c								

3-5-4-5 Ceramic Fibers (Cerakwool 1300 Blanket)

Cerakwool Blanket is a light weight, flexible and high thermal insulation processed from basic Bulk fiber, as Cerakwool Blanket contains neither inorganic nor organic binder, it never contaminates furnace atmosphere and never emits offensive odors during furnace operating

Moreover it has High thermal insulation for general use (electric furnace, diffusing furnace, etc), insulating lining material for furnace ceiling and walls (annealing furnace, heat treatment furnace, etc,). The used Blanket has 600 mm width and 25 mm thickness. Table (3.14) shows some thermal properties.

Table 3.14 Physical and Thermo-mechanical Properties for Ceramic Fiber

Density	96 -128 kg/m3
Thermal conductivity	*0.045-0.06* W/m ^{o}c (200 ^{o}c)
	0.085-0.11 W/m ^{o}c (400 ^{o}c)
	0.152-0.2 W/m ^{o}c (600 ^{o}c)
Color	White
Maximum .Service Temperature	1316 ^{o}c
Tensile Strength	0.06Mpa
Specific Heat	1000 J/kg. ^{o}c

3-5-4-6 Regular Gypsum (hydrated calcium sulphate) CaSO4.2H2O

Gypsum "Gypsum board" is a common fire barrier used in house and general building construction. The thermal conductivity of gypsum is shown in figure (3.7) as a function of temperature[67, 68].

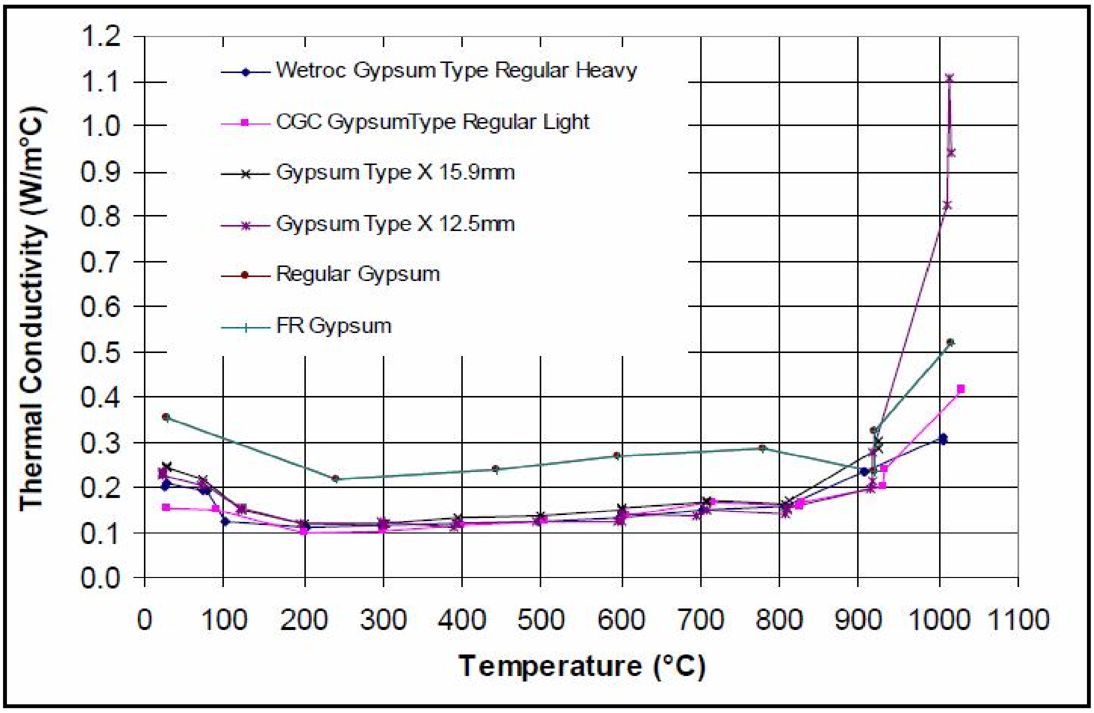


Fig. 3.8 Thermal Conductivity versus Temperature for different types of Gypsum

The thermal conductivity, for all types of gypsum, decreases almost linearly up to a temperature of 200°C, then shows a slight increase from 200°C to about 800°C by an average value 0.17 w/mk, and finally a sharp increase especially after a temperature of 900°C. The thermal conductivity of regular gypsum and FR gypsum is higher than that of the other types in the temperature range of 40°C to 900°C with an average value 0.25 w/mk.

This can be attributed to the higher crystallinity of Regular gypsum and FR gypsum as compared to other materials. The higher the crystallinity, the more the thermal conductivity and its rate decrease with temperature. This can also be due to more cracks and propagation in Regular gypsum and FR gypsum, which increases the rate of heat transfer in the specimen.

3-5-4-7 Standard Cement Mortar

The standard cement mortar used as plastering, have been used as insulating material, the standard mixing ratio is Cement: Standard Sand: Water = 1: 2.75: 0.4.

3-5-4-8 Cement – Gypsum Mix

Mixing Cement with gypsum will lead to maintain both relatively high strength, low thermal conductivity and decrease cracks propagations due to high mechanical properties

Cement and thermal properties for Gypsum respectively, the mixing ratio was Cement: Gypsum: Water = 1:0.5:1

3-5-4-9 Standard Cement paste

Standard cement paste used for insulating the CFRP layers, the water content was about 30% of cement weight.

Thermal and mechanical properties for the used insulating material have been summarized in table (3.15)

Table 3.15 Summary for the Thermal and mechanical Properties for the used insulating materials

	Thermal and Mechanical Properties*					
Insulating Material	Thermal Conductivity W/mK	Specific Heat **J/kg .°c**	Density Kg/m^3	Strength N/mm^2	Max. Service Temp. **°c**	**Water Required (%)**
Rock wool	0.04 at 50 °c 0.052 at 150 °c 0.069 at 250 °c 0.097 at 350 °c	840	100	**N.A.**	**750**	**N.A.**
Ceramic Fibers	**0.045-0.06 at 200 oc 0.085-0.1 at 400 oc 0.152-0.2 at 600 oc**	**1000**	**128**	**Tensile 0.06**	**1316**	**N.A.**
Sikacrete 213 F	**0.149 at 20 oc**	**N.A.**	**550**	**4.0**	**1350**	**100**
Thermal Concrete	**0.25 at 20 oc**	**N.A.**	**1400**	**3.0**	**1200**	**20-30**
Structural Perlite	**0.12 at 20 oc**	**837**	**1200**	**1.3-1.4**	**1280**	**33**
Gypsum	**0.17 at 20 oc**	**1090**	**2300**	**6.0**	**N.A.**	**100**
Standard Cement Mortar	**1.16 at 20 oc**	**1200**	**3120**	**36**	**N.A.**	**40**
Cement – Gypsum Mix	**N.A.**	**N.A.**	**2700**	**25**	**N.A.**	**100**
Standard Cement Paste	**1.0 at 20 oc**	**1550**	**3120**	**30**	**N.A.**	**30**

* The values listed were obtained from manufacturer.

3-5-5 Insulating Process

Four thermocouples were installed and bonded on the CFRP surface before being covered by insulating materials. All specimens were insulated either by wrapping with fibrous insulating material or pouring the granular insulation mixture around it using special molds, as shown in figure (3.9). The insulating thickness was constant for both fibrous and granular insulating material equal 40mm. The columns insulated with granular materials have being cured for 28 days by covering it with wet burlap to ensure that the internal water has been react with all insulating granular materials.

After testing the insulated columns by subjecting them to the purposed elevated temperature, all the insulating materials have been removed to inspect the CFRP sheets and the bond between CFRP sheets and concrete surface.

Fig. 3.9 Insulating the tested Columns using different insulating materials.

3-6 THE ELECTRIC FURNACE

3-6-1 Electric Heating Methodology

Electric heating is method of converting electric energy to heat energy by resisting the free flow of electric current, it has several advantages; it can be precisely controlled to allow a uniformity of temperature within very narrow limits; it is cleaner than other methods of heating because it does not involve any combustion; it is considered safe because it is protected from overloading by automatic breakers; it is quick to use and to adjust; and it is relatively quiet. For these reasons, electric heat is widely chosen for industrial, commercial, and residential use.

Resistance heaters produce heat by passing an electric current through a resistance coil, wire, or other obstacle which impedes current and causes it to give off heat. Heaters of this kind have an inherent efficiency of 100% in converting electric energy into heat. The degree of heat generation by electric conductors carrying current is proportional to the electrical resistance of the conductor. If the resistance is high, a large amount of heat is generated, and the material is used as a resistor rather than as a conductor. In addition to having high resistivity, heating elements must be able to withstand high temperatures without deteriorating or sagging. Other desirable characteristics are low temperature coefficient of resistance, low cost, formability, and availability of materials. Most commercial resistance alloys contain chromium or aluminum or both, since a protective coating of chrome oxide or aluminum oxide forms on the surface upon heating and inhibits or retards further oxidation

Since heat is transmitted by radiation, convection, or conduction or combinations of these, the form of element is designed for the major mode of transmission. The simplest form is the helix, using a round wire resistor, with the pitch of the helix approximately three wire diameters. This form is adapted to radiation and convection and is generally used for room or air heating. It is also used in industrial furnaces, utilizing forced convection up to about 1200°c. Such helixes are stretched over grooved high-alumina refractory insulators and are otherwise open and unrestricted

3-6-2 Electric Furnace Manufacturing

The furnace has been constructed to serve this experimental program, so it has special specification for this specific purpose. It was manufactured by **ABU-KIER FERTILIZERS AND CHEMICAL INDUSTRY COMPANY**. It has rectangular shape with over-all dimension 1000*1000*1100 mm and clear space inside the furnace 500*500*900 mm, having square opening in its movable roof with dimension 250*250 mm for column entering. It is designed to have ultimate temperature 1000oc using six rows of electric coils.

3-6-2-1 Construction Stages of the Furnace

The construction of this furnace passed through several stages from construction the skeleton then the electric installation and isolation the furnace wall and roof, operation experimentation, and then finally the furnace calibration

3-6-2-1-1 Building the Furnace Skeleton

The first step was building the external steel skeleton using steel plate 6 mm thickness and yield stress 360 MPa welded together by "welding wire CST 35.8, No. E6013" with steel angles at edges, in addition to two I.P.E. beams No. 100 were welded to the bottom of the floor externally to help in holding the furnace and to make the furnace settled on it.

Secondly, the floor has been built using 200 mm of thermal concrete placed above it a steel plate of 20 mm thickness to ensure that the column specimen rest on a smooth, rigid, and horizontal surface. Thirteen stainless steel tubes with 10 mm diameter were welded to the backside steel wall of the furnace by Argon welding "Stainless steel 308", twelve of them as an outlet for the six rows of the electric coils, and the other single tube was placed in the center of the furnace wall as an inlet for the thermocouple that measures the furnace temperature, inside these tubes a thin ceramic tubes with 8mm diameter was inserted inside them to avoid electric conduction to the furnace. Figure (3.10) shows the steel skeleton, hangers, and the aluminum tubes.

Fig.3.10 Furnace steel skeleton and the stainless steel tubes

Subsequently, two layers of concrete have been poured to build the furnace wall, these layers also represent a internal thermal isolation layer as it consist of highly resistance and isolation thermal concrete. The first layer 50 mm of light thermal concrete "29% Alumina", while the second layer 100 mm thermal concrete " 42% Alumina". Six rows 30 mm height have been grooved in this layer during pouring concrete using wooden moulds, this rows act like shelves to settle the electric coils on it.

The furnace roof was made of steel plates, having 350mm square opening to facilitate the entrance of the column specimen through it, the roof designed to be portable for repair or maintenance purposes might be done for the furnace.

Eight stainless steel bars covered by ceramic tubes were placed in front of the furnace wall and fixed from top and bottom of the wall, in order to hinder moving or falling down the electric coils from its position. As shown in figure (3.11), four of them placed in each corner and the other four were placed in the middle of each wall.

Fig. 3.11 Grooving the coils shelves and installing the coils hinders

3-6-2-1-2 Electric Installation

The source of temperature was six rows of electric coils passed around the circumference of the furnace inside their groves, these coils made of nickel- chrome having 2 mm diameter and electric capacity of 2 K.W per each row.

All these coils connected to an electric source 380 volt, 3 phase power supply. Each two electric coil connected to one phase, all the start of coils are connected to 380 volt and the ends collecting in one point in a cupper bar, to achieve the maximum capacity for coils and lowest ampere.

A control panel was supported on the furnace wall externally having the fuses circuit cutoff 36 ampere, as shown in figure (3.12). In addition to18 kw conductor and digital displayed temperature unit were fixed on it.

Fig. 3.12 Electric coils insides grooves and electric circuit

3-6-2-1-3 Furnace External Insulation

A Rock Wool layer of 70 mm thickness covered with a thin layer of aluminum sheets was used to isolate the whole furnace walls and roof. The furnace roof was internally insulated by a 130 mm layer of Glass Wool as it will be facing the furnace temperature directly.

Double layer of Ceramic Fibers connected to the steel roof by anchors welded by welded wire "Incaloy No.82". Also thin layer of "Teflon "were added between the roof and the wall to prevent any thermal leakage through this interface. Figure(3.13) shows the external insulation for walls and roof


Fig. 3.13 External insulation for walls and roof

3-6-2-1-4 Operation Experimentations

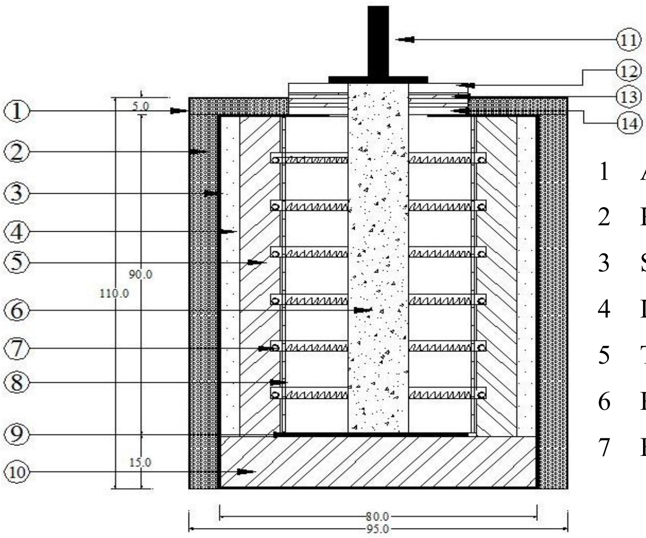
The final stage was to test the furnace after operating, so the electric current switched on and the temperature was increased gradually. After temperature reached about 110^{o}c the temperature suddenly falls down to 100^{o}c, this is due to the evaporation of the water vapor comes out from the concrete walls, and condensing on the electric coils which making the cooling of furnace again.

Another externally electric coil was inserted into the furnace to cure the concrete walls until it got rid of most gases and water vapor, then turn on the furnace electric coils and increase the temperature very slowly during week to reach the ultimate temperature 800^{o}c.

A valve nozzle with 40 mm diameter was welded on the furnace roof to permit the gases and water vapor inside the furnace wall or concrete specimen moves outside, and to prevent any condensation of water vapor on the electric coils, as shown in figure (3.14)

Fig. 3.14 Furnace curing and nozzle welding

The furnace was sponsored by **ABU-KIER FERTILIZERS AND CHEMICAL INDUSTRY COMPANY**. The details of the furnace are shown in figure (3.15).



1	Aluminum sheets	8	Ceramic tube
2	Rock wool layer	9	Steel plate
3	Steel plate	10	Thermal concrete
4	Light thermal concrete	11	Hydraulic jack
5	Thermal concrete	12	Glass wool layer
6	R.C. column specimen	13	Thermal concrete
7	Electric coils	14	Glass wool layer

Fig. 3.15 Schematic diagram for furnace cross section

CHAPTER 4

EXPERMENTAL RESULTS

4-1 GENERAL

In the following sections, the results obtained from testing nineteen columns included in the experimental program are presented, discussed and analyzed. This section divided to two main parts. First, the structural behavior for the strengthened R.C. columns at various elevated temperature degrees for different durations, the results recorded for each test included measurements of strains in both longitudinal and transverse directions for the tested columns at various load stages, failure load, the observed crack pattern and mode of failure at ultimate are reported. Furthermore comparisons between the test results to investigate the tested variables affecting both strength and ductility of the strengthened columns are reported and discussed. Secondly, the thermal treatment using nine different local available and economic thermal insulating materials to obtain the thermal endurance for each material according to the constructed furnace heating rate, all data for temperature levels on the insulating material surface and CFRP surface are recorded at constant time intervals

4-2 STRUCTURAL BEHAVIOUR UNDER ELEVATED TEMPRATURE

All columns were get out of the furnace after expose to the tested variable temperature on the CFRP surface for the specific durations, then the insulating material have been removed, and prepared for testing using the universal testing machine

The stress-strain curves were plotted for both axial and transverse strains for all tested specimens. The tested specimens were grouped to six groups according to the effecting temperature levels "room temperature, below 100^{o}c, 200 ^{o}c, 250 ^{o}c, 300^{o}c, and 350 ^{o}c", each group have different duration for constant temperature level" 4 hrs, 8 hrs, 12 hrs, and 24hrs".
The test results of the nineteen columns are listed in Table (5.1) which includes:

1. The ratio between column failure stress (f) and the characteristic compressive strength for concrete (f_{cu}), this normalization due to small deviations in the characteristic compressive strength for concrete cubes in the used concrete batches, which will affect the ultimate column capacity in the specimens. The column failure stress measured by dividing the ultimate column capacity by the column cross section.
2. Modes of failure (Crushing in concrete followed by rupture in CFRP Or De-bonding between CFRP and concrete surface.)

3. The ultimate strains in both axial and transverse directions
4. The ratio between the ultimate transverse strains to the corresponding strain for the confined control specimen tested at room temperature.
5. The loss in Confinement effectiveness with respect to control columns

Table 4.1 Structural test results

1	2	3	4	5	6	7	8
Col. No.	*Column*	f/f_{cu}	*Failure Mode*	*Ultimate Axial Strain*	*Ultimate Transverse Strain*	$\varepsilon_{t,cu} / \varepsilon_{t,co}$	*Loss in Confinement effectiveness with respect to control columns*
1	CFRP Control	1.78	Crushing	0.015	0.006	1	0.0 %
2	RC Control	1.09	Crushing	0.009	0.0004	0.06	100 %
3	T.C.- 70- 24	1.78	Crushing	0.01	0.006	1	0.0 %
4	G- 80- 24	1.78	Crushing	0.01	0.005	0.83	0.0 %
5	C.F.- 90-24	1.77	Crushing	0.01	0.005	0.83	1.50 %
6	R.W.- 100-24	1.76	Crushing	0.01	0.005	0.83	2.9 %
7	C.F.- 200-4	1.69	Crushing	0.008	0.005	0.83	13.0 %
8	R.W.-200-8	1.64	Crushing	0.008	0.005	0.83	20.0 %
9	S- 200-12	1.61	Crushing	0.007	0.005	0.83	24.6 %
10	G-200-24	1.55	Crushing	0.005	0.003	0.5	33.3 %
11	U-250-4	1.57	Crushing	0.008	0.005	0.83	30.4 %
12	U-250-8	1.51	Crushing	0.005	0.005	0.83	39.1 %
13	S-250-12	1.47	Crushing	0.005	0.003	0.5	44.9 %
14	C+G -250-24	1.05	De-bonding	0.006	0.0005	0.08	105 %
15	C.M.-300-4	1.49	Crushing	0.004	0.005	0.83	42.1 %
16	C.P.- 300-8	1.05	De-bonding	0.001	0.0002	0.03	105 %
17	U-350-4	1.31	De-bonding	0.001	0.001	0.16	68.1 %
18	T.C.- 350-8	1.02	De-bonding	0.003	0.0004	0.06	110 %
19	P-200 / 400-12	1.05	De-bonding	0.001	0.003 / 0.0004	0.5/0.06	100 %

G	***:Gypsum***	***C.M.***	***:Cement Mortar***	***C.P.***	***:Cement Paste***
C+G	***:Cement + Gypsum***	***T.C.***	***:Thermal Concrete***	***S***	***:Sikacrete***
P	***:Perlite***	***C.F.***	***:Ceramic Fiber***	***R.W.***	***:Rock Wool***

$\varepsilon_{t,\ cu}$ = The maximum transverse strain measured at failure.

$\varepsilon_{t,\ co}$ = The maximum strain for control specimen.

4-2-1 Behavior of control specimens at room temperature

In the control un-confined reinforced concrete column (RC Control), the concrete cover spalled off and the longitudinal steel reinforcement buckled at an applied load of 400 kN, and the ratio between column stress at failure and concrete characteristic compressive strength (f/f_{cu}) was 0.9. On the other hand, while testing the control confined column (CFRP Control), which was strengthened with one layers of CFRP, an early noise due to concrete cracking was noticeable when the applied load approached 390 kN. This level may be corresponding to the unconfined strength of the column. The column could attain an ultimate load of 650 kN, and the ratio between column stress at failure and characteristic compressive strength (f/f_{cu}) was 1.9. The test was terminated due to the rupture of CFRP sheets. De-bonding between CFRP and concrete did not occur. Figure (4.1) shows Columns mode of failure.

Fig. 4.1 Failure mode for both confined and un-confined columns at room temperature

The stress versus transverse and axial strain for both columns is illustrated in Figure (4.2). The curves to the right represent the plots of axial stresses versus transverse strains, whereas the curves to the left show the plots of axial stresses versus axial strains. The response of FRP-confined concrete can be considered bilinear with no descending branch. Other investigators[13,14] also confirm the bilinear trend for circular and rectangular columns. The response consists of three distinct regions. In the first region, the behavior is similar to the plain concrete, because the lateral expansion of the core is insignificant with micro-cracking increasing, then a transition zone results in which the CFRP jacket exerts a lateral pressure on the core to counteract the core's stiffness degradation. Finally, a third region is recognized, in which the jacket is fully activated and the stiffness is generally stabilized around a constant rate. The response in this region is mainly dependent on the stiffness of the jacket.

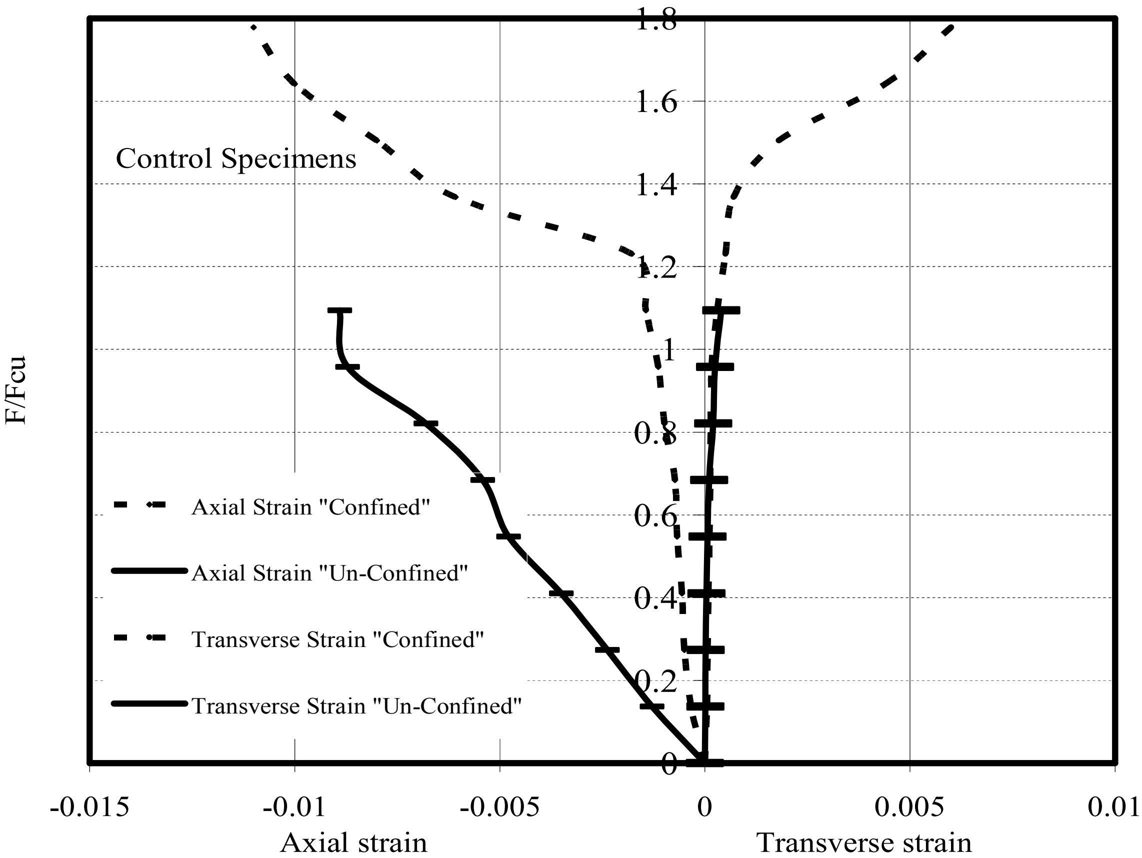


Fig. 4.2 Axial stress vs. transverse and axial strains for both confined and Unconfined Columns at room temperature

The presence of one layers of CFRP could improve the column capacity by about 63.3%, and could improve the ultimate transverse strain from 0.0004 for the Un-confined column to 0.006 for the confined column. Concerning the ultimate strain the confined Column could undergo large axial strain 0.015 as compared to a strain of 0.006 achieved when CFRP does not exist. It should be reported herein that the maximum measured transverse strain in CFRP in confined column at failure was approximately 0.006 mm/mm, which corresponded to 40 %

only of the reported ultimate strain of CFRP. This implies that failure initiated at a location away from the location of strain gage.

The concrete constituent did not significantly influence the behavior of columns because the temperatures in the concrete remained well below the temperature (about 300˚C) at which it begin to play an important role. Similarly, the temperatures in the reinforcing steel can be assumed (on the basis of the temperatures measured at the surface of the concrete), sufficiently low as to not have significantly reduced the mechanical properties of the steel during the fire test.

4-2-2 Behavior of R.C columns confined by CFRP below 100^{o}c

In this series, four R.C. columns confined by CFRP were tested under 70^{o}c, 80^{o}c, 90^o, and 100^{o}c for 24 hours; they were insulated by Thermal Concrete, Gypsum, Ceramic fibers, and Rock wool respectively. The aim of increasing the testing temperature level by 10^{o}c only was to ensure that continues exposure to temperature above the glass transition till 100^{o}c haven't any effect on the CFRP confining system efficiency.

All columns were subjected to the elevated temperature for 24 hours, a slight decrease in the ultimate capacity of the column that subjected to 100^{o}c for 24 hours by only 2.9 %, in spite of that all R.C. columns failed by the rupture in the CFRP sheets. On the other hand no change in both strength and ductility for R.C. subjected to elevated temperature till 90^{o}c. De-bonding between CFRP and concrete did not occur, and the failure occurs around the mid height of the column. Furthermore, by visual inspection, no changes had occurred to the CFRP surface after heating to 100^{o}c as shown in figures (4.3) and (4.4).

Fig. 4.3 Failure in Columns T.C.-70-24, and G-80-24

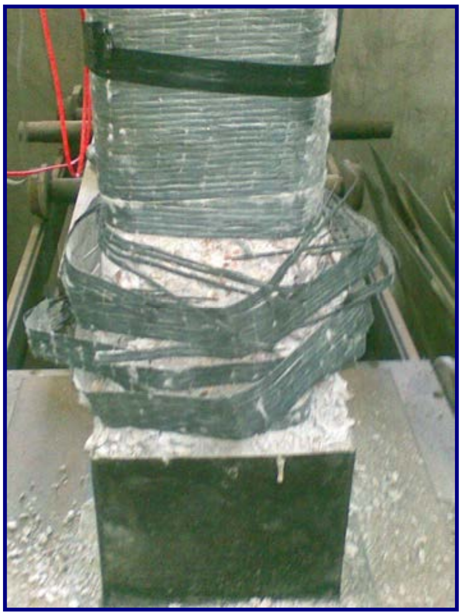


Fig. 4.4 Failure in Columns C.F.-90-24, and R.W.-100-24

Comparisons between the stress versus transverse and axial strain curves for the four R.C. columns at different temperature levels are illustrated in Figure (4.5). No significant deterioration in both axial and transverse strains was observed for all columns subjected to the raise in temperature till 100^{o}c.

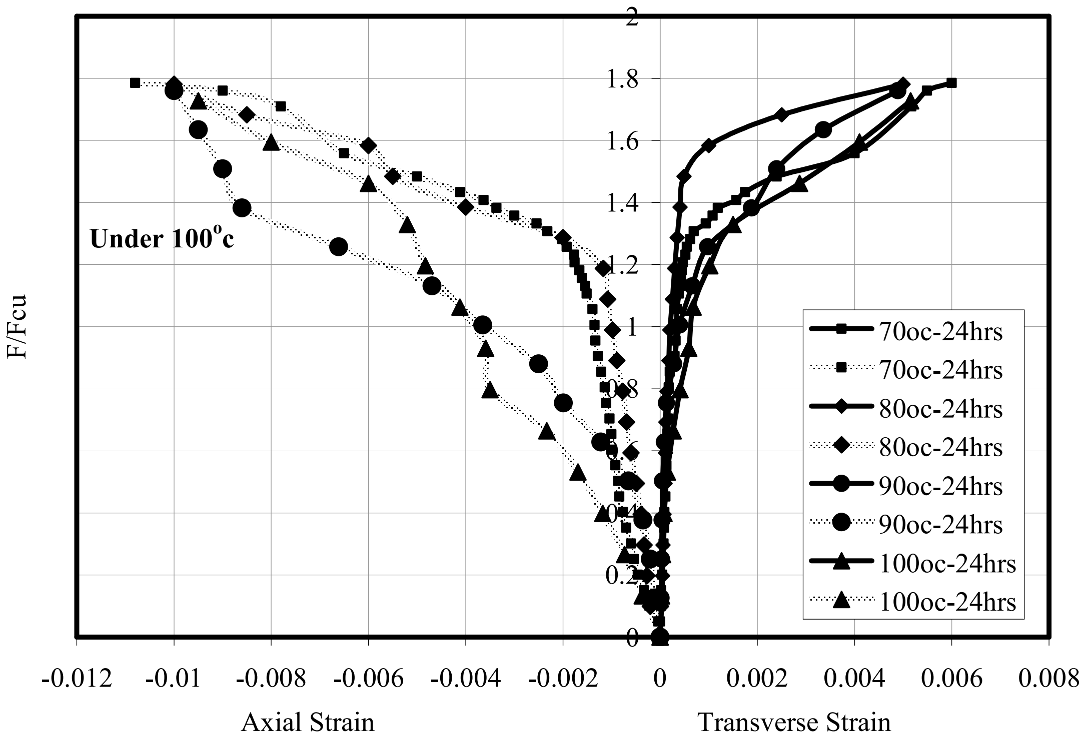


Fig. 4.5 Axial stress vs. axial and transverse strains for R.C column subjected to temperature below 100^{o}c

It is interesting to point out herein, which will be discussed in details later, that the thermal endurance according to the furnace heating rate and the thermal tests done on the insulated R.C. columns at temperature $100^{o}c$ on the CFRP surface is about 4.2 hours for sikacrete213f, 3.4 hours for all of Gypsum, Perlite, Cement + Gypsum, and cement paste, and about only one hour for thermal concrete, Cement mortar, Ceramic fiber, and Rock wool.

This finding implies that, the importance in choosing the suitable insulating material in protecting CFRP sheets and its epoxy resin according to the exposed temperature level and duration.

4-2-3 Behavior of R.C columns confined by CFRP at $200^{o}c$

In this series, four R.C. columns were insulated with Ceramic fiber, Rock wool, sikacrete213f, and Gypsum, and then subjected to the furnace temperature till CFRP surface temperature reach $200^{o}c$ and keep constant at this temperature level for four, eight, twelve, and twenty four hours respectively for each insulating material. The corresponding ultimate furnace temperatures for the four columns were $650^{o}c$, $670^{o}c$, $800^{o}c$, and $790^{o}c$ respectively.

The loss of the CFRP wrapping effectiveness for columns exposed to elevated temperature $200^{o}c$ compared to the control wrapped unheated column was 7%, 9%,11%, and 15% for continues exposure four, eight, twelve, twenty four hours respectively.

The mode of failure was observed in all columns in this series, as shown in figures (4.6) and (4.7), the failure occurred by rupture of CFRP sheets at the corner of the columns. The CFRP sheets and the epoxy resin pulled off taking part of the concrete cover and the steel reinforcement was exposed. Also it can be observed small de-bonding spots on the CFRP surface after being rupture for column G-200-24 that subjected to this temperature level for 24 hours, which indicate partially de-bonding occurred after exposed to $200^{o}c$ for 24 hours.

Fig. 4.6 Failure in Columns C.F.-200-4, and R.W.-200-8

Fig. 4.7 Failure in Columns S-200-12, and G-200-24

Comparisons between the curves for the four columns are shown in Figure (4.8). A slight decrease in both axial and transverse strains was observed in all columns, for the columns subjected to 200^{o}c for 4, 8, and 12 hours their transverse strain decrease by about 17%

compared by the control confined specimen, while it decrease by 50% for the column that subjected to 200°c for 24 hours.

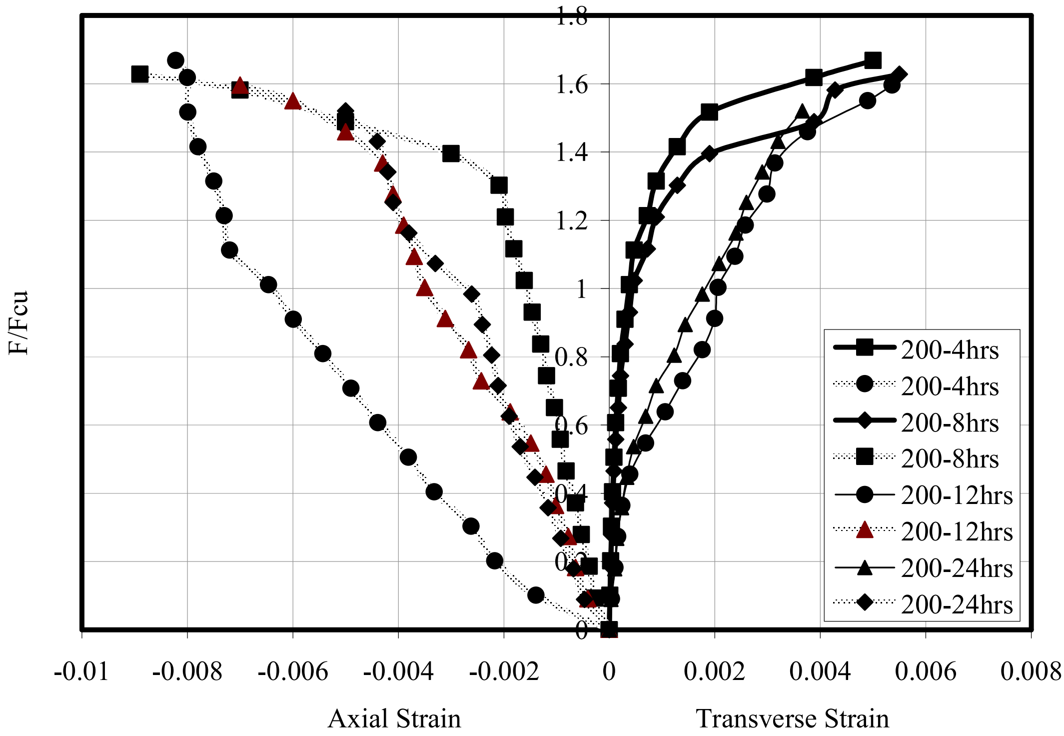


Fig. 4.8 Axial stress vs. axial and transverse strains for R.C column subjected to temperature at 200°c

Thermal endurance of the insulating materials at 200°c is quiet different than 100°c, Sikacrete-213f has the superior behavior they reach 200°c in 5.6 hrs, while Cement+Gypsum, Perlite, and Gypsum reach it about 4.5 hrs, and Thermal concrete in 3.2 hrs, and all of other insulating material" Ceramic fiber, Rockwood, sikacrete213f "2nd cycle", and Cement mortar reach 200°c in 1.9 hrs only.

4-2-4 Behavior of R.C columns confined by CFRP at 250°c

Four R.C.columns have been tested, two of them were un-isolated and subjected to 250°c for 4, and 8 hours. While the other two columns were isolated by Sikacrete213f and Cement + Gypsum, they subjected to 250°c for 12, and 24 hours respectively. There is a significant loss in CFRP confinement effectiveness comparing to the control specimen, the percentage of the axial load capacity with respect to the un-heated specimen was 13%, 17%, 20% for the columns subjected to 200°c for 4,8,and 12 hours respectively. While, the G-200-24 specimen fails with load equal that of the unconfined R.C. column, the (*f/fcu*) ratio is 1.05 which below the unconfined control specimen having (*f/fcu*) ratio is 1.09

Inspection of the failed specimens relevant that there is a partially de-bonding in some areas of the of CFRP sheet during subjected to continues temperature 250^{o}c for 4 and 8 hours, while the mode failure for the specimen subjected to 250^{o}c for 12 hours was govern by de-bonding in the overlap distance between CFRP sheets. Full de-bonding between the CFRP sheets and concrete surface accompanied by deterioration in the CFRP sheets have been observed in the specimen subjected to 250^{o}c for 24 hours. Visual inspections observe changing the color of CFRP to white when subjected to 200^{o}c for 24 hours. Figure (4.9) shows the different modes of failure for this series of specimens.

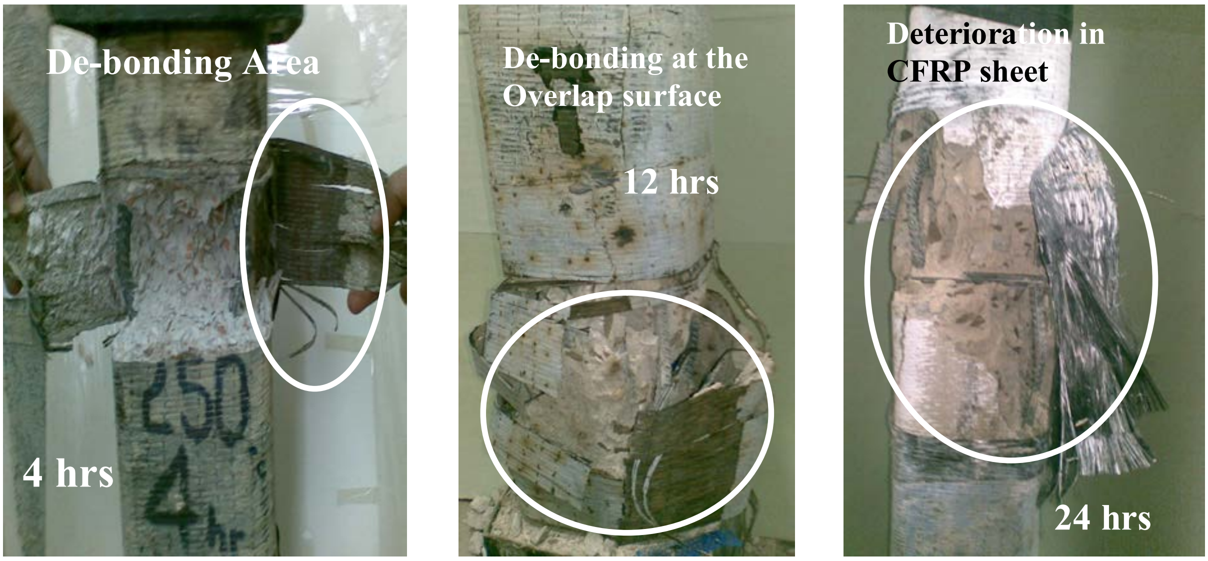


Fig. 4.9 Failure in Columns exposed to 250^{o}c at various durations

Figure (4.10) shows the axial and transverse strain versus (*f/fcu*) ratio, the ultimate transverse strain for columns U-250-4, U-250-8, and S-250-12 have been decrease than the confined control column by 16%, 16%, and 50% respectively. On the other hand column (C+G -250-24) having ultimate transverse strain of 0.0005 less than the confined control specimen by 92%, and equal to the unconfined R.C. column, this is related to the de-bonding in CFRP sheets leads it to behave like the unconfined columns completely.

It should be noticed that, there is a gradually loss in stiffness and ductility of the tested specimen while increasing the effecting temperature duration. And it lose all its ductility for column subjected to 250^{o}c for 24 hours

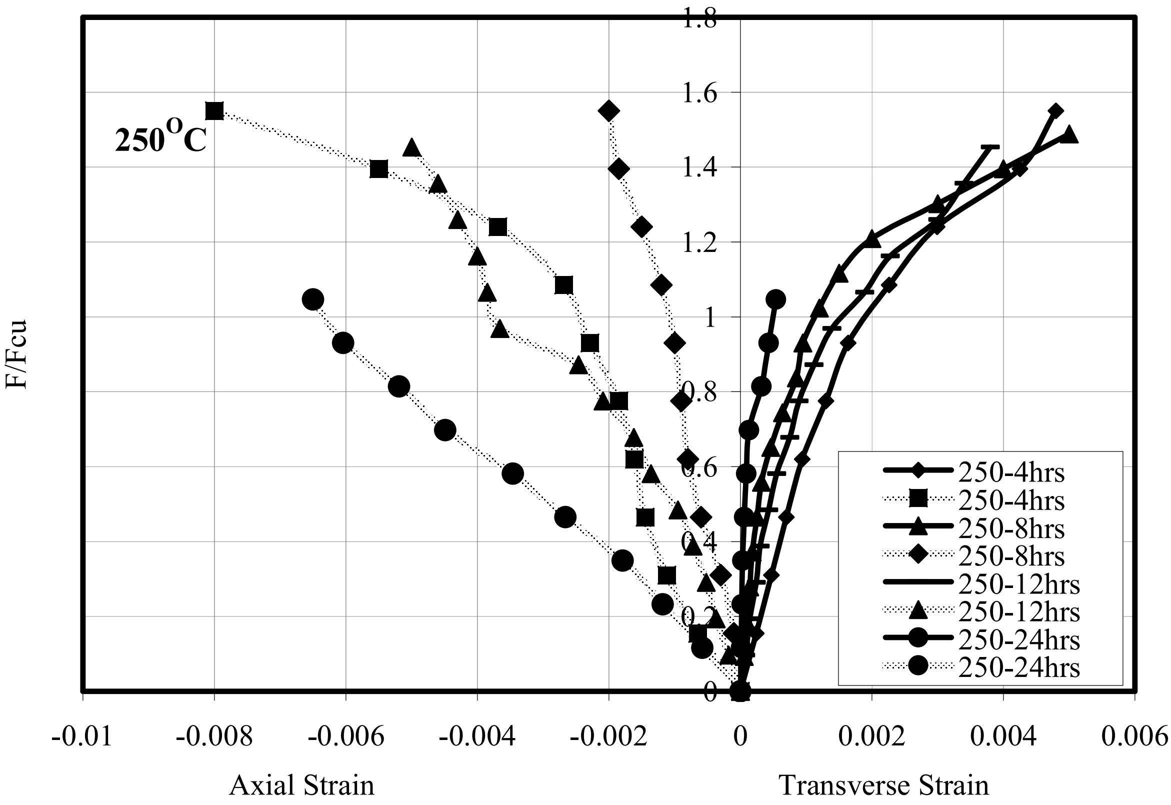


Fig. 4.10 Axial stress vs. axial and transverse strains for R.C column subjected to temperature at 250°c

4-2-5 Behavior of R.C columns confined by CFRP at 300°c

Two columns C.M.-300-4, C.P.-300-8 have been tested under 300°c with duration 4 and 8 hours respectively. There is no need to test this temperature level at 12 and 24 hours because it totally failed at 8 hours. There is a significant loss in CFRP confinement for column C.M.-300-4 due to exposure to 300°c for 4 hours that leads to de-bonding in some areas between CFRP and concrete surface before rupture of CFRP sheets. On the other hand, in column C.P.-300-8 the CFRP confinement was negligible, as the de-bonding occurs from the beginning of loading and take the behavior of unconfined column, as shown in figure (4.11).

The ultimate capacity for both columns C.M.-300-4, C.P.-300-8 was decrease by 20%, and 44% with (f/f_{cu}) ratio equal 1.47 and 1.05 respectively.

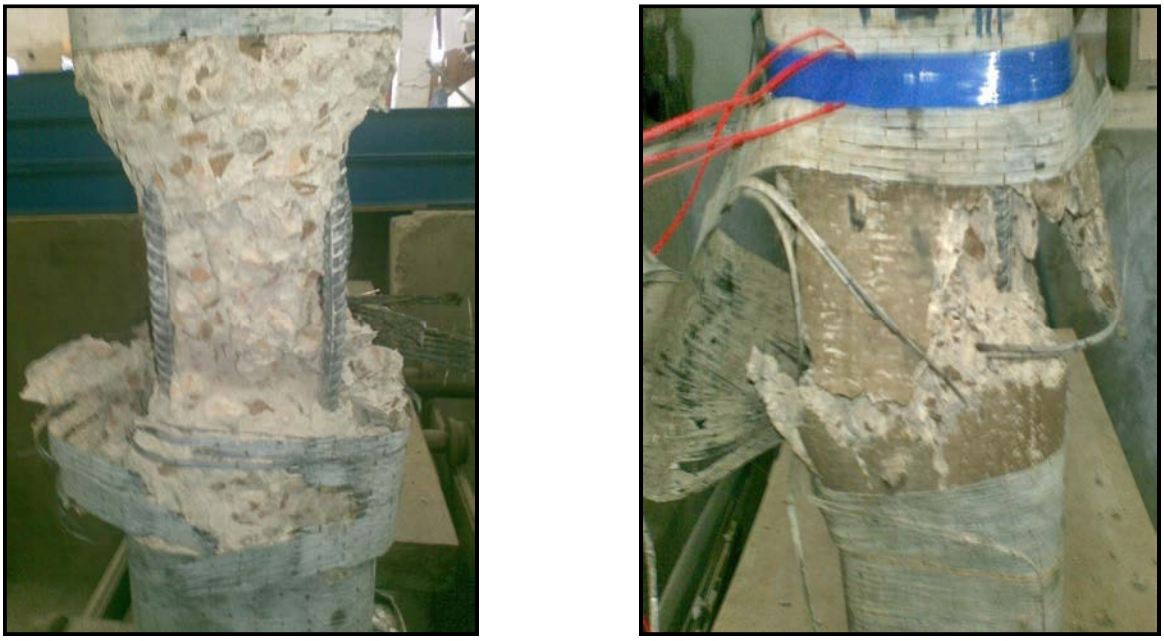


Fig. 4.11 Failure in Columns C.M.-300-4, C.P.-300-8

Comparisons between the (f/f_{cu}) ratios versus strain curves for the two columns are shown in Fig.(4.12). Both ultimate axial and transverse strains have been decreased for columns C.M.-300-4 by 60% and 16% respectively. It should be reported herein that the maximum measured transverse strain in CFRP in column C.P.-300-8 at failure was approximately 0.0002 mm/mm, which corresponded to 3.3 % only of the ultimate strain of control confined column. The leads us to conclude that the CFRP sheet don't exert any confinement from the early loading stages, and the column behave like the unconfined control specimen. Moreover, the measured ultimate axial strain for column C.P.-300-8 was approximately 0.001 mm/mm, having 91% less than the control confined column.

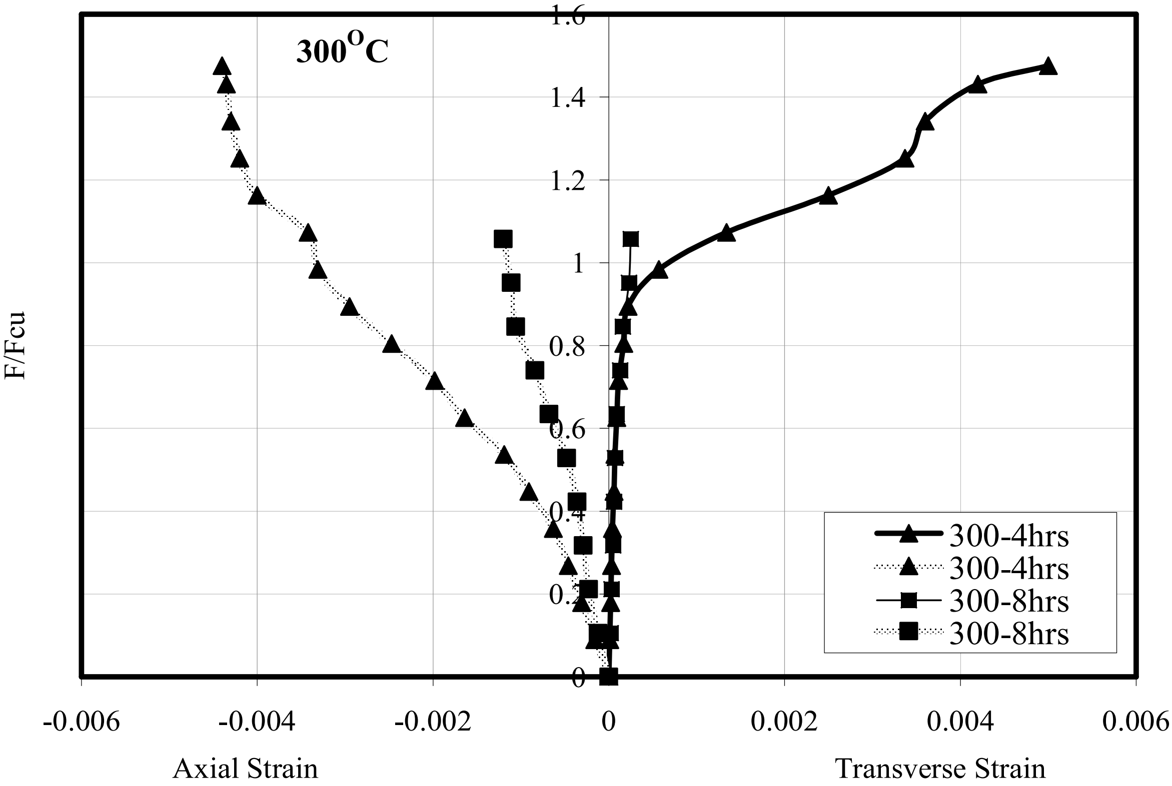


Fig. 4.12 Axial stress vs. axial and transverse strains for R.C column subjected to temperature at 300°c for 4 and 8 hours.

4-2-6 Behavior of R.C columns confined by CFRP at 350°c

Three R.C. columns were tested under 350°c for different durations. First column designated by U-350-4 was un-insulated and subjected to 350°c for 4 hours, its (f/f_{cu}) ratio equal 1.27 less than the control confined column by about 30%. The CFRP sheets lose some of its confinement effectiveness due to a large de-bonding area between CFRP sheets and concrete surface, while the CFRP sheets itself doesn't greatly effected. Second column, T.C-350-8 was insulated by Thermal concrete subjected to 350°c for 8 hours; it is clearly shown that CFRP sheets lose all of its effectiveness before testing as there were fully de-bonding for CFRP sheets, it behave similar to the control unconfined column having (f/f_{cu}) ratio equal 1.02.

Finally, the third column P-200/350-12 was insulated by Perlite and subjected to 200°c from three sides and 350°c from the other side for 12 hours; this is related to the variable insulating thickness from 40mm for three sides and 20mm for the other two sides. While one side only effected by 350^{o}c it govern the structurally behavior of the column, leads to full de-bonding of CFRP along the column height and the (f/f_{cu}) ratio equal 1.05. Figures (4.13)and (4.14) show the modes of failure for the columns.

Fig. 4.13 Failure in Column U-350-4

Fig. 4.14 Failure in Columns T.C-350-8, and P-200/350-12

The failure modes for all specimens tested at this temperature level govern by de-bonding of CFRP sheets, this leads to large extreme loss of the measured ultimate axial and transverse strains. The column U-350-4 loss about 83% and 90% for transverse and axial strain respectively compared by the control confined specimen. While column T.C-350-8 behaves similar to unconfined column, do not offer a significant ductility compared with the confined column. On the other hand, column P-200/350-12 has a remarkable difference between the transverse strains measured on the side subjected to 200°c equal 0.003 mm/mm, and the corresponding strain measured at the side subjected to 350°c equal 0.0004 mm/mm which equal to the strain measured for the unconfined control column. Figures (4.15) and (4.16) show the versus transverse and axial strain for tested columns at 350°c

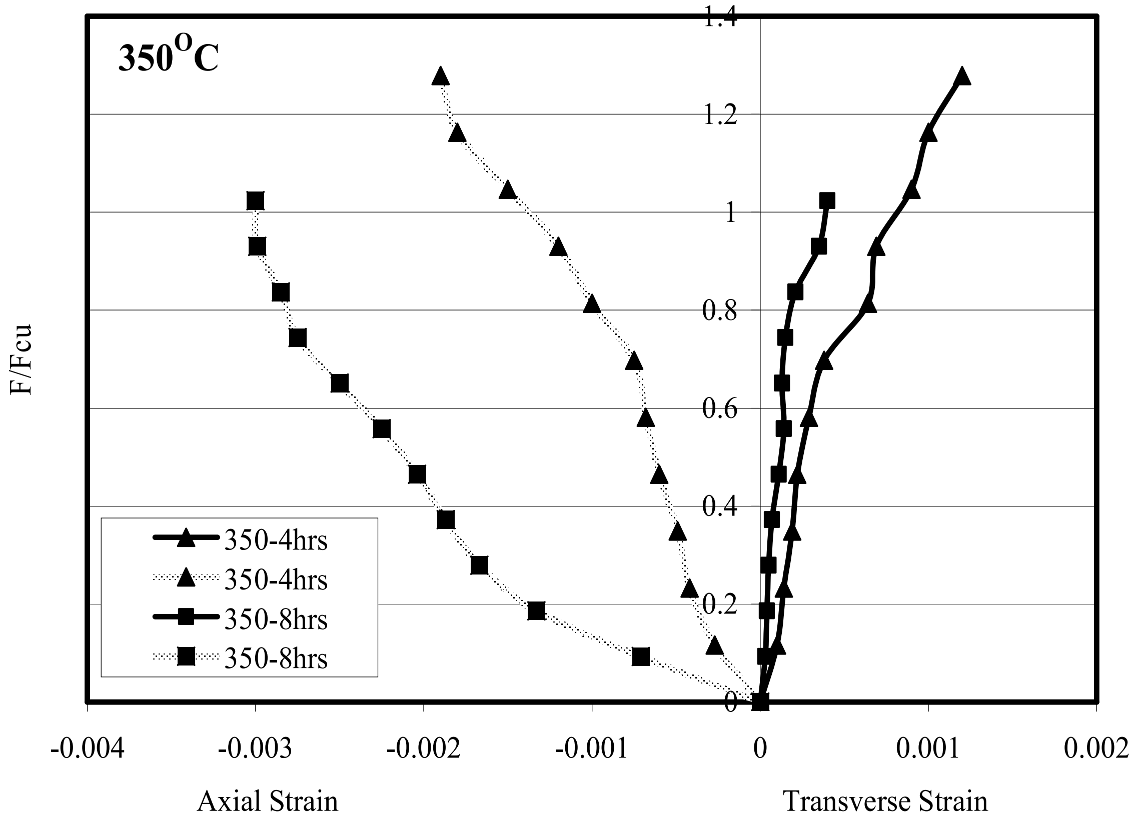


Fig. 4.15 Axial stress vs. axial and transverse strains for U-350-4, and T.C-350-8

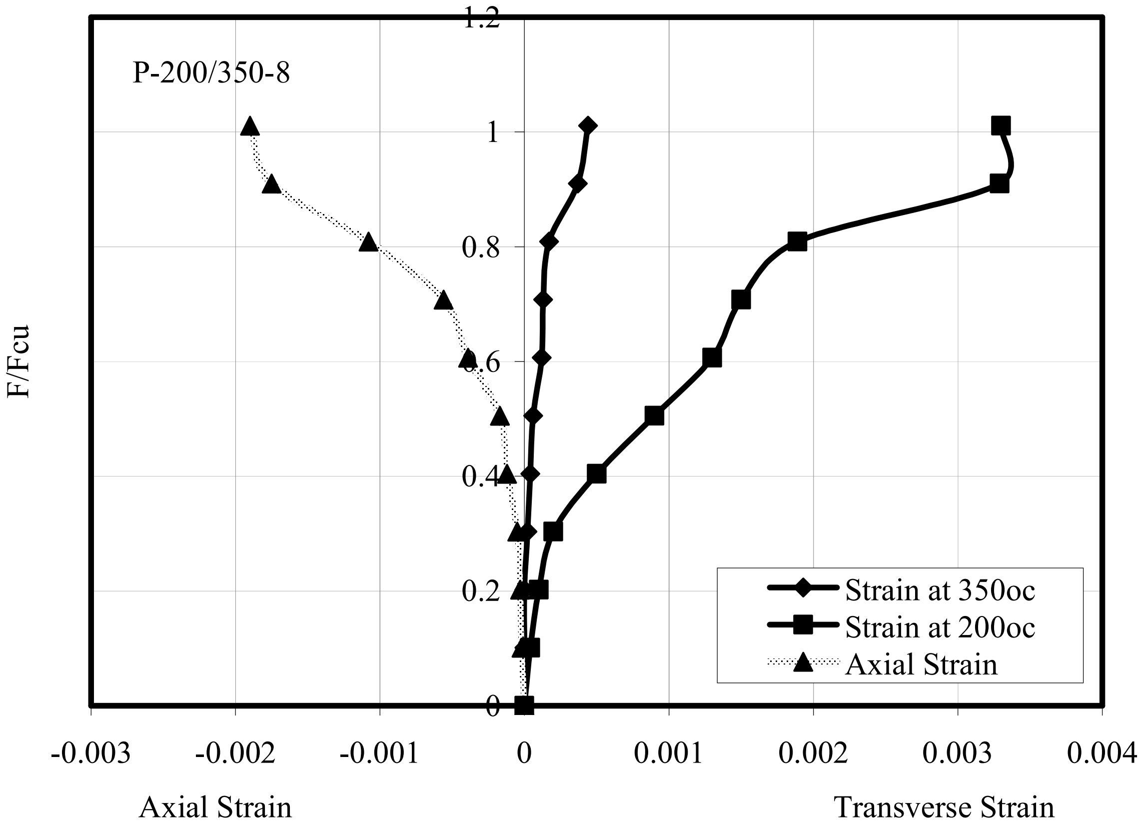


Fig. 4.16 Axial stress vs. axial and transverse strains for P-200/350-12

According to the above mentioned test results. The deterioration of the CFRP confinement effectiveness does not depend only on elevated temperature level but also on the exposure duration. A comparison between (f/fcu) ratio which refer to the ultimate load capacity for the tested columns are shown in Figure (4.17). No significant deterioration of the CFRP confinement effectiveness occurs at 100^{o}c till 24 hours. While at 200^{o}c the CFRP confinement effectiveness depend mainly on the exposure duration, it lose only 7% for exposure for 4 hours, and 9%,12%, and 15% for 8, 12, and 24 hours respectively. The different in the ultimate load capacity of the confined columns subjected to constant temperature 250^{o}c depend mainly on the exposure duration, the columns lose about 13%, 17%,20% when exposed 250^{o}c for 4, 8, 12 hours. While it lose all it capacity after 24 hours

Partially loss of CFRP effectiveness has been observed at 300^{o}c, 350^{o}c for 4 hours it lose about 17.5% and 28.5% from its original capacity, while it lose all its effectiveness for continuous heat exposure for duration more than or equal 8 hours

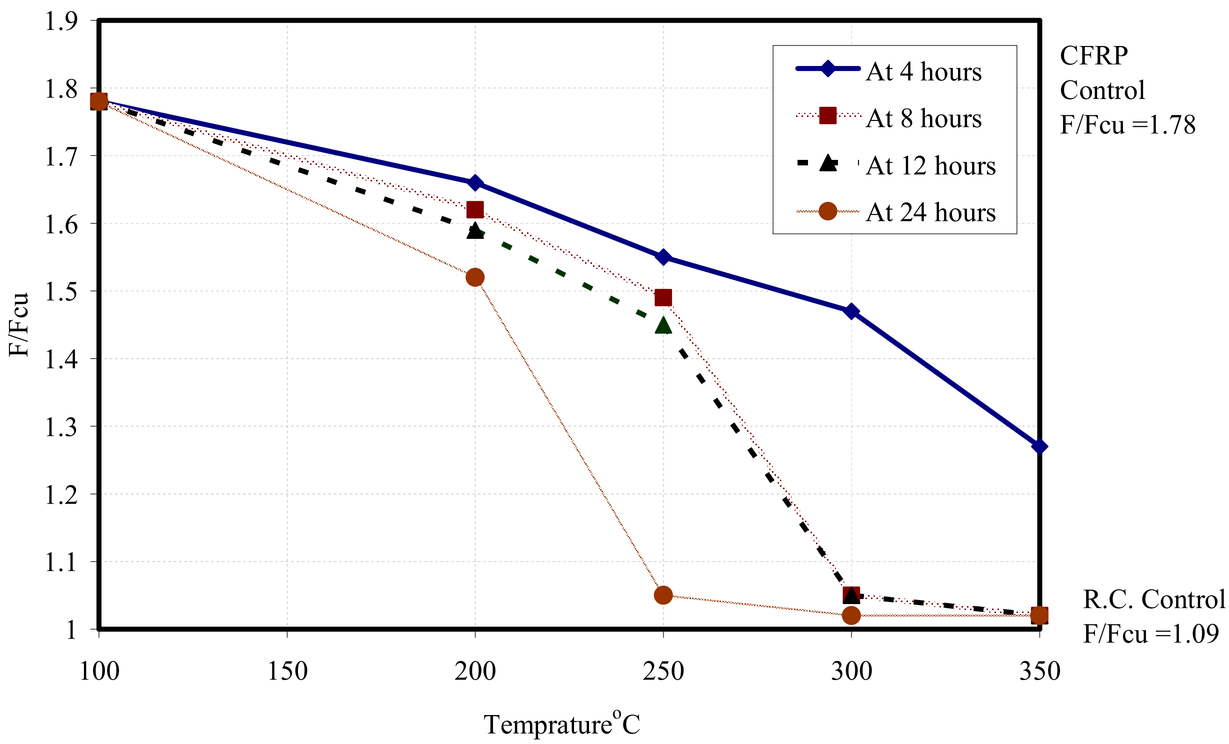


Fig. 4.17 Deterioration for columns confined by CFRP with temperature and time

4-3 THERMAL BEHAVIOUR UNDER ELEVATED TEMPRATURE

Results from the thermal experimental study were used to study the effect of the tested insulating materials in retarding heat transfer toward the CFRP surface and on the thermal endurance for the R.C. specimens according to the furnace heating rate. The rate of heating of the furnace is variable depending on the used insulating material, the level inside the furnace, and water ratio inside the insulating material. Then the rate of heating of the furnace when it is empty will differ than insulated R.C. specimen inside it. So it is important to study the furnace calibration.

4-3-1 Electric Furnace Calibration

The rate of heating inside furnace is not constant as it rose extremely rapidly till reach about 700% of the initial room temperature during the first 10 minute to reach about 220°C , and then the rate of heating suddenly decrease to about 34% during the second 10 minute, and continue to flocculating with value about 7%. This manner is similar to the standard fire curve behavior "ATSM E119", figure (4.18) shows the % of rate of increasing temperature versus time.

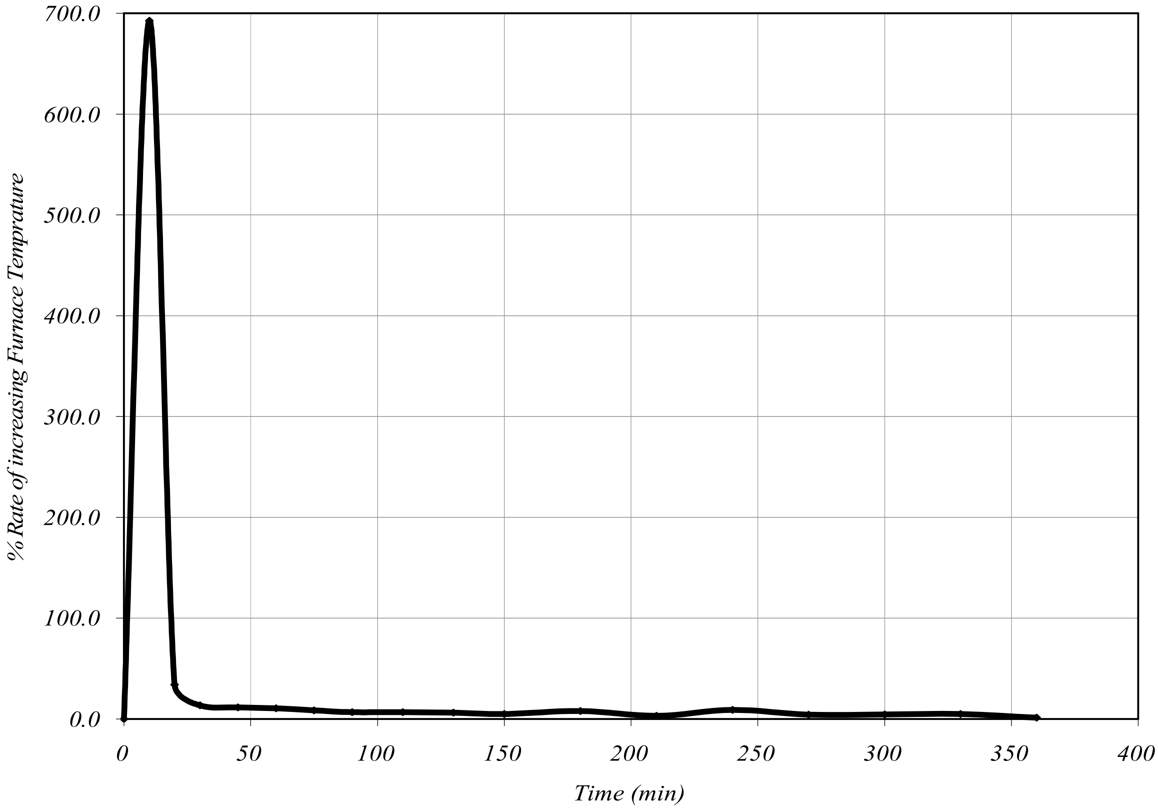


Fig. 4.18 The rate of heating of the furnace with time

The furnace temperature is not uniform along its height, this is due to the air convention heating system relied on passive air circulation where the greater density of cooler air caused it to sink into the furnace bottom, and the lesser density of the warmed air caused it to raise up to the furnace duct, figure (4.19) shows the time versus temperature curves for thermocouples at varies levels of the furnace height. It is clearly shown that the time versus temperature curves for both the furnace thermocouple "located at the back of the furnace wall" and the middle thermocouple "in the center of the furnace vertically and horizontally" are coincident to each other. This indicates that there is no variation in temperature across furnace cross section at the same vertical level.

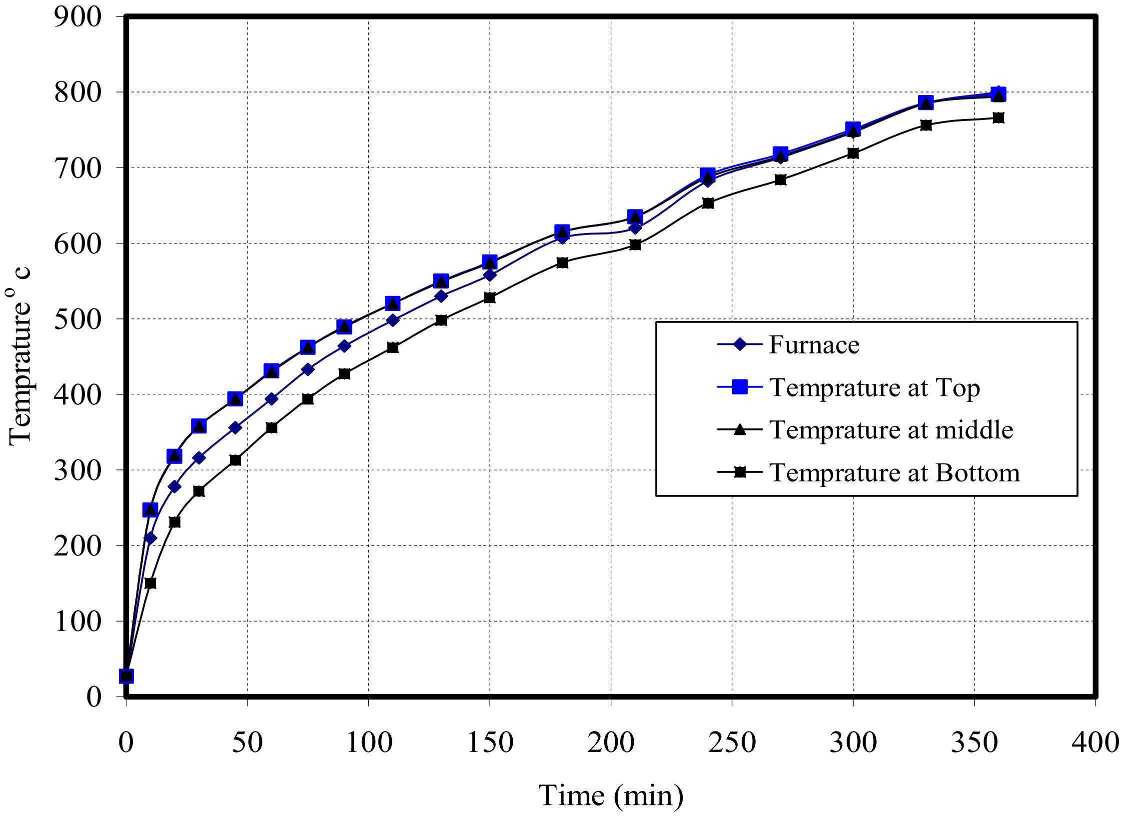


Fig. 4.19 Time versus Temperature curves for furnace at various levels

The non uniformity behavior in heat distribution is not longer remains constant, but it decrease with time till it reach a steady state of heat distribution along furnace height. The difference between the upper and lower thermo-couples temperature begin with 40% in the beginning of operating the furnace then decrease extremely to 20% in 50min, and reach 10% after 120 min, the difference between the upper and lower temperatures become insignificant after 200min. Figure (4.20) shows the variation in the % difference between upper and lower temperatures with time.

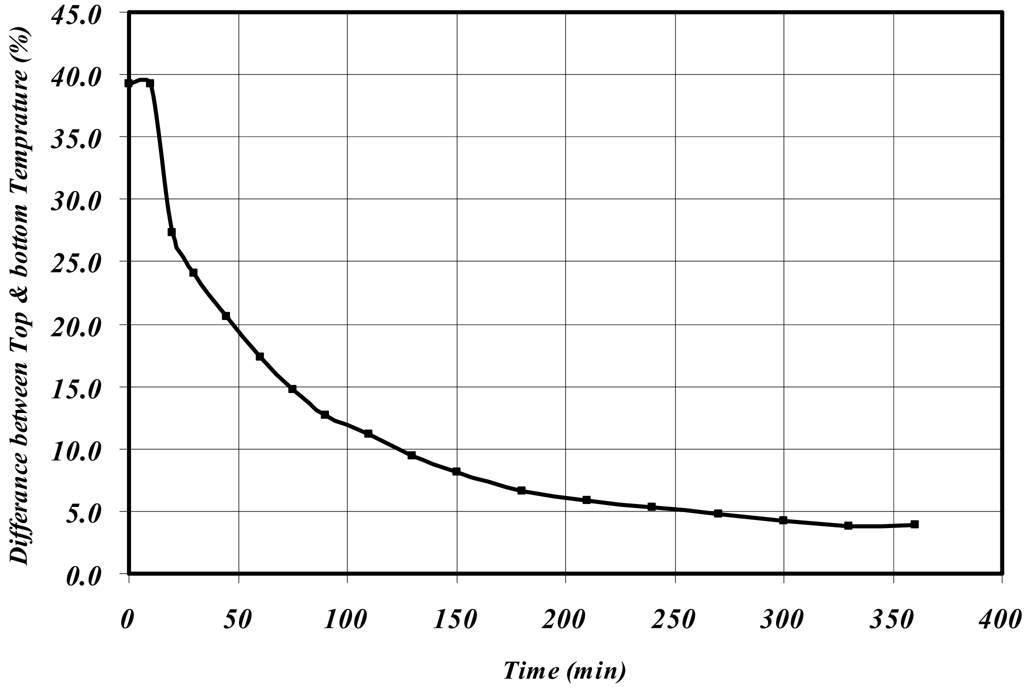


Fig. 4.20 The difference between top & bottom temperature of the furnace with time

4-3-2 Thermal Endurance for insulating materials at different tempratures levels

The efficiency of insulating material measured by the time takes to reach a specific temperature and the corresponding furnace temperature at this time, if the insulating material take more time to maintain specific temperature and reach higher furnace temperature levels at this time, that's means, the more efficiency for the insulating material.

The furnace temperature rose rapidly till reach about 200 °C , then begin to increase slowly, this is due to evaporation of moisture from the concrete and insulating material that condensate on electric coils leads to cooling the furnace media, which simulate the standard fire curve in behavior. This lead to different furnace temperature- time curves for each insulating material depends on how much the water content it store.

For all the tested specimens, time versus temperature curves were plotted for both the average furnace temperature *(temperature on the insulation surface)* and the temperature just beneath the surface of the insulation material *(temperature on the CFRP surface)*. The behavior of insulating materials were compared at five stages; below 100^{o}c, at 100^{o}c, 200^{o}c, 250^{o}c, and at

300^{o}c, for each stage the results compared the time takes to reach this specific temperatures on the CFRP surface, and also comparing the corresponding furnace temperature.

Table (4.2) shows the thermal test results, the maximum furnace temperature, the corresponding temperature at CFRP surface, and the time takes to reach this target FRP temperature.

Table 4.2 The thermal test results

1	2	3	4	5	6
Col. No.	Fire protection type	Thickness of protective layer	Maximum Furnace Temp.	Corresponding Temp. at FRP surface	Duration to reach the FRP surface temp.
1	T.C	40mm	320 ^{o}c	70 ^{o}c	35 min
2	G	40mm	400 ^{o}c	80 ^{o}c	50 min
3	C.F.	40mm	400 ^{o}c	90 ^{o}c	35 min
4	R.W.	40mm	480 ^{o}c	100 ^{o}c	40 min
5	P	40mm	360 ^{o}c	110 ^{o}c	50 min
6	C.F.	40mm	650 ^{o}c	200 ^{o}c	120 min
7	R.W.	40mm	670 ^{o}c	200 ^{o}c	105 min
8	G	40mm	790 ^{o}c	200 ^{o}c	265 min
9	S	40mm	800 ^{o}c	200 ^{o}c	350 min
10	S "2cycles"	40mm	700^{o}c	250^{o}c	255 min
11	C.+G.	40mm	700 ^{o}c	250 ^{o}c	340 min
12	C.M	40mm	510 ^{o}c	300 ^{o}c	160 min
13	C.P.	40mm	700 ^{o}c	300 ^{o}c	320 min
14	T.C.	40mm	700 ^{o}c	350 ^{o}c	340 min
15	P	40mm	770 ^{o}c	250 ^{o}c	310 min
	P	20mm	770 ^{o}c	400 ^{o}c	310 min

4-3-3 Behavior of insulating material just below100^{o}c

According to time to reach 100^{o}c, Gypsum and Sikacrete-213f have superior behavior they reach 100^{o}c in 100 min, while Cement +Gypsum reach it in 80 min, and Thermal concrete in 60 min, and all of Ceramic fiber, Rockwood, Perilte, Cement mortar reach 100^{o}c in only 40 min.

On the other hand, According to the average furnace temperature when the CFRP surface temprature reachs 100^{o}c, Also Gypsum and Sikacrete-213f in addition to Ceramic fiber and Rock wool their maximum furance temprature reach about 500^{o}c while Cement +gypsum and thermal concrete reach about 400^{o}c, and Perilte and cement mortar reach 300^{o}c. Figures (4.21) and (4.22) comparing the insulating material through their thermal endurance and average furnace temperature at 100^{o}c

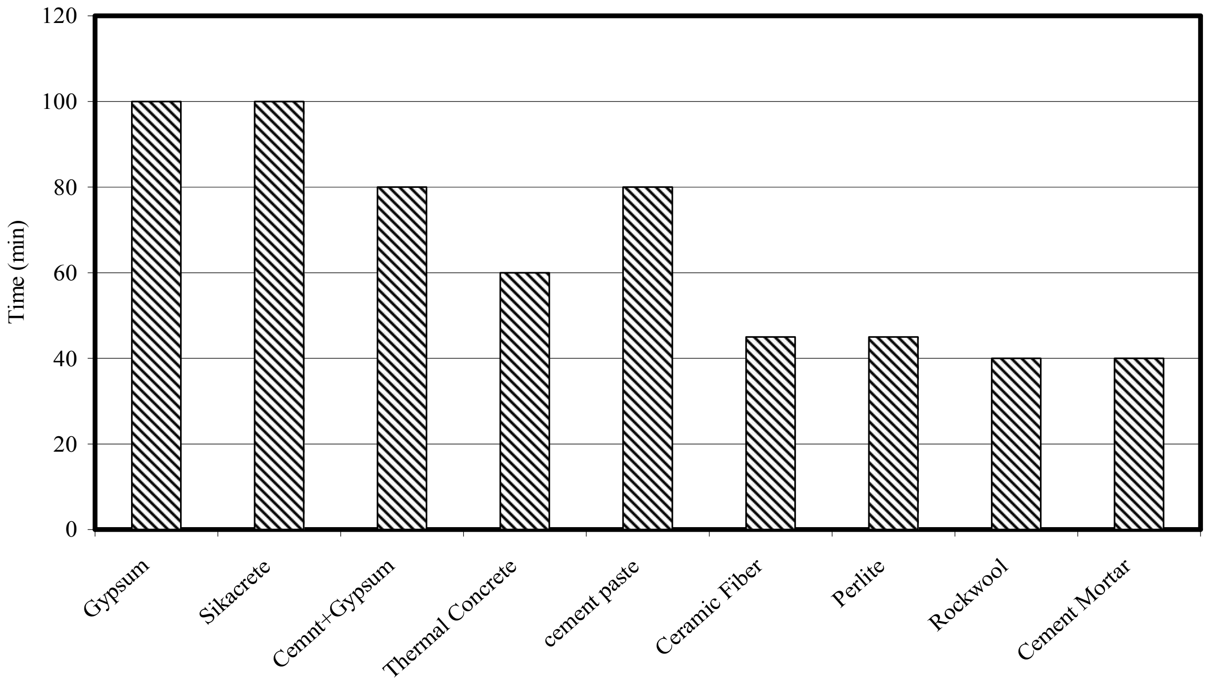


Fig. 4.21 Comparing the insulated material according to the time takes to reach 100^{o}c at CFRP Surface.

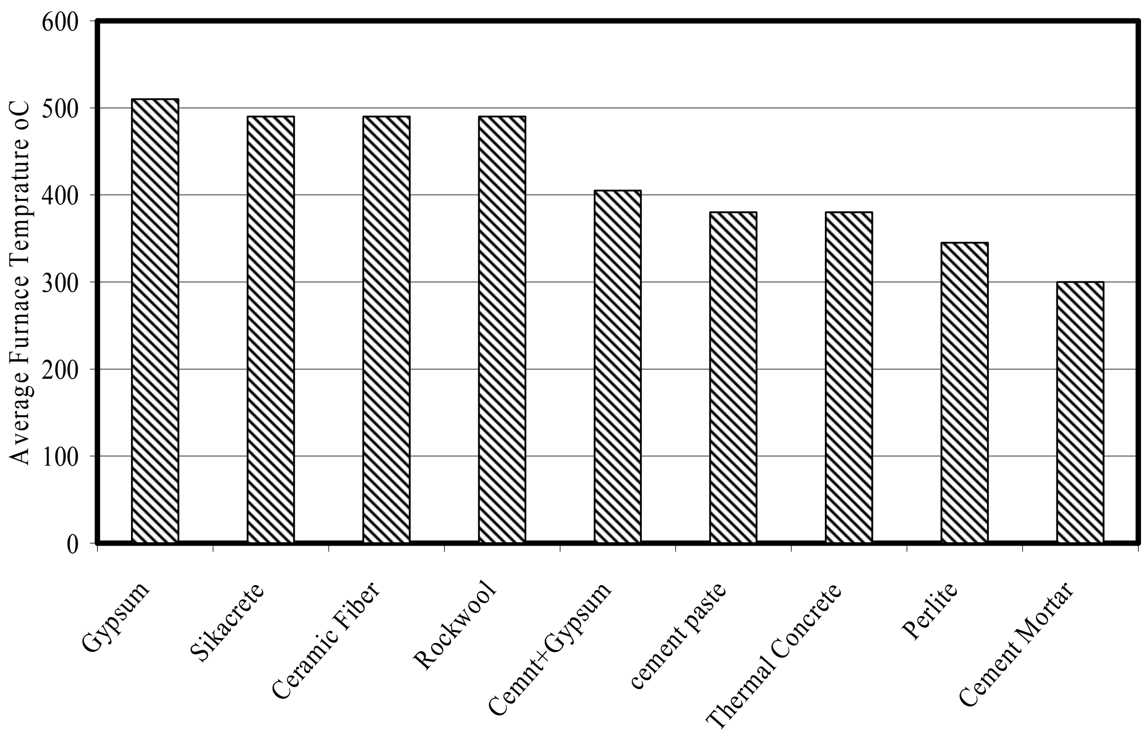


Fig. 4.22 Comparing the insulated material according to corresponding furnace temperature to reach 100^{o}c at CFRP Surface.

According to visual inspections after removing the insulating material, both of the CFRP sheets and the epoxy resin haven't been effected by this level of temperature. Moreover, as mentioned before that no changes occur on the ultimate capacity or ductility of the tested columns. Figure (4.23) shows the CFRP surface after subjecting the columns to 100^{o}c and removing the insulating material. On the other hand, no cracks have been observed on the granular insulating material surface after getting out of furnace and cooled to room temperature.

Fig. 4.23 CFRP surface while removing insulating material after subjecting to 100^{o}c

4-3-4 Behavior of insulating material at 100^{o}c

The thermal behavior at 100^{o}c, differ extremely rather than any other temperature acting on CFRP surface, that appear greatly in some insulating material specially that contain moisture content in its mixture. This phenomenon related to the evaporation of moisture from the insulating material at temperatures close to 100^{o}c, which helps to maintain constant temperature in the insulating material around 100 ^{o}c until all of the water has been driven off as steam. After that the temperature continue to increase again with an increasing rate

Each insulating material according to its water content can sustain and keep its surrounding temperature closely to 100 ^{o}c for a certain time, that lead to retardation of the transmission of heat, thus improving the overall proofing characteristics and material thermal endurance to elevated temperature increase .

Figures (4.24) to (4.32) show the time-temperature curves for some insulating materials. The upper curve is the average furnace temperature and, as mentioned before, it is variable for each insulating material due to the quantity of emitted water vapor from each insulating material that leads to minimize the increasing rate of furnace temperature as it condense on electric coils and cool them. While the lower curve is the temperature on the CFRP surface beneath the insulating material, it is clearly appear that the temperature at 100 ^{o}c is constant for a specific duration for each insulating materials especially granular insulating material with high water content.

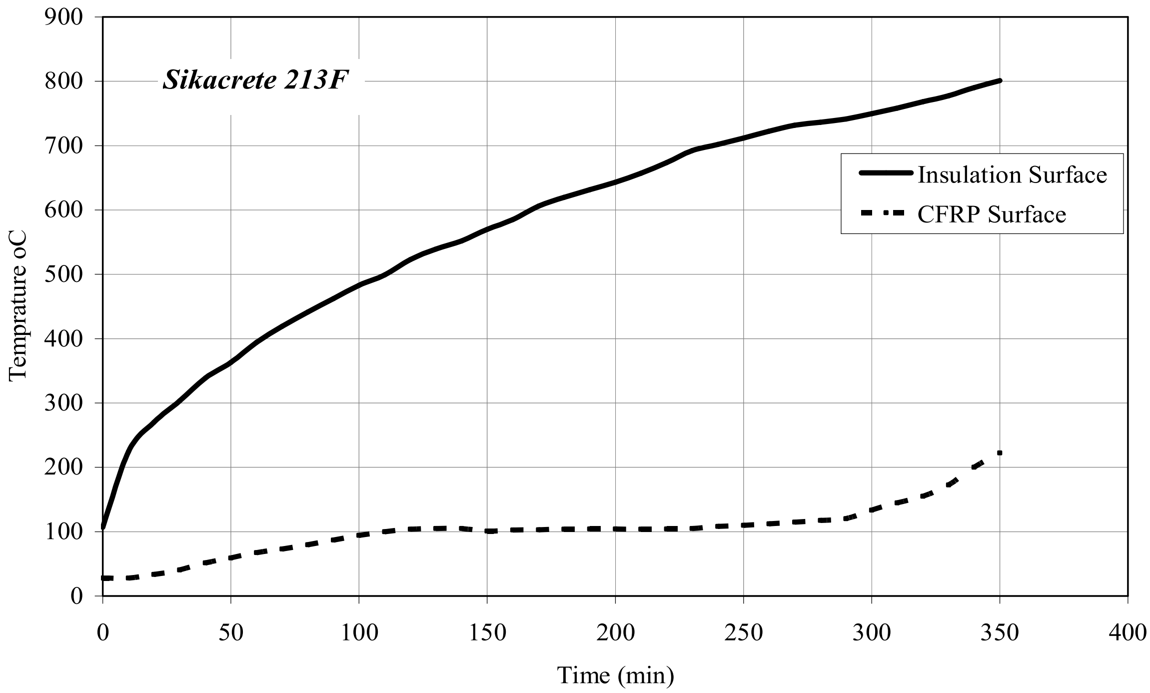


Fig. 4.24 Time versus temperature curves for both Furnace and beneath insulating material for Sikacrete 213f

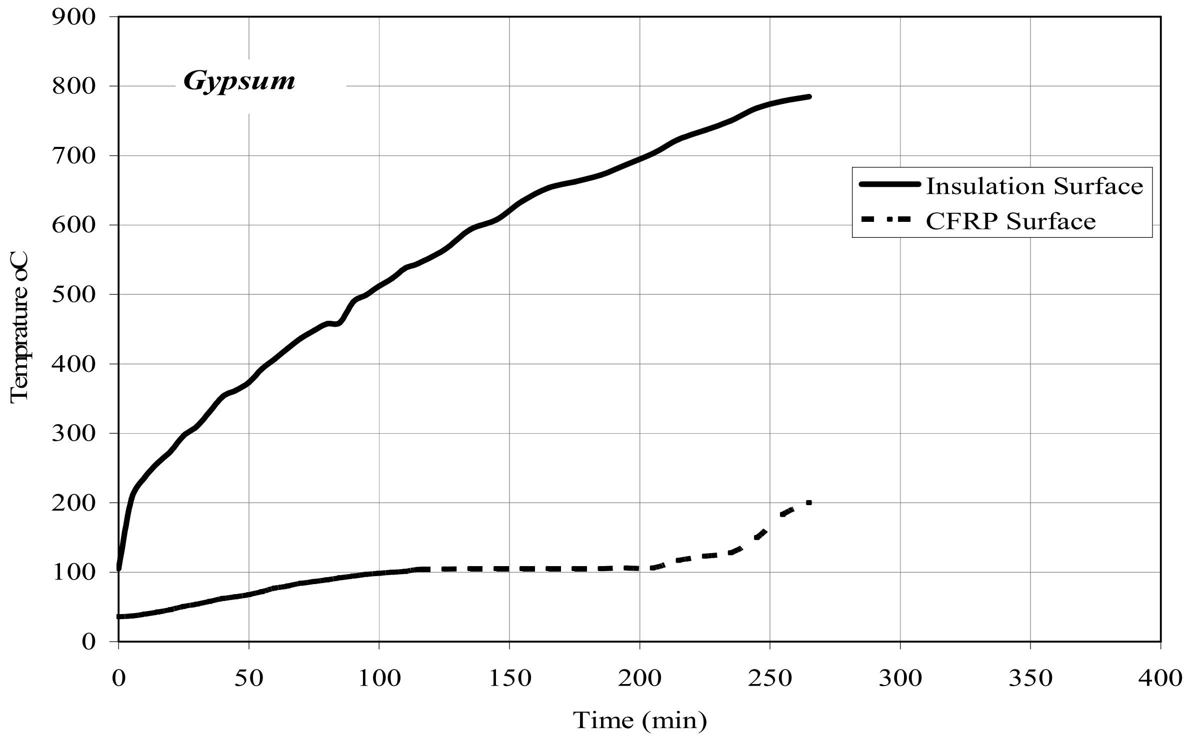


Fig. 4.25 Time versus temperature curves for both Furnace and beneath insulating material for Gypsum

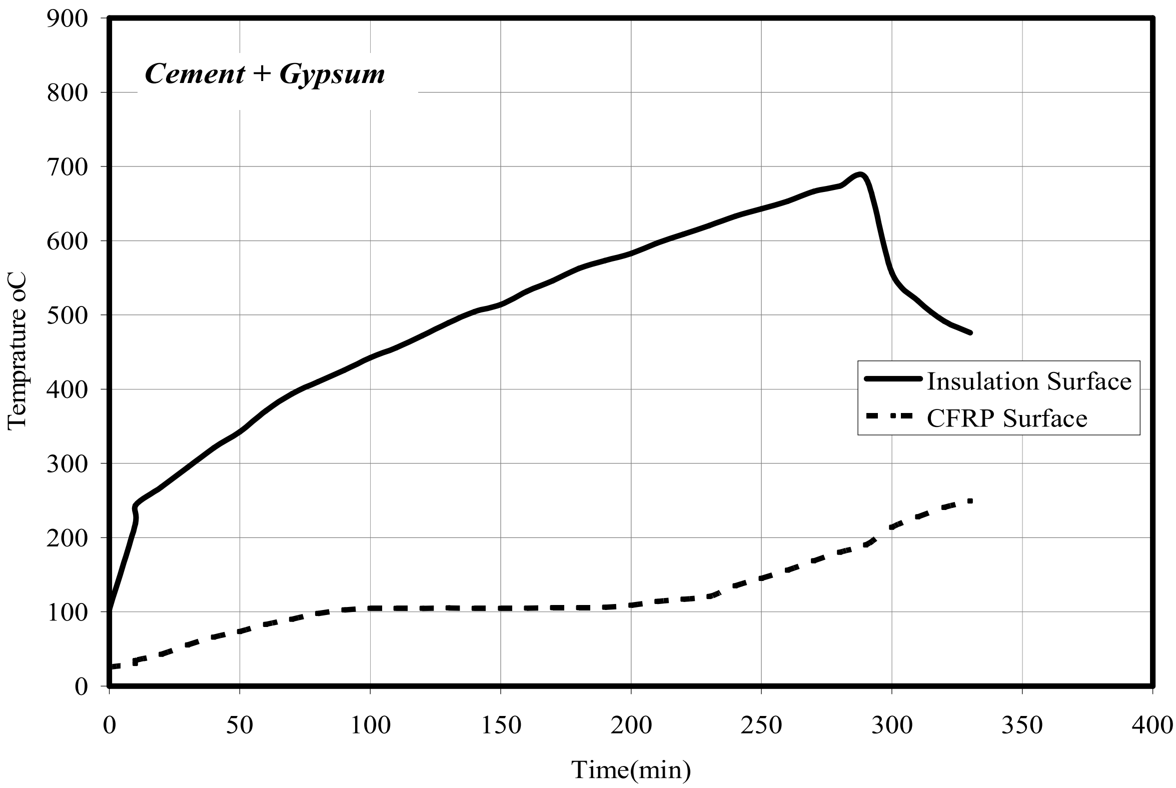


Fig. 4.26 Time versus temperature curves for both Furnace and beneath insulating material for Cement + Gypsum

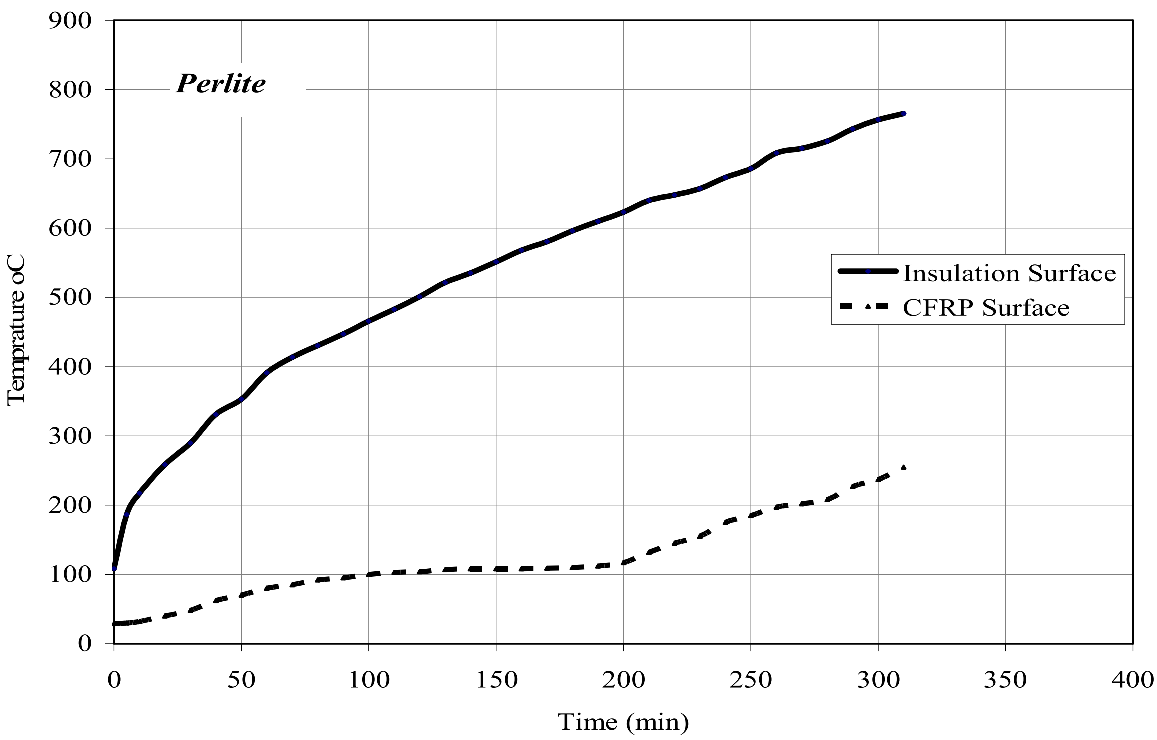


Fig. 4.27 Time versus temperature curves for both Furnace and beneath insulating material for Perlite.

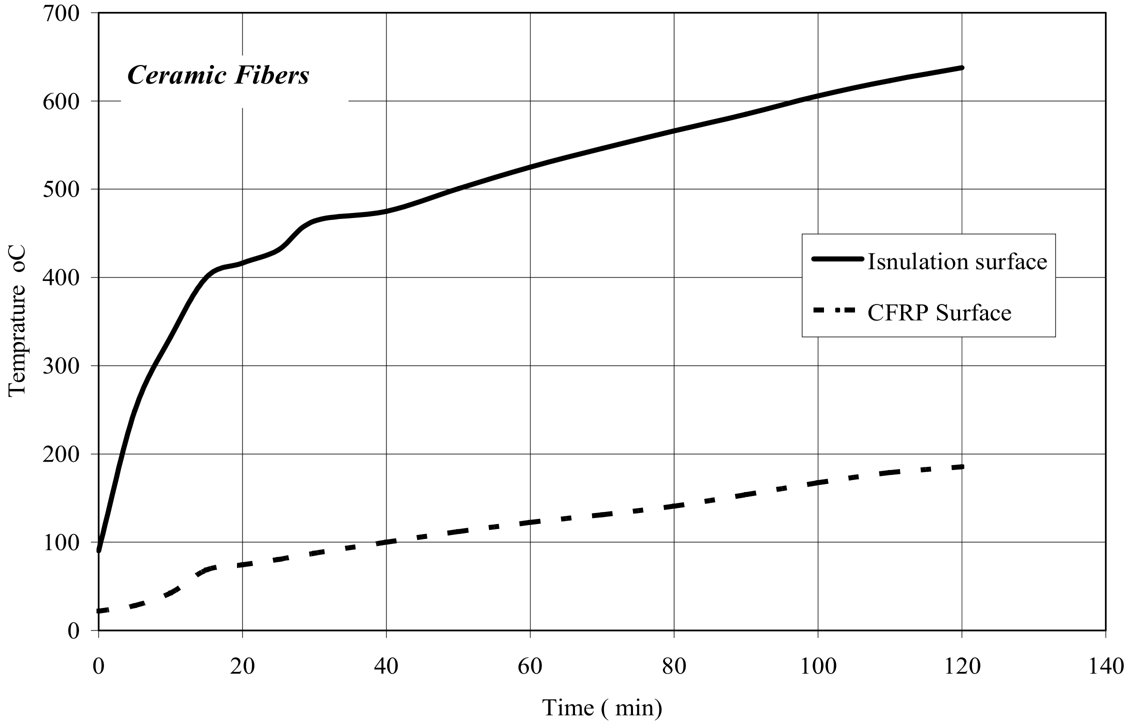


Fig. 4.28 Time versus temperature curves for both Furnace and beneath insulating material for Ceramic fiber

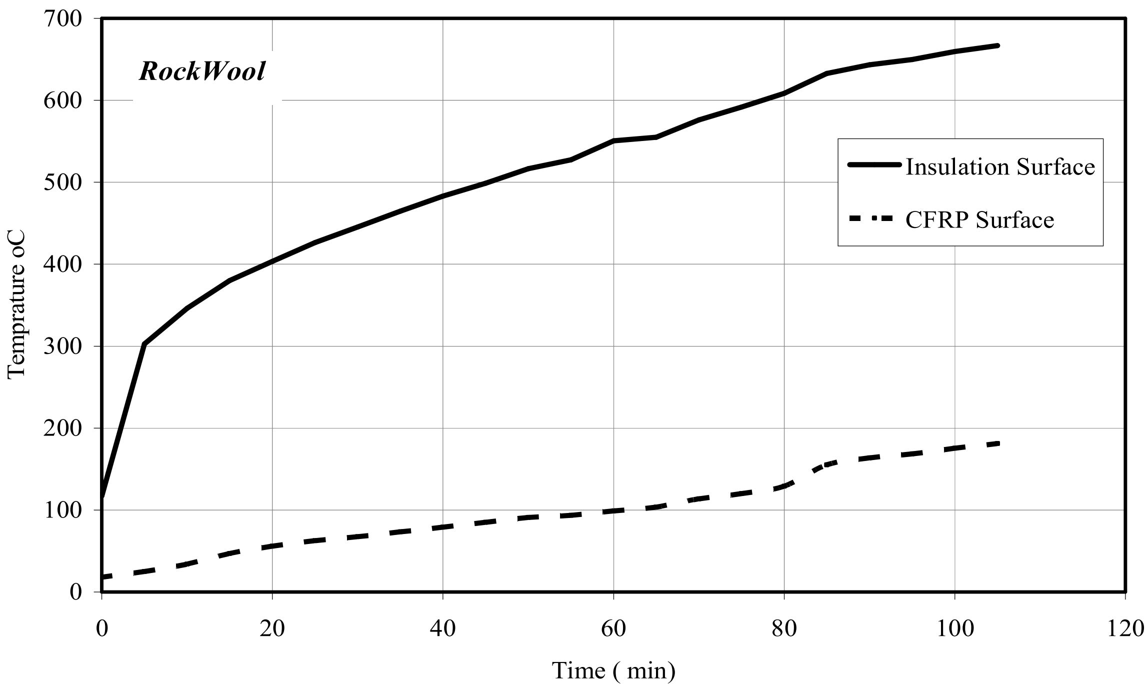


Fig. 4.29 Time versus temperature curves for both Furnace and beneath insulating material for Rock wool

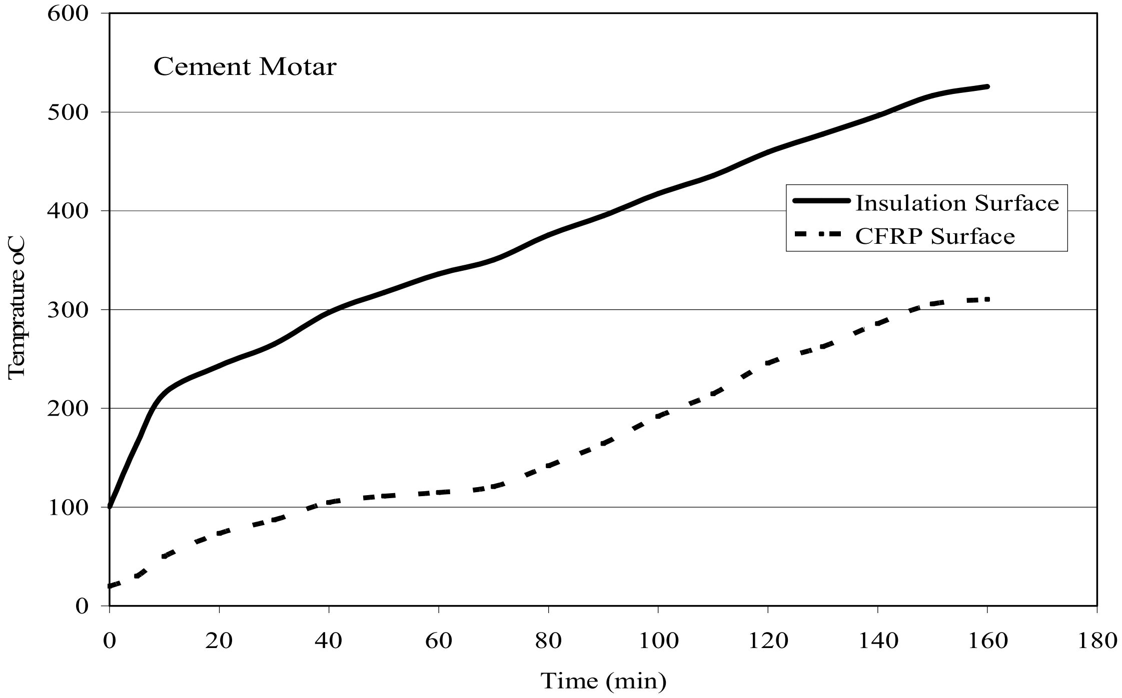


Fig. 4.30 Time versus temperature curves for both Furnace and beneath insulating material for Cement mortar

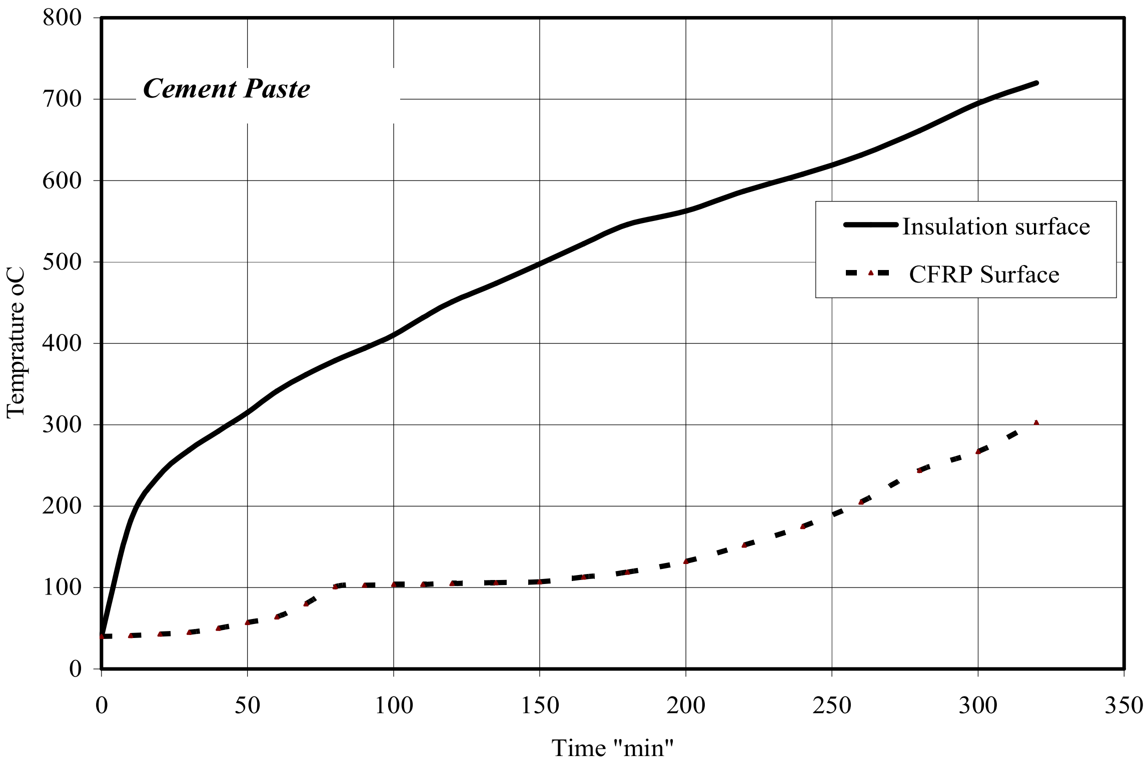


Fig. 4.31 Time versus temperature curves for both Furnace and beneath insulating material for Cement Paste

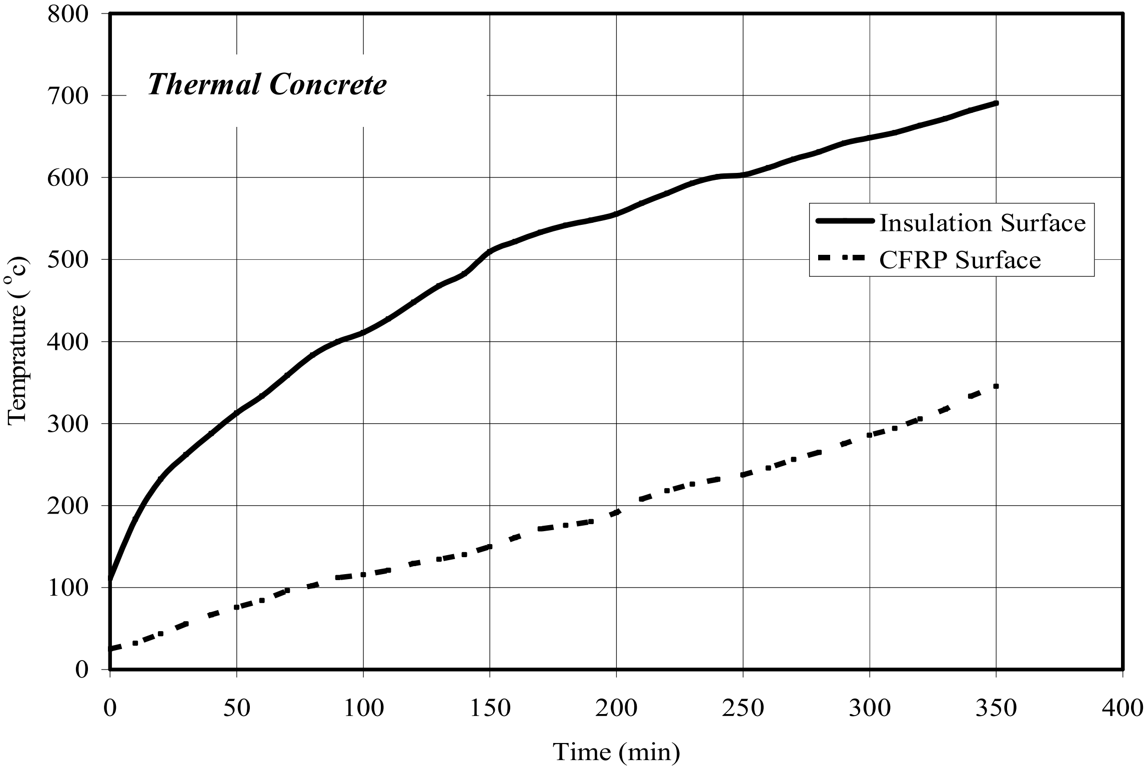


Fig. 4.32 Time versus temperature curves for both Furnace and beneath insulating material for Thermal Concrete

Figure (4.33) shows the duration that the insulating material can inhibit the heat transfer and preserve the temperature on the CFRP surface at 100°c. Sikacrete213f can maintain 250 min in 100°c with water content 100%. On the other hand, Gypsum, Perlite, Cement+Gypsum, and Cement paste can withstand about 200min at 100°c with water content 150%, 33%,100%, and 30% respectively. Despite of both Thermal Concrete and Cement mortar contain 40% and 30% water content respectively they offer a very small thermal endurance of 80 min and 40 min respectively at 100°c. This can be related to the percentage of sand in the mixture couldn't preserve ant moisture inside it's the mixture. Finally as expected both of Rock wool and Ceramic fiber can't sustain any thermal resistance at 100°c as they don't contain any water content.

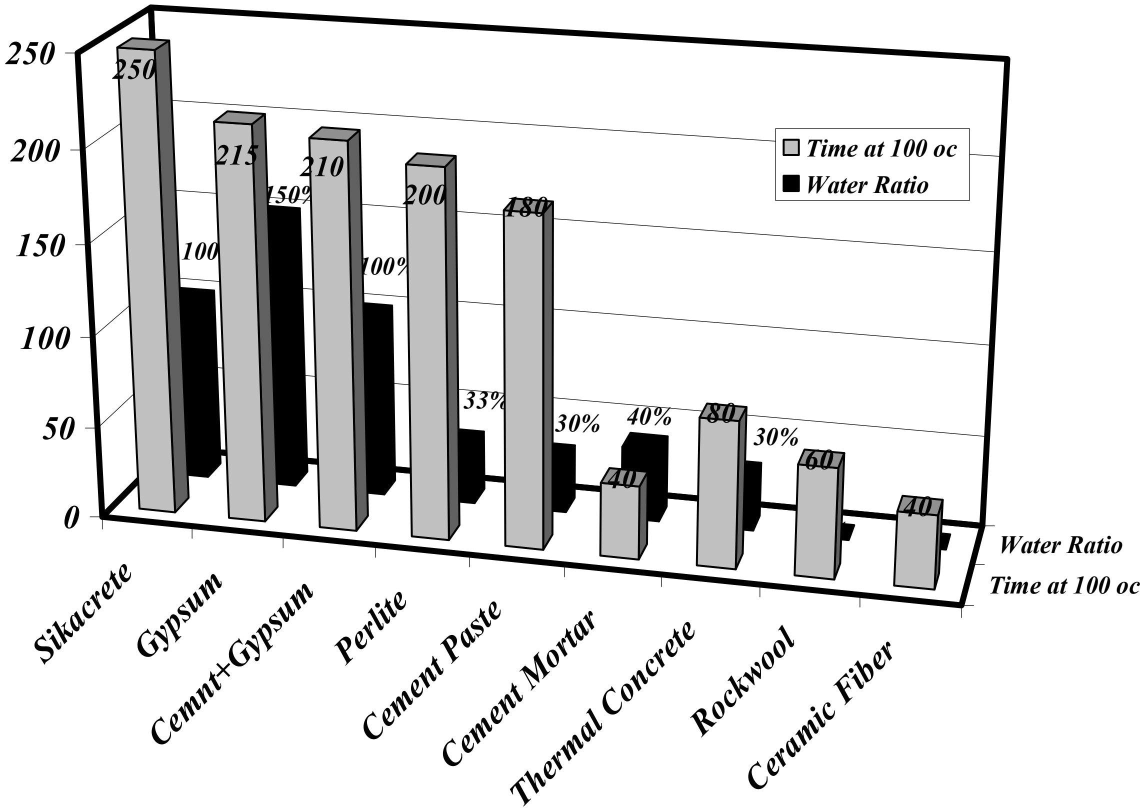


Fig. 4.33 Effect of Water content on the thermal endurance of insulating material at 100 °c

4-3-5 Effect of heating and cooling cycles on the thermal properties of the insulating material

A unique experiment has been conducted to examine the effect of removing the internal moisture inside the insulating material though out the first cycle of heating then cooling to room temperature and repeating heating another cycle, and how it will effect on the thermal properties on the insulating material. Sikacrete 213f has been selected to examine this heating and cooling cycles as it has the superior thermal endurance.

During the first heating cycle Sikacrete 213f takes about 90min to reach 100°c then continue to be steady around 100°c for another 155min, consequently the heat endurance for the first heating cycle is 245min to begin the increasing over 100°c, also the furnace temperature at this time reached 540 °c.

On the other hand, during the second cycle of heating after cooling the specimen to room temperature, the insulation doesn't offer any endurance at 100 °c. Moreover it reached 100 °c in only 55min and continues increasing without any stopping at 100°c. While it reached

200°c after 245min, with furnace temperature 700°c. The difference in FRP temperature in first and second cycles is a result of evaporating all moisture inside the insulating material leads to decrease its efficiency for heat resisting.

Figure (4.34) shows the FRP and furnace temperature for both first and second cycles of heating, it is also clearly showed that the furnace curve in the second cycle higher than the first cycle due to absence of moisture in the second cycle that could cool down the furnace temperature like in the first cycle of heating

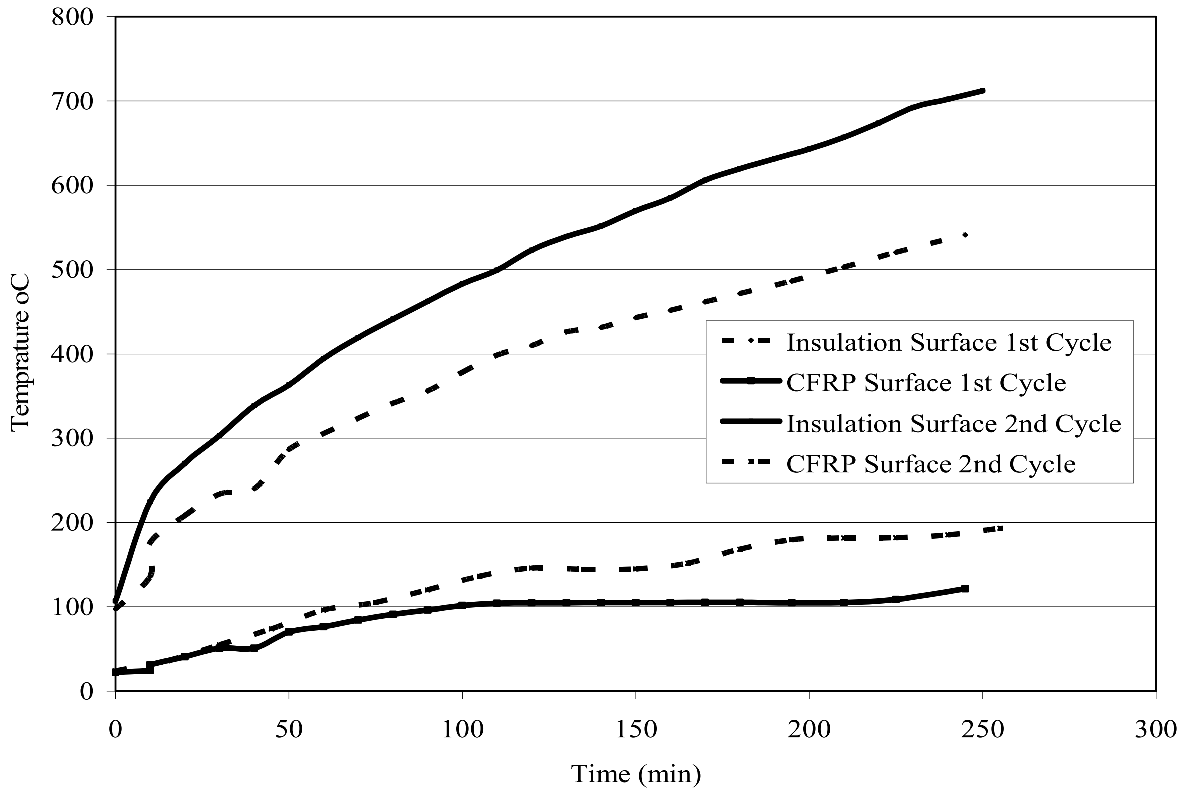


Fig. 4.34 Effect of heating and cooling cycles on the thermal endurance of insulating materials

4-3-6 Behavior of insulating material at 200°c

Thermal endurance and behavior of insulating materials at 200 °c is quiet different than their behavior at 100°c. According to the time to reach 200°c, Sikacrete-213f has the superior behavior they reach 200°c in 340 min, while Cement +Gypsum, Perlite, and Gypsum reach it about 270 min, and Thermal concrete in 190 min, and all of other insulating material" Ceramic fiber, Rockwood, sikacrete213f "2nd cycle", and Cement mortar reach 200°c in 110 min only.

It should be noted that, despite the lowest thermal conductivity of Ceramic Fiber and Rock wool in all temperature degrees, they don't govern any thermal endurance due to absence of internal moisture that control the thermal endurance at 100°c which increase the whole thermal endurance of insulating material

On the other hand, According to the average furnace temperature for different insulating material when the CFRP surface temperature reach 200°c, Gypsum and Sikacrete-213f reach maximum furnace temperature about 800°c while Perlite, Cement +gypsum, sikacrete-213 after drying, , Ceramic fiber, and Rock wool reach about 700°c, Finally Thermal concrete and Cement mortar reach 570°c and 420°c respectively.

The small difference in Average furnace temperature for most insulating material in 200°c, related to the decreasing rate of increasing temperature of furnace at high temperature degrees, as mentioned before.

Figures (4.35) and (4.36) comparing the insulating material through the thermal endurance and average furnace temperature at 200°c

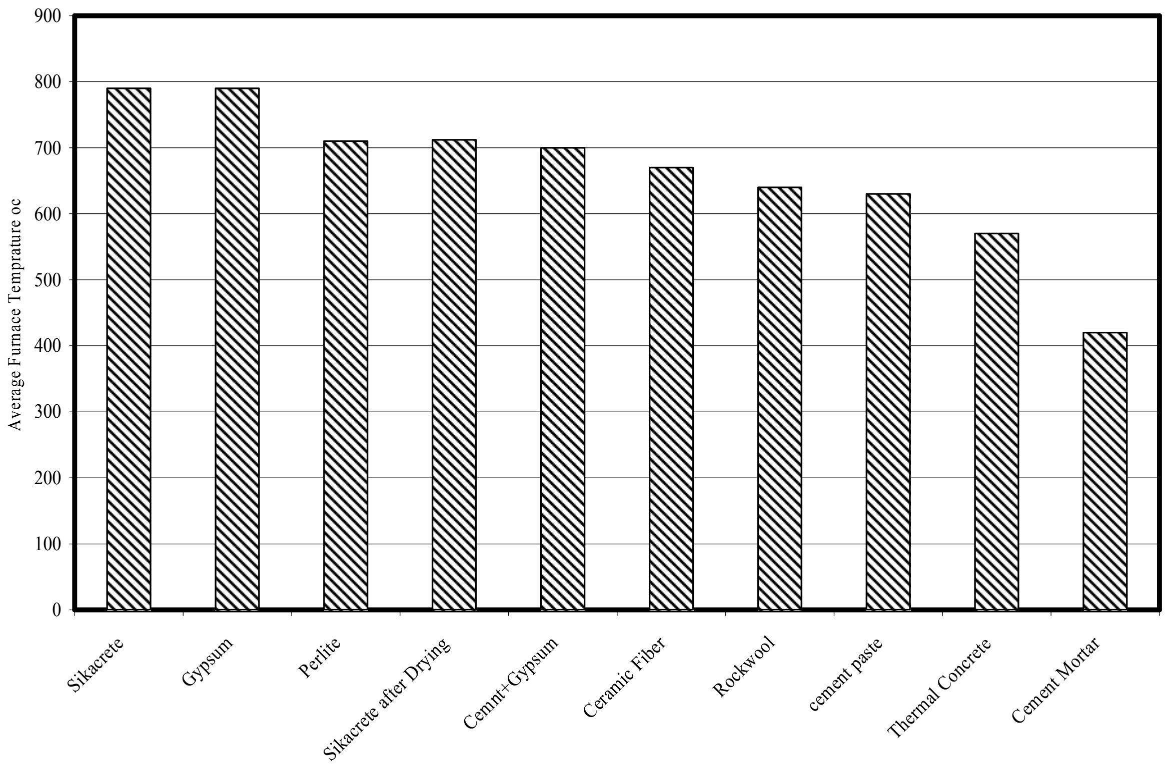


Fig. 4.35 Comparing the insulated material according to the corresponding furnace temperature at 200°c on CFRP Surface

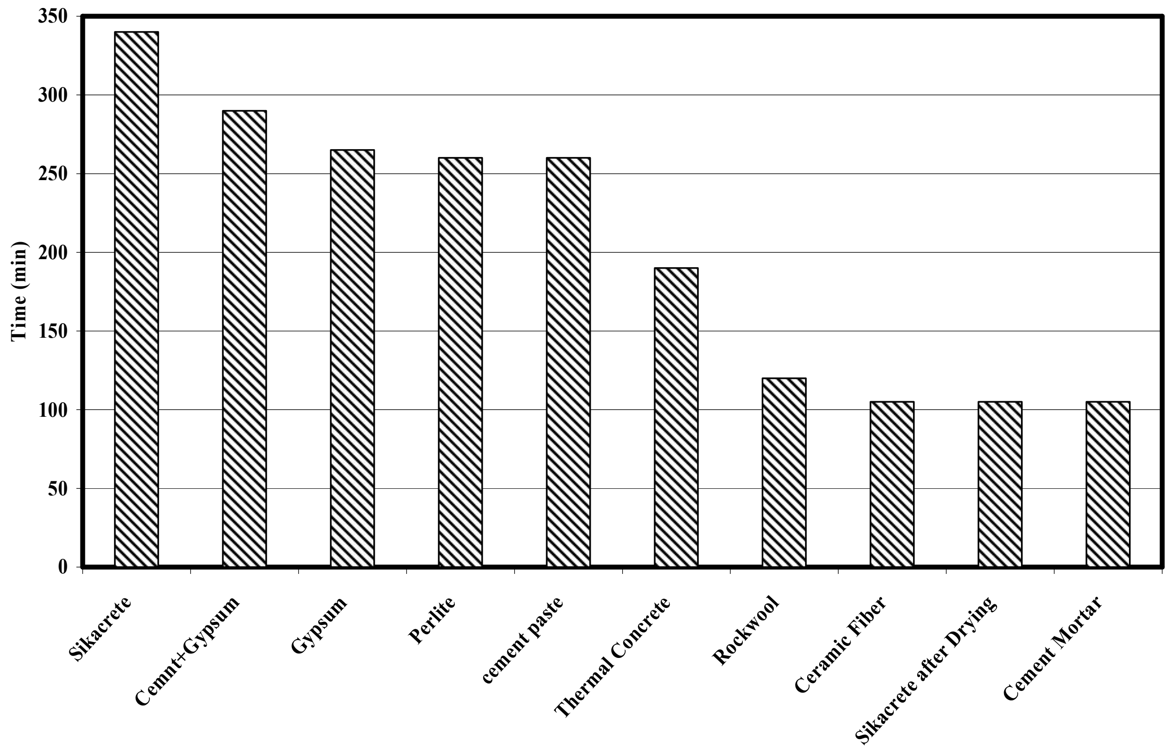


Fig. 4.36 Comparing the insulated material according to the time takes to reach 200°c at CFRP Surface

At this temperature level, some changes had been takes place for the CFRP sheets specially when subjected for long durations. CFRP sheets colors turn to be darker and the columns lost about 33.3 % from its ultimate capacity for continues exposure for 24 hours.

4-3-7 Behavior of insulating material at 250°c

Six insulating materials have been tested till temperature at CFRP surface reached 250°c. Ceramic fiber and Rock wool have been eliminated due to their poor thermal resistance in both 100°c and 200 °c. The overall behavior of the insulating material resembles their behavior at 200 °c. The thermal endurance for sikacrete213f reached 400min till heat transfer through this material and reaches CFRP surface at 250 °c. The ratio between the thermal endurance of other insulating material compared to Sikacrete213f was 82%, 78%,70%,65%,52%, and 30% for Cement+ Gypsum, Perlite, Cement paste, Thermal Concrete, Siakcrete213f "2nd cycle", and Cement mortar respectively.

It is clearly showed that the effect of pre-heating the insulating material"Sikacrete213f" and getting rid of all its internal moisture decrease its thermal resistance by 90%

According to average furnace temperature when CFRP surface reached 250 °c, most of the insulating materials behave similarly, as shown in figure (4.37) and (4.38) comparing the insulating material according to maximum furnace temperature and heat transfer time at 250^{o}c on CFRP surface

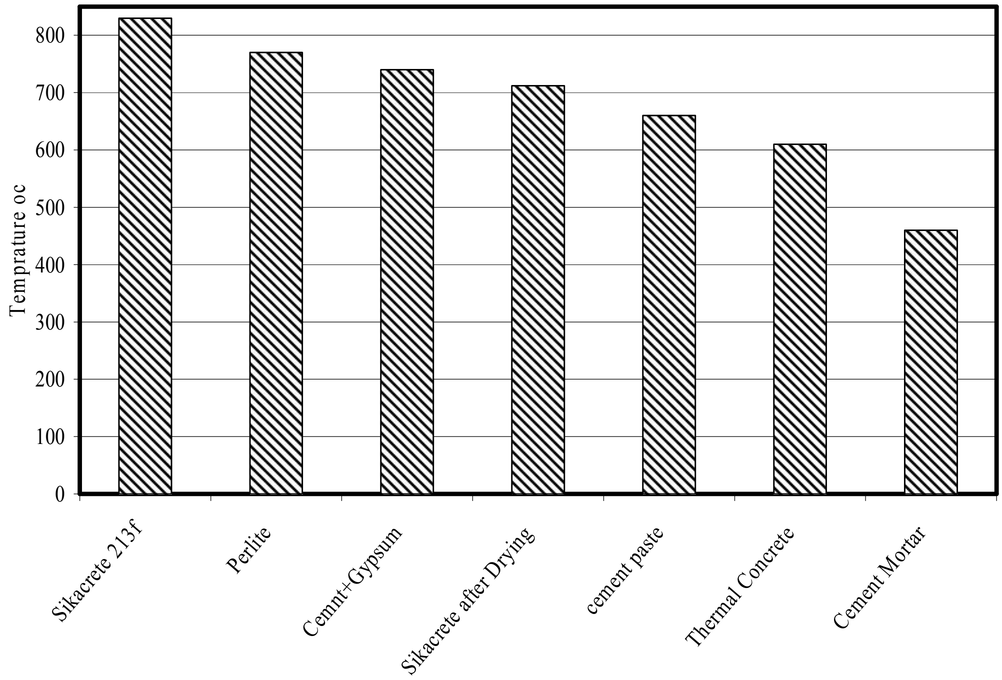


Fig. 4.37 Comparing the insulated material according to the corresponding furnace temperature to reach 250^{o}c at CFRP Surface

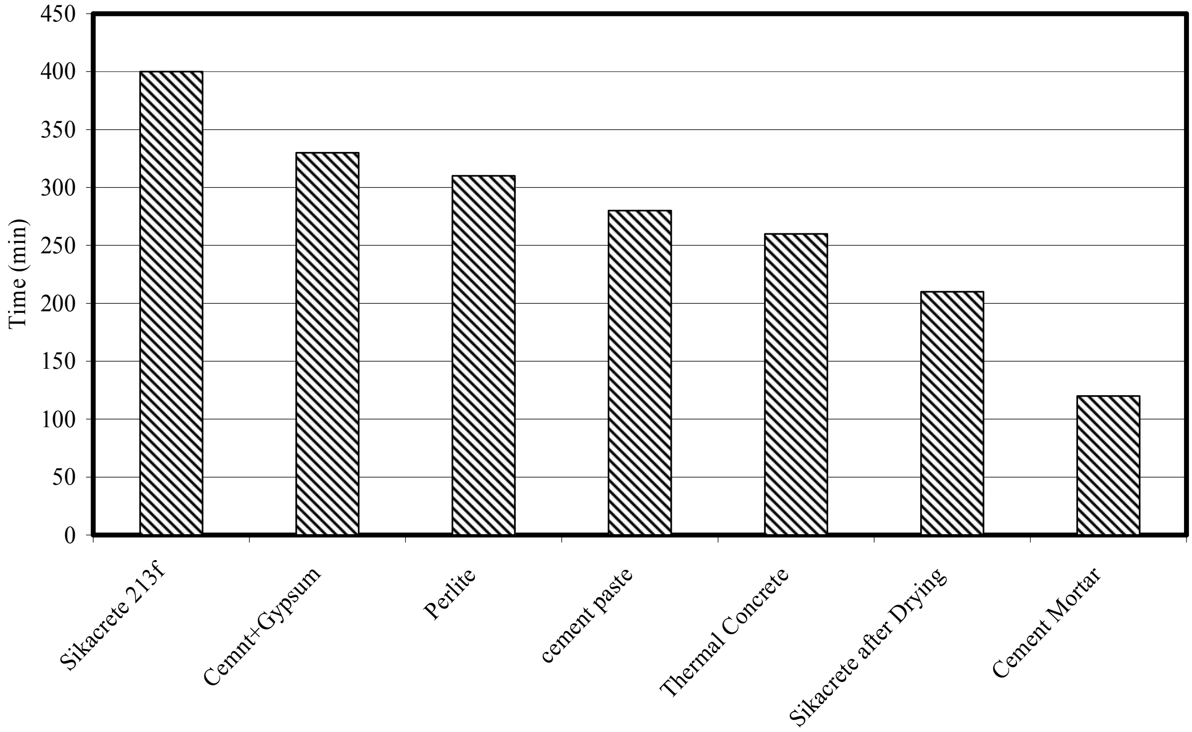
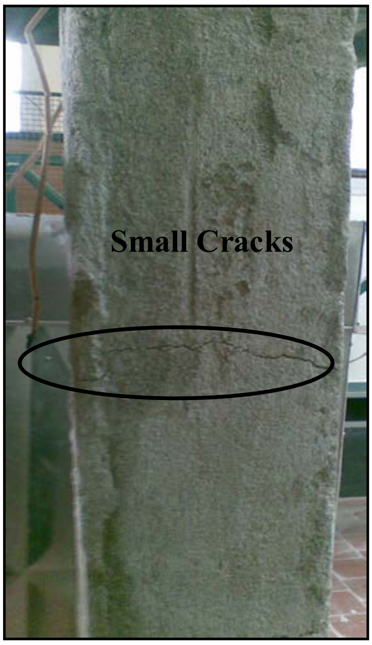


Fig. 4.38 Comparing the insulated material according to the time takes to reach 250^{o}c at CFRP Surface

According to the structural behavior for these tested columns at this temperature level, they lost about 45 % of their efficiency after 12 hours. On the other hand, the bond between CFRP and concrete surface has been totally lost after continuous exposure for 24 hours. Moreover, wide cracks have been appeared in all granular insulating material after being cooled to room temperature specially when subjected to 24 hours, as shown in figures (4.39) and (4.40).



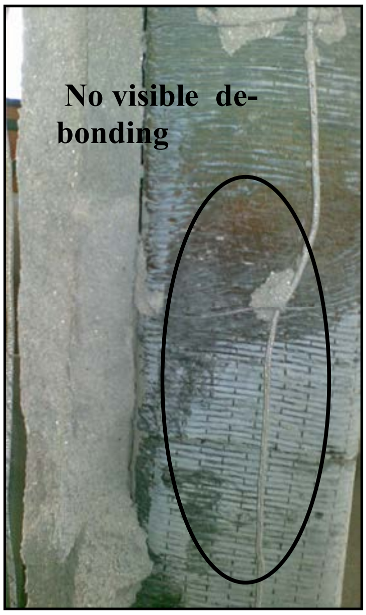


Fig. 4.39 Shows the cracks at insulating materials and the bond of CFRP while removing insulation after exposure to 250^{o}c for 12hrs

Fig. 4.40 shows the cracks at insulating materials and the bond of CFRP while removing insulation after exposure to 250^{o}c for 24 hours.

4-3-8 Behavior of insulating material at 300°c

Cement paste, Thermal concrete, and Cement mortar have been tested till CFRP temperature reached 300°c, Cement paste and Thermal concrete have same thermal endurance of 320 min to reach 300°c for CFRP surface at average furnace temperature 720°c and 665°c, while cement mortar is less than other tested insulating material by 113% with thermal endurance 150min and average furnace temperature 520°c only. Figure (4.41) comparing both thermal concrete and cement mortar through the heat endurance and average furnace temperature at 300°c

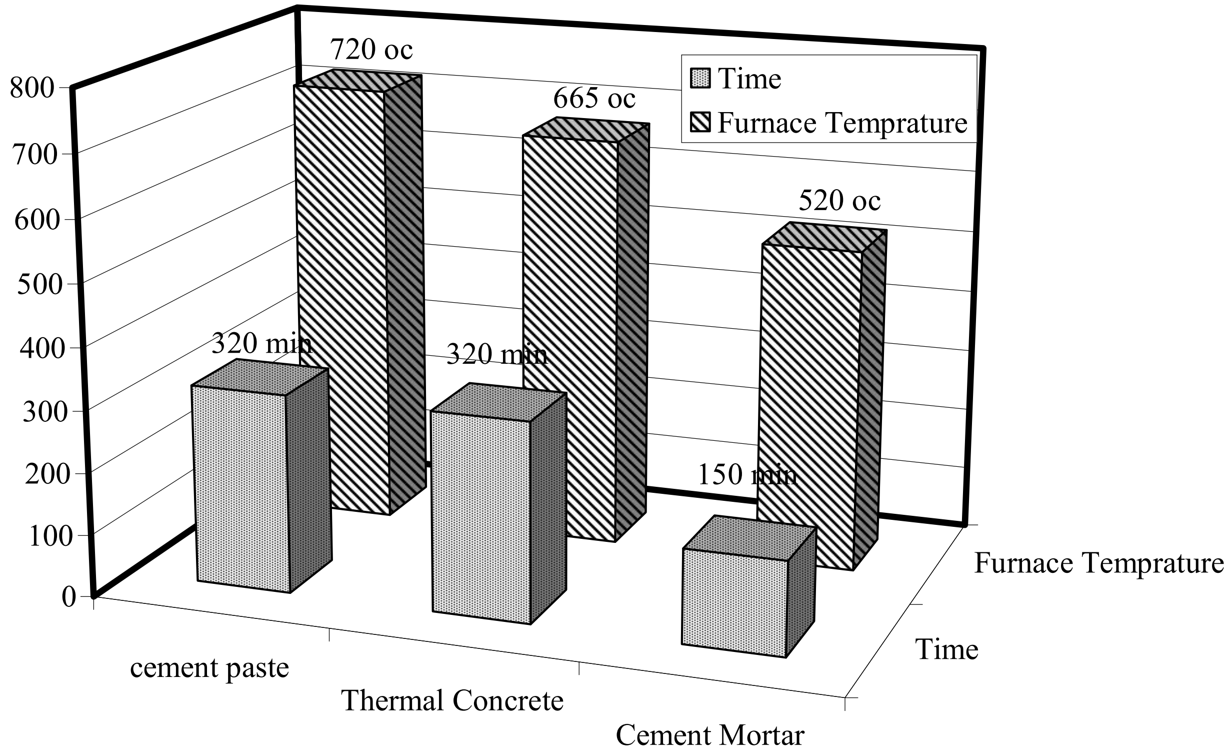


Fig. 4.41 comparing both thermal concrete and cement mortar through the heat endurance and average furnace temperature at 300°c at CFRP Surface

4-4 Summary for thermal Endurance of Insulating Materials

A comparison of the thermal endurance for the tested columns is shown in Figure (4.42). This difference among the thermal behavior of the different insulating materials emphasizes their role in protecting CFRP strengthening system from elevated temperature ranged from 100°c to 300°c at CFRP surface for a specific duration. In fact, the poorest insulating material were noticeable for (Rock wool, Ceramic fiber, Cement mortar, Thermal concrete, and Sikacrete213f after the 2nd heating cycle) where their thermal endurance to reach 100°c varied from 40 min to 75 min with an average duration of about one hour. In spite of Thermal concrete have poor thermal endurance at 100°c, its thermal endurance upgrades with increasing temperature. On the other hand, (Cement paste, Perlite, Gypsum, Cement + Gypsum) have more thermal endurance at 100^{o}c ranged between 180 min to 215 min with an average duration of about 3.3 hours. Sikacrete213f which was designed for fire protection has the superior behavior its thermal endurance at 100^{o}c equal 4.2 hours.

It is evident from figure (4.42) that the thermal endurance time increase with increasing the temperature reaches the CFRP surface, while there is variable deterioration in CFRP confinement effectiveness according to temperature on CFRP surface and how long it remains constant at this temperature level, as mentioned before.

It is well documented in the literature that the use of insulating material to protect CFRP confined columns does not eliminate heat transfer but it merely reduce it and increase the heat transfer time till reach to the CFRP surface for all tested temperature levels.

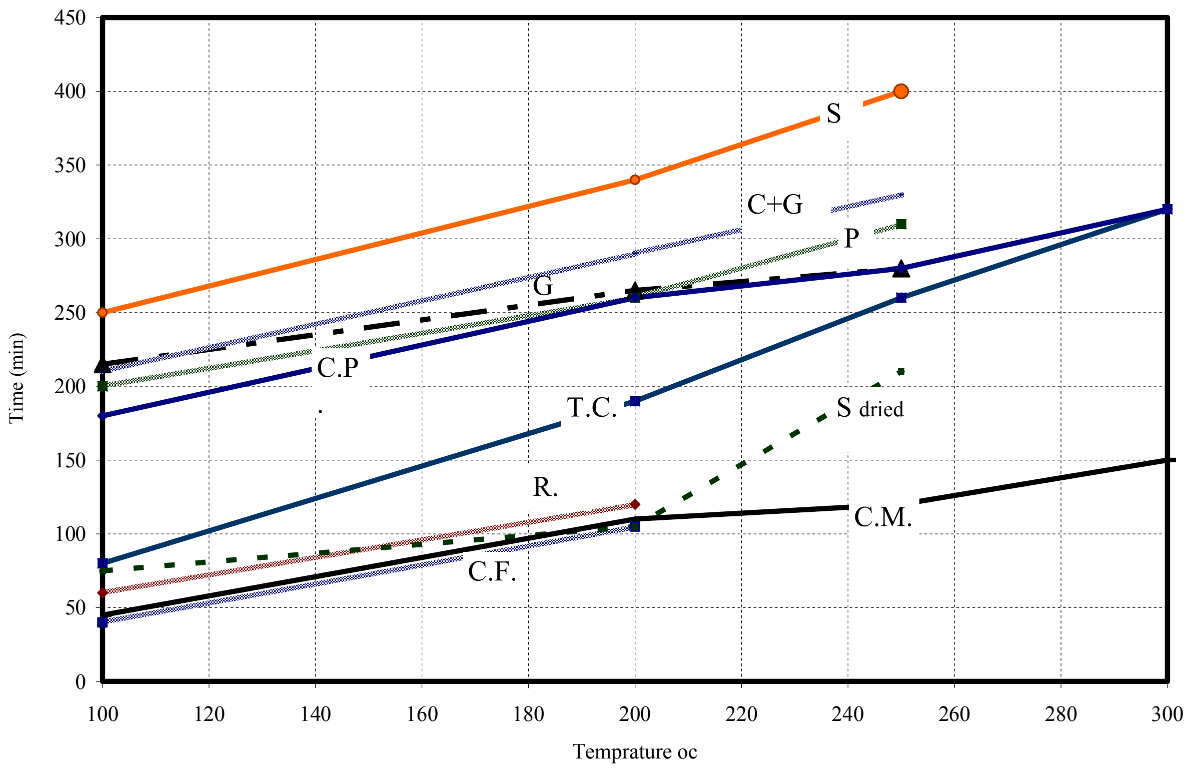


Fig. 4.42 Thermal Endurance for the tested insulating material

From the overall prospective, it may be concluded based on experimental evidences that the overall structural effectiveness and thermal endurance of FRP-wrapped columns can be enhanced by applying supplement insulation to the exterior FRP surface.

CHAPTER 5
ANALYTICAL APPROACH

5-1 GENERAL

The study of the behavior of concrete structures at elevated temperature is a great practical importance and has been a main area of research over the last 25 years. The researches have suggested analytical models in order to study the behavior of steel and RC structures under elevated temperature environments. Any such effort has not yet been done in the case of FRP reinforced members. This is due to the fact that reliable methods to determine residual FRP reinforced members performance at elevated temperature are currently unavailable. Therefore, the prediction of response of FRP reinforced structures and validations of theoretical results against the experimental data are not yet possible at present.

The deterioration in CFRP confinement effectiveness do not depend only on the temperature level for exposure, but it depend mainly on the rate of heating and to the duration it will face the temperature exposure[65, 69-72]. This time dependent make the heat transfer a transient problem. This research developed a finite element thermal model conducted on insulated square R.C. columns confined by CFRP sheets and subjected to elevated temperature.

The model simulates the transient heat transfer through different insulating material in accordance to the furnace heating rate. The ultimate goal of this analytical approach is to validate the proposed finite element model with the experimental results conducted in this research according to the furnace heating rate and other experimental studies for heat transfer through insulating material according to the standard fire curve. Once the model being verified it can be used to make parametric studies in accordance with the standard fire curve. Moreover, the model provide design recommendations and guidelines that can be suggested for protecting R.C. confined by CFRP using different insulating materials. Also, model could predict the temperature distribution at different interfaces of the insulating material and concrete specimen.

5.2 INTRODUCTION FOR HEAT TRANSFER

Heat transfer is science that seeks to predict the energy transfer that may take place between material bodies as a result of temperature difference. Thermodynamics teaches that this energy transfer is defined as heat. The science of heat transfer seeks not merely to explain how heat energy may be transferred, but also the rate at which the exchange will take place under certain specified condition. There are three modes of heat transfer: *conduction*, *convection*, and *radiation*[65].

Conduction is the transfer of energy from the more energetic particles of a substrate to the adjacent, less energetic ones as a result of interaction between particles. *Convection* is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. *Radiation* is the energy emitted by matter in the form of electromagnetic waves. So our problem concerns the heat transfer through insulation material /FRP/concrete, deals with heat transfer by conduction.

5.2.1 Heat Transfer by Conduction

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from high-temperature region to the low temperature region. We say that the energy transferred by *conduction* and the heat-transfer rate per unit area is proportional to the normal temperature gradient and can be expressed in the following equation[65]:

$$\frac{q}{A} \approx \frac{\partial T}{\partial x} \qquad \text{------------------------------(5.1)}$$

When the Proportionality constant k is inserted, so we can satisfy the second law of thermodynamics and we can conduct the Fourier's law of heat conduction.

$$q = -kA\frac{\partial T}{\partial x} \qquad \text{------------------------------(5.2)}$$

Where:

q : heat transfer rate

$\frac{\partial T}{\partial x}$: Temperature gradient in the direction of heat flow

k : thermal conductivity of material, which measure the ability of a material to conduct heat , and its units (watt / m / ^{o}c)

5.2.1.1 Thermal Conductivity "*k*"

The rate of heat transfer through a unit thickness of material per unit area per unit temperature difference, Moreover Thermal Conductivity is a measure of how fast heat will flow in that material. A large value of thermal conductivity indicates that the material is a good heat conductor, while a low value indicates that the material is a poor heat conductor *"insulator"*

The thermal conductivities of material vary with temperature; this variation of thermal conductivities over certain temperature ranges is negligible for some materials, but significant for others, also thermal conductivities of materials don’t have constant trend with temperature. This temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Therefore, it is common practice to evaluate the thermal conductivity *k* at the average temperature and treat it as constant in calculations.

The effective thermal conductivity increases with temperature. For granular insulation materials this effect can be described with a linear approach, measured values of the effective thermal conductivity fore different insulating materials are compared in figure (5.1)[65]

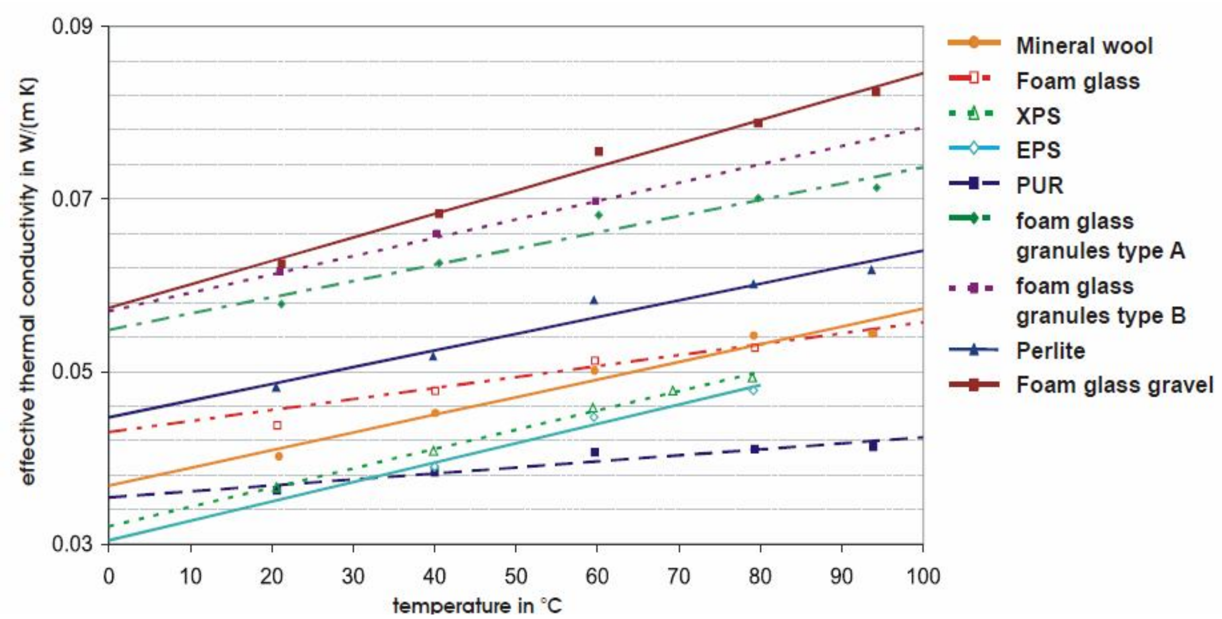


Fig. 5.1 Variation of Thermal conductivity with temperature for various types of insulating materials

Moisture content also affects the *effective conductivity* of porous mediums such as soils, building material, and fibrous insulations, and thus *heat transfer* through them. Several studies have indicated that heat transfer increases almost linearly with moisture content, at a rate of 3% to 5% for each 1% increase in moisture content by volume[65]

5.2.1.2 Specific Heat "c_p"

It is the heat required to raise the temperature of a ***unit mass*** of the material by one degree, material often contain water and this water will removed in certain temperature regions. In these regions, most of the heat supplied to the material will be used for removal of water and only small amount is available for rising the temperature of the materials. As a consequence, the specific heat may be different from one region to another according to the amount of water enclosed. Also the specific heat may be different with temperature of material.

5.2.1.3 Thermal Capacity "ρc_p"

It is the heat required to raise the temperature of the ***unit volume*** of material by one degree, which represent the heat storage capability of a material.

5.2.1.4 Thermal Diffusivity "α"

It represents how fast heat diffuses through a material, and is defined as the ratio between thermal conductivity and thermal capacity, as expressed in the following equation

$$\alpha = \frac{\kappa}{\rho Cp} \qquad \text{------------------------------(5.3)}$$

This property appears in the transient heat conduction analysis as it measures the rate of heat transport from the exposed surface of a material to the inside. It is therefore a measure of the rate of temperature rise at a certain depth of the material

Heat transfer problems are often classified as being ***steady-state*** or ***transient***" ***unsteady state"***, the term ***steady*** implies no change with time at any point within the medium, while ***transient*** implies variation with time or time dependence. During transient heat transfer, the temperature normally varies with time as well as position.

Since fire ignition or rising in temperature is a suddenly change in environmental then some time must elapse before an equilibrium temperature condition will prevail in the body. The analysis of transient heating process must be modified to take into account the change in internal energy of the body with time and the boundary condition must be adjust to match the physical situation which is apparent in the transient heat transfer problem .

5.3 THERMAL TRANSIENT PROBLEM

Fire resistance of building elements is established by exposing them to a heat inside a furnace, the temperature inside a furnace follows a standard fire curve called the standard fire. This standard fire is time dependant and makes the heat transfer a transient problem. When an object is heated in an enclosed environment, such as furnace, heat flows to the exposed surfaces of the object through convection and radiation where as heat transfer inside the body is carried out through conduction.

The objective of performing a thermal transient analysis is to calculate the temperature distribution through the insulation material and concrete substrate passing through the insulating material to the FRP and epoxy resin, which help in carrying out a thermal stress analysis.

5.3.1 Transient Heat Transfer Analysis

The thermal analysis is based on two dimensional steady state flow equation, which is derived from the law of conservation of energy, which states that the total inflow of heat in a unit time across a body must be equal to the total outflow per unit time.

Consider the semi-infinite solid in figure (5.2) maintained at some initial temperature T_i. The surface is suddenly heated to T_o and we seek an expression for the temperature distribution in the solid a function of time[65].

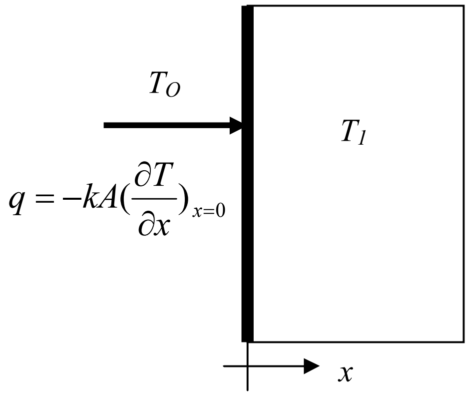


Fig. 5.2 Nomenclature for transient heat flow in semi-infinite soild

This temperature distribution may subsequently be used to calculate the heat at any *x* position in the solid as a function of time. For constant properties, the differential equation for the temperature distribution T(*x*, *t)* is expressed in the following equations.

$$\frac{\partial^2 T}{\partial \chi^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{------------------------------(5.4)}$$

The boundary and initial conditions are

$T(x, 0) = T_i$ ----------------------------(5.5)

$T(0, t) = T_o$ for $t>0$ ----------------------------(5.6)

This is a problem that may be solved by Laplace- Transfrom technique. The solution is given as

$$\frac{T(x,\tau) - T_0}{T_i - T_0} = erf\,\frac{\chi}{2\sqrt{\alpha\tau}} \qquad \text{----------------------------(5.7)}$$

Where Gauss error function is defined as

$$erf \frac{\chi}{2\sqrt{\alpha\tau}} = \frac{2}{\sqrt{\pi}} \int^{\chi/2\sqrt{\alpha\tau}} e^{-\eta^2} d\eta \qquad \text{-----------------------------(5.8)}$$

It will be noted that in this definition" ŋ" is a dummy variable and the integral is a function of its upper limit. When the definition of the error function is inserted in Equation (5.7), the expression for the temperature distribution becomes as follow.

$$\frac{T(\chi,t)-T_0}{T_i - T_0} = \frac{2}{\sqrt{\pi}} \int^{\chi/2\sqrt{\alpha\tau}} e^{-\eta^2} d\eta \qquad \text{-----------------------------(5.9)}$$

The heat flow at any x position may be obtained from

$$q = -kA\frac{\partial T}{\partial x} \qquad \text{-----------------------------(5.10)}$$

Performing the partial differentiation of Equation (5.9) gives

$$\frac{\partial T}{\partial x} = (T_i - T_0)\frac{2}{\sqrt{\pi}} e^{-\chi^2/4\alpha\tau} \frac{\partial}{\partial \chi}\left(\frac{\chi}{2\sqrt{\alpha\tau}}\right) = \frac{T_i - T_0}{\sqrt{\pi\alpha\tau}} e^{-\chi^2/4\alpha\tau}$$

At the surface (x=0) the heat flow is

$$q_0 = \frac{kA(T_0 - T_i)}{\sqrt{\pi\alpha\tau}} \qquad \text{-----------------------------(5.11)}$$

For the same uniform initial temperature distribution, we could suddenly expose the surface to a constant surface heat flux q_o / A the initial and boundary condition on Equation (5.4) would then become

The initial temperature $T(x,0) = T_i$

$$\frac{q_o}{A} = -k\frac{\partial T}{\partial \chi} \Big]_{x=0} \quad for\ t \succ 0 \qquad \text{-----------------------------(5.12)}$$

The solution for this case to calculate the temperature beneath the insulation material "T" having thermal diffusivity "α" with thickness "x", and initial temperature T_i due to raise in the outer temperature "T_o"

$$T(x,\tau) = T_0 + (T_i - T_0)\ erf \frac{x}{2\sqrt{\alpha\tau}} \qquad \text{-----------------------------(5.13)}$$

The above mentioned equations can predict the temperature beneath the insulating material with transient state of heat transfer taking into consideration; the initial temperature, outside temperature, the exposure duration, thermal properties of insulating materials and the exposure time, however these equation neglect an important factor which is the rate of heat transfer according to the heating furnace or the fire exposure this factor will make the problem transient heat transfer with variable heating rate and make it more complex and not accurate to be solved by mathematically model, then the use of finite element model will solve this transient problem as it solve those equation using iteration procedure every given time intervals taking into consider the time- temperature curve for each insulating material.

5.4. TRANSIENT HEAT TRANSFER MODEL (FINITE ELEMENT ANALYSIS)

Thermal analyses are used to determine the temperature distribution, thermal gradient, heat flow, and other such thermal quantities in a structure. Initially, all required information is inputted into the analytical program. This includes cross-section details, mechanical and thermal properties for concrete and insulating materials, type of elements used in modeling, , number of steps for solution output, and rate of heating "time versus temperature Curve". The temperature is then obtained at each instant for the required time duration according to the furnace heating rate or the standard temperature-time curve described by ASTM E119

The following assumptions are adopted for analyzing the high-temperature performance of isolated R.C. confined columns

1. The temperature of R.C. columns is evenly distributed along the length. However, the variation of the temperature over the member section is taken into account.
2. The fire protection materials on R.C. columns are uniformly pasted
3. Neglect the effect of reinforcing steel in concrete core in heat transfer analysis

5.4.1 Finite Element Modeling Program "Ansys ver.11.0"

ANSYS[73] is finite element analysis software suitable for analyzing the non-linear behavior of various structures, and heat transfer analysis at elevated temperatures. The basis for thermal analysis in ANSYS is a heat balance equation obtained from the principle of conservation of energy Equation (5.2).

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are; the temperature distribution, the amount of heat lost or gained, thermal gradients, and thermal fluxes

There are two types of thermal analysis: First, steady-state thermal analysis determines the temperature distribution and other thermal quantities under steady-state loading conditions. A steady-state loading condition is a situation where heat storage effects varying over a period of time can be ignored. Second, transient thermal analysis determines the temperature distribution and other thermal quantities under conditions that vary over a period of time.

The finite element modeling divide the time versus temperature curve to different number of steps depend on the time corresponding to the ultimate furnace temperature or the maximum fire temperature, the time step size is constant in all insulating materials modeling equal 100 second.

The finite element modeling depends mainly on the thermal diffusivity. It represents how fast heat diffuses through a material, and is defined as the ratio between thermal conductivity and thermal capacity as expressed in Equation (5.3). This property appears in the transient heat conduction analysis as it measures the rate of heat transfer from the exposed surface of a material to the inside. It is therefore a measure of the rate of temperature rise at a certain depth of the material

The following elements of ANSYS are adopted for this analytical study on thermal - endurance of various insulating materials

5.4.1.1 Solid 70 (3-D Thermal Solid)

This element simulates the insulation materials; it has 3-D thermal conduction capability. The element has eight nodes with a single degree of freedom, temperature, at each node. The element is applicable to a 3-D, steady-state or transient thermal analysis. The element also can compensate for mass transport heat flow from a constant velocity field. If the model containing the conducting solid element is also to be analyzed structurally, the element should be replaced by an equivalent structural element. The element is defined by eight nodes and the orthotropic material properties. A prism-shaped element, a tetrahedral-shaped element, and a pyramid-shaped element may also be formed. The geometry, node locations, and the coordinate system for this element are shown in figure (5.3)[73]

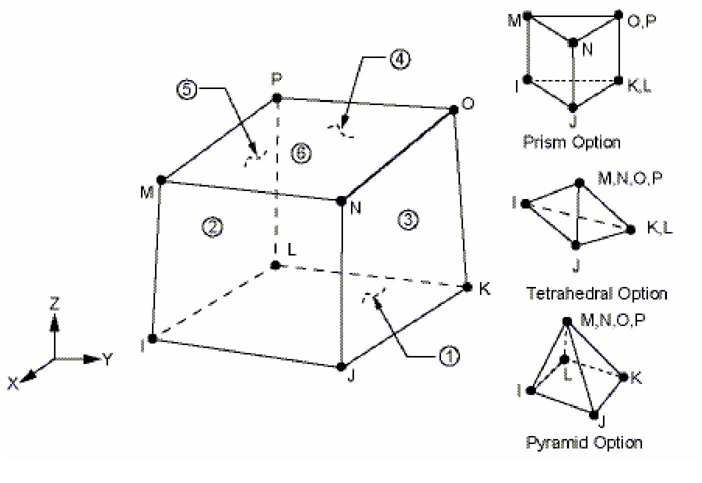


Fig. 5.3 Solid 70 Geometry

5.4.1.2 Solid 65(3D Reinforced Concrete Solid)

This element simulates the R.C. column, it is used for the 3-D modeling of solids with or without reinforcing bars (rebar). The solid is capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete while the rebar capability is available for modeling reinforcement behavior. Other cases for which the element is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions, as shown in figure (5.4)[73].

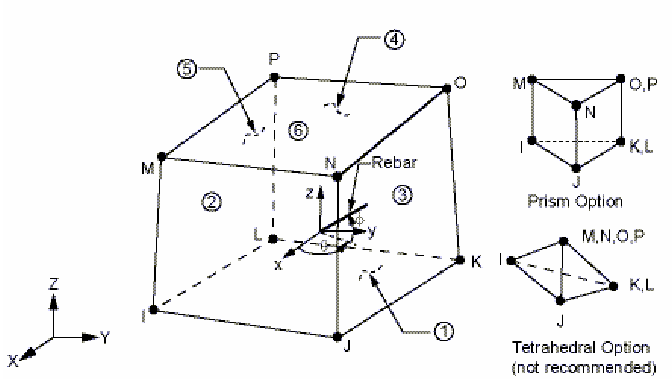


Fig. 5.4 Solid 65 Geometry

5.4.2 Finite Element Model Validation

The temperature distribution of the member can be calculated with three-dimensional model. The R.C. column meshed with (Solid 65) element while the insulating material meshed with (Solid 70) element, heat through conduction load was applied around the side areas of the column, and each element size along the column height and cross section is 10 mm. Figure (5.5) shows the mesh for the cross-section and how the heat convection load was applied.

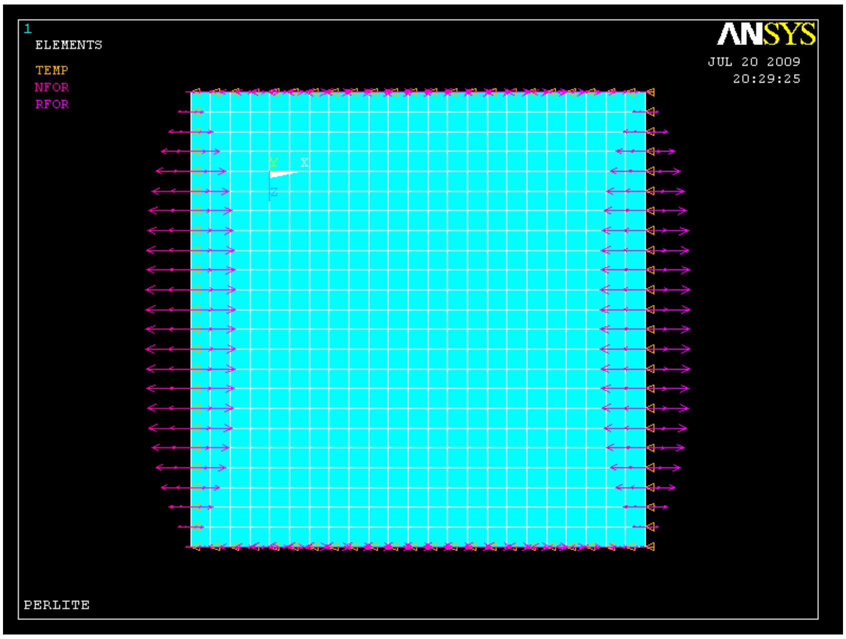


Fig. 5.5 Element meshes of the section and heat convection load.

The validity of the model was first verified by comparing the FEM prediction for time- temperature curves to the measured values obtained in the experimental study, as shown in Figures (5.6) to (5.14).

The recorded experimental temperature on the insulation surface was the average of recorded temperature for the four thermocouples on the column sides, attached on the mid height of the column.

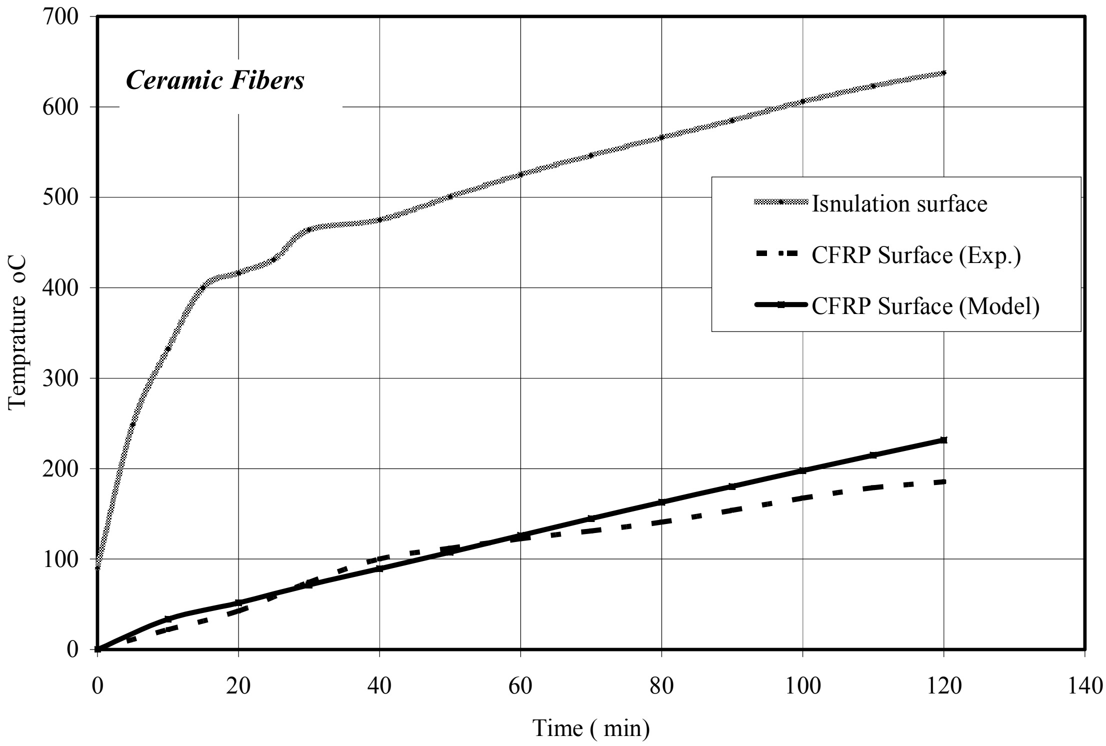


Fig. 5.6. Time versus temperature curves for Furnace and CFRP surface for both experimental and the predicted model for Ceramic fiber

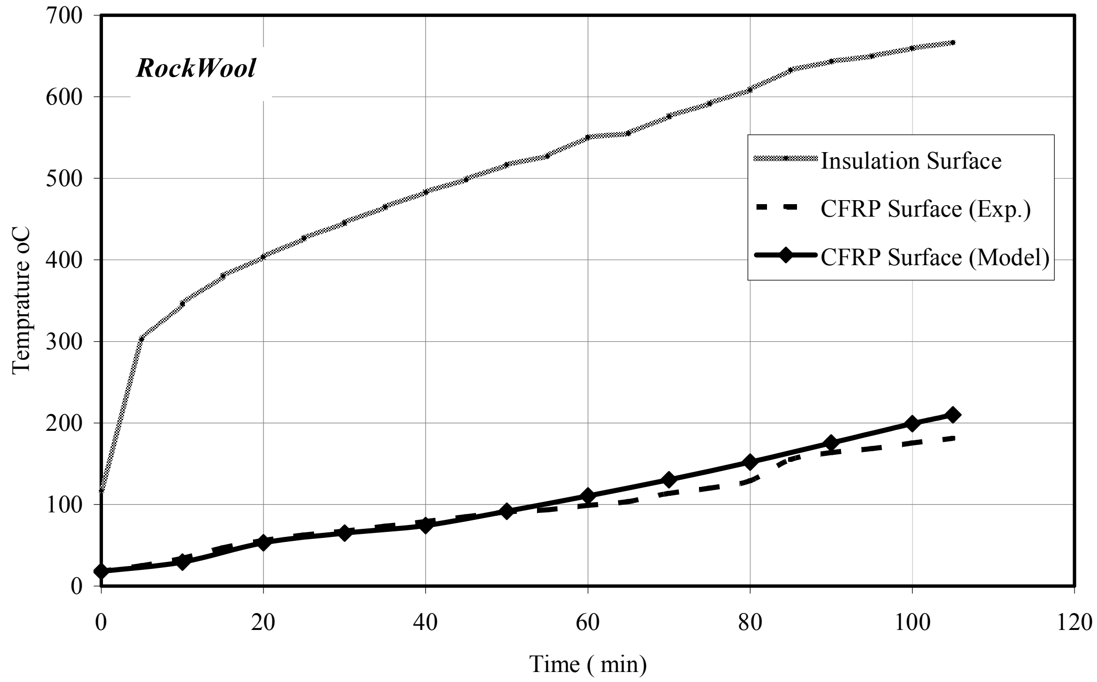


Fig. 5.7 Time versus temperature curves for Furnace and CFRP surface for both experimental and the predicted model for Rock wool

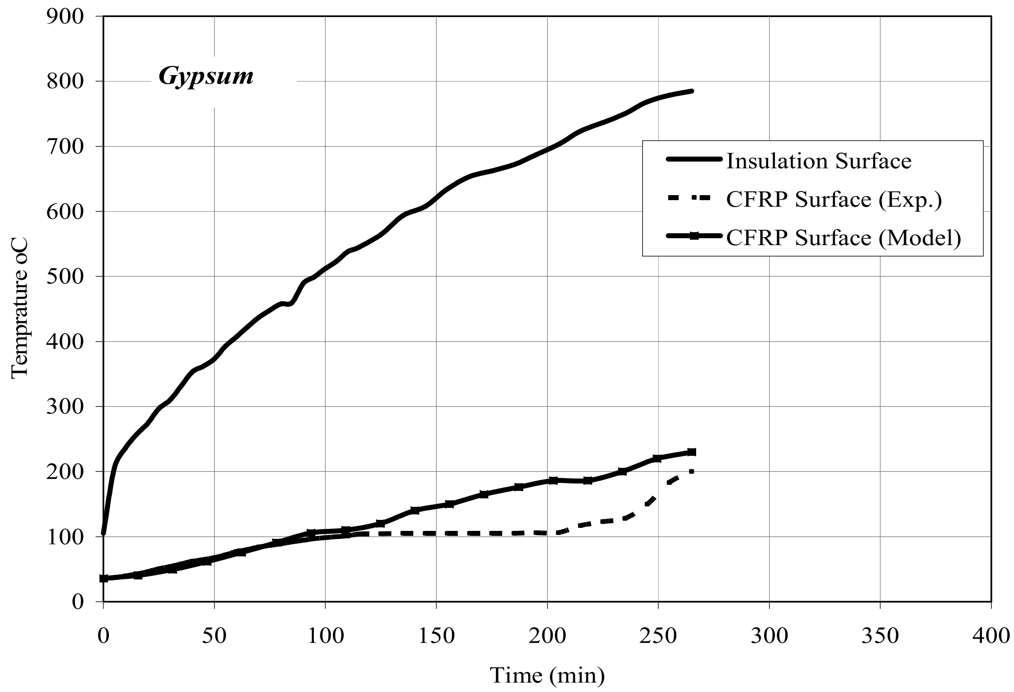


Fig. 5.8 Time versus temperature curves for Furnace and CFRP surface for both experimental and the predicted model for Gypsum

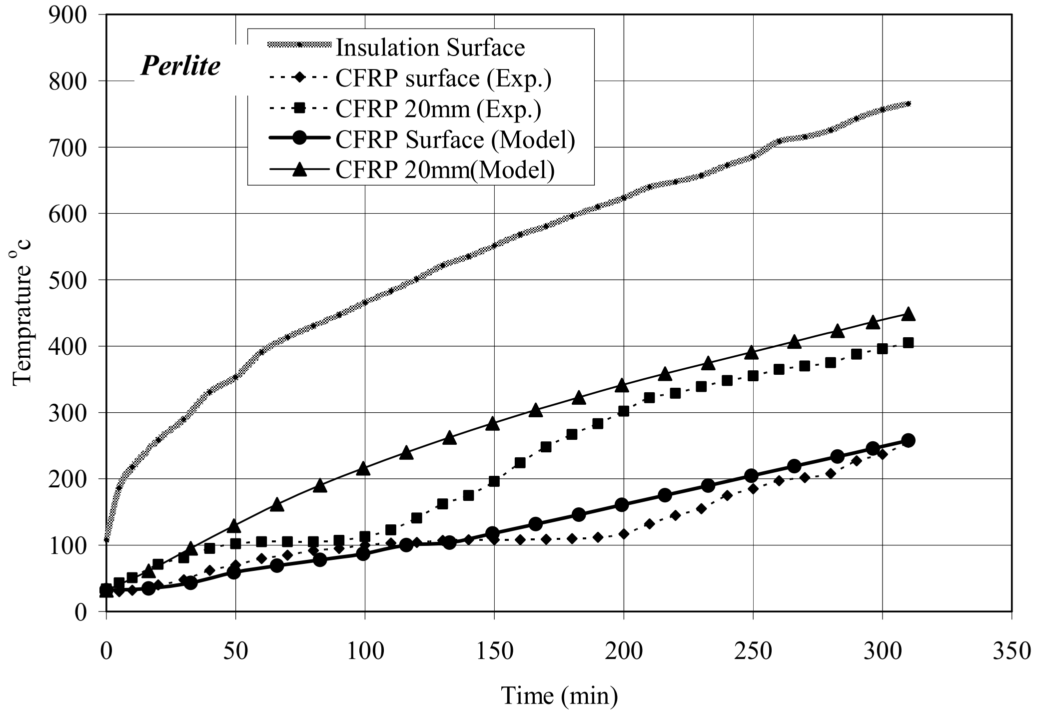


Fig. 5.9 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Perlite

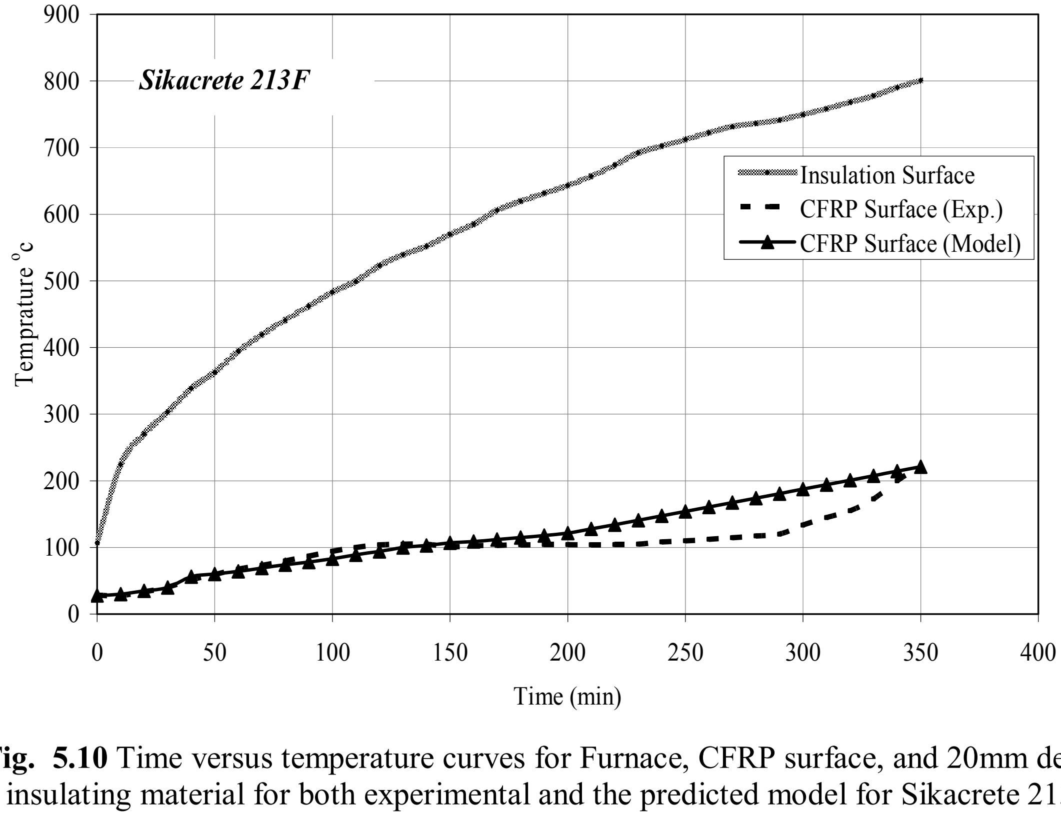


Fig. 5.10 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Sikacrete 213f

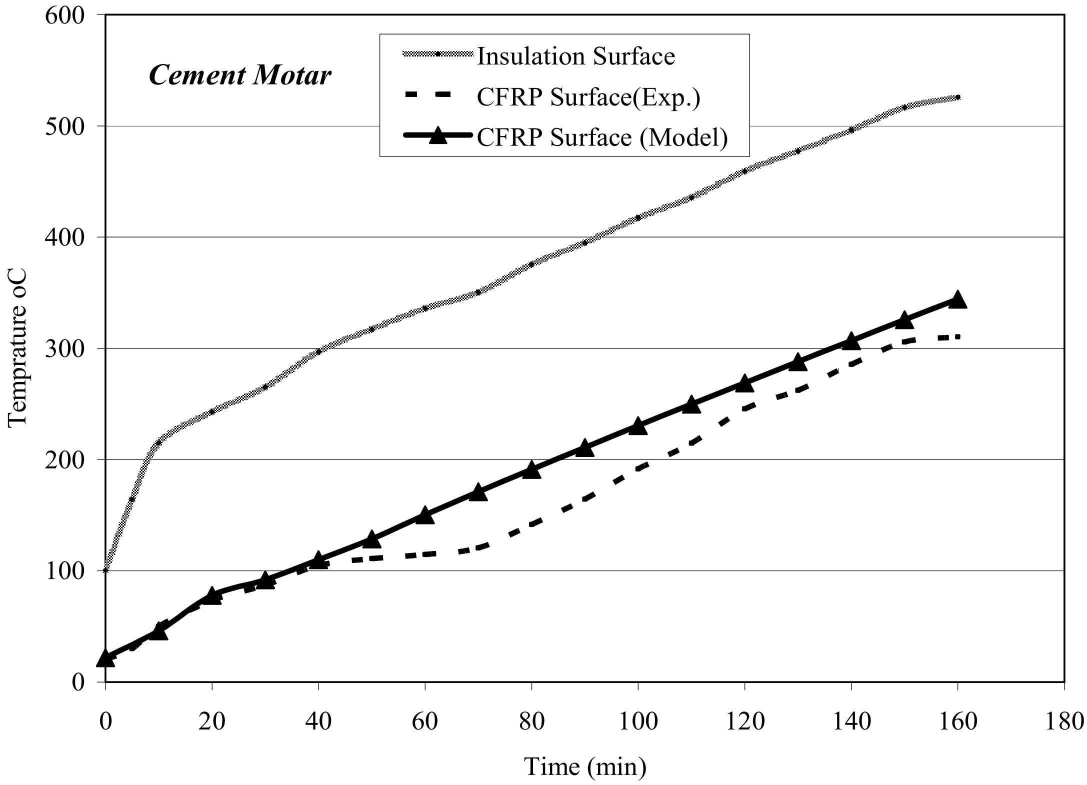


Fig. 5.11 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Cement Mortar

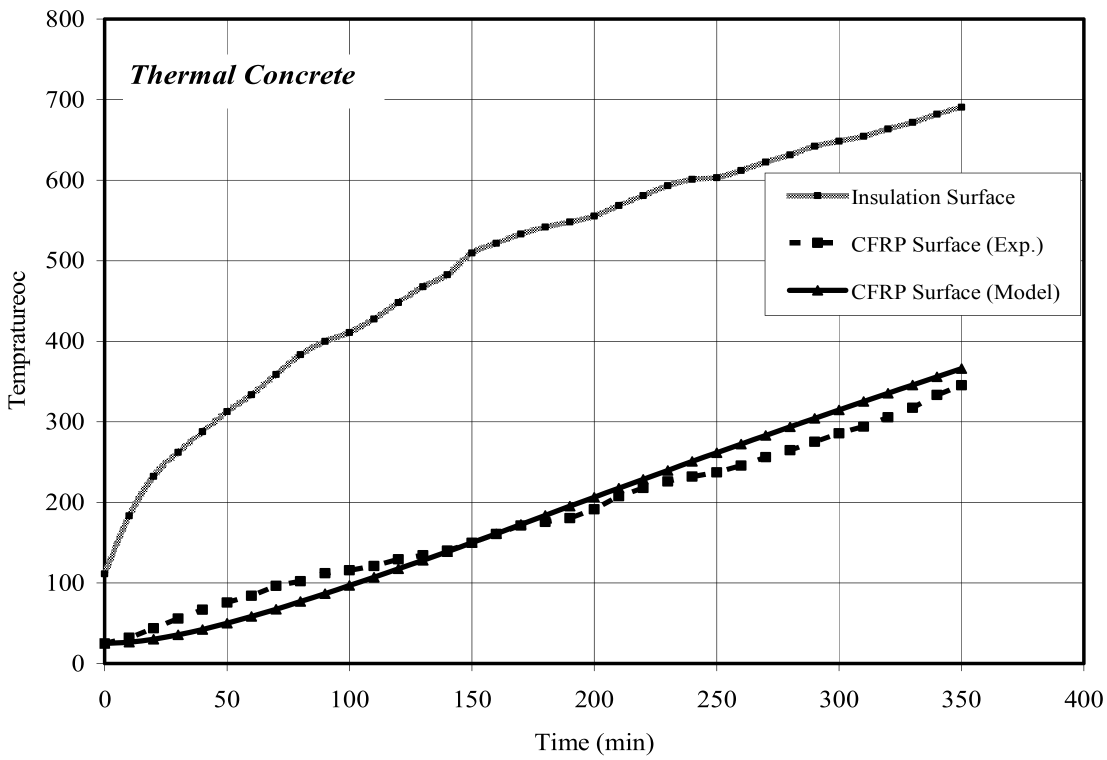


Fig. 5.12 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Thermal Concrete

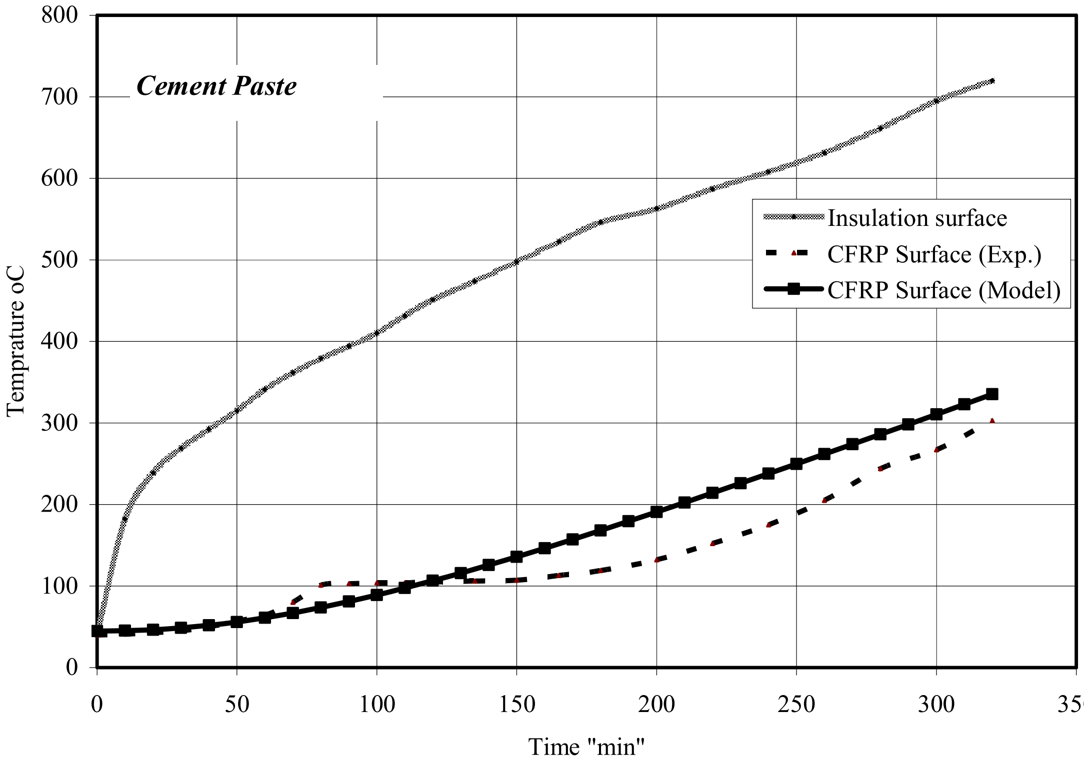


Fig. 5.13 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Cement paste

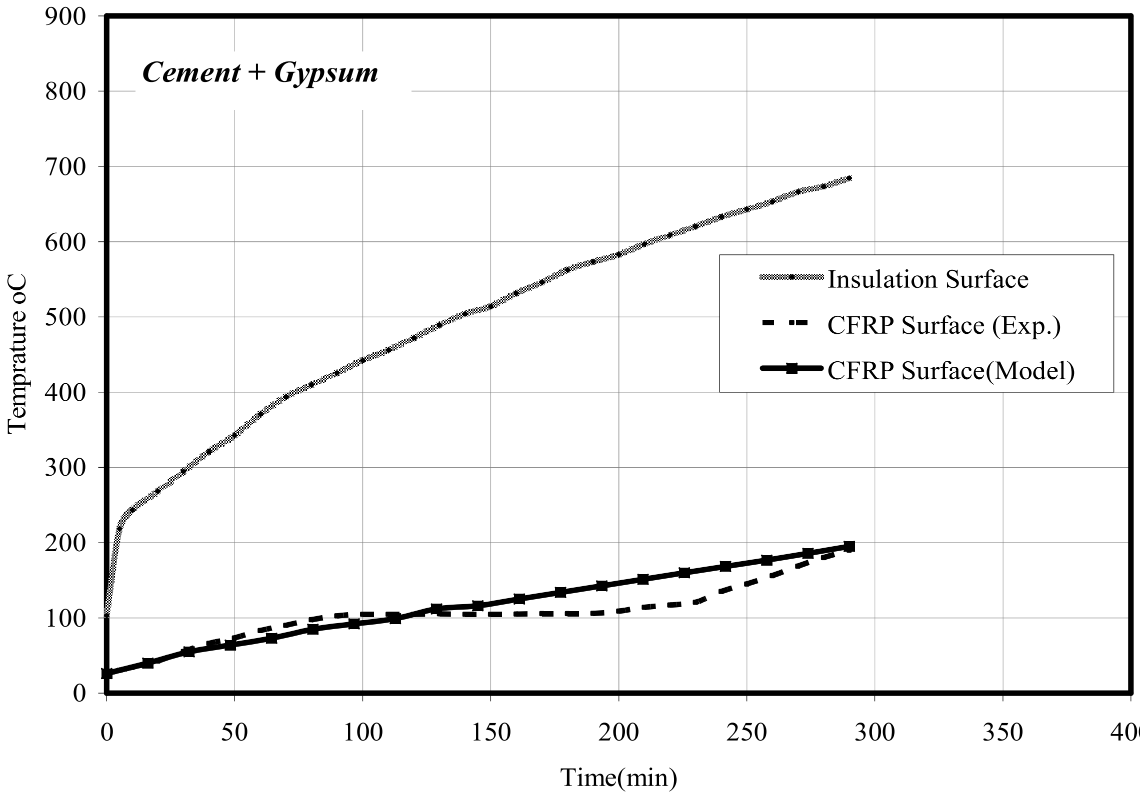


Fig. 5.14 Time versus temperature curves for Furnace, CFRP surface, and 20mm depth insulating material for both experimental and the predicted model for Cement + Gypsum

It can be seen in the previous figures (5.6) to (5.14) that the correlation between predicted and measured temperature is fairly accurate and conservative for the entire time-temperature history. The deviation of the analytical curves from the recorded data after 100^{o}c was due to the negligible of water vapor, which is physical phenomenon, however, it can be seen that both curves run nearly to parallel to each other. The thermal analysis tends to overestimate temperature at FRP surface than the experimental.

It has been noted from the experimental tests that the temperature along the circumference of the column cross section is not longer uniform throughout the four sides of the column that is due to the horizontal spinning air flow inside the furnace. Moreover that the temperature through the column height is not equal, the highest temperature appear in the top of column and the lowest temperature in the bottom, this is due to the hot air have lower density so it flow up to the upper of furnace and this circulation continue while the air with lower heat temperature remain at the bottom. Also this phenomena has been observed in the F.E.M results as shown in figures (5.15) to (5.19) which represent the temperature distribution across the column cross section

The temperature gradient for column cross section can be observed at every step of the finite element model, as shown in Figures (5.15) to (5.19). The time increment for each step equal 300 second and the total number of steps were variable according to the total time of the experiment for every insulating material.

Furthermore, as shown in figures (5.1) to (5.19), it can be noticed that the temperature gradient across the horizontal section (between the two sides of column cross section) less than its gradient along the diagonal section (between the column corners), this could be related to the elevated temperature concentration on the column corner inside the furnace. However the predicted temperature gradient reading for insulation material temperature was taken along the horizontal section to be in accordance with the place of the thermocouples placed in the experimental study.

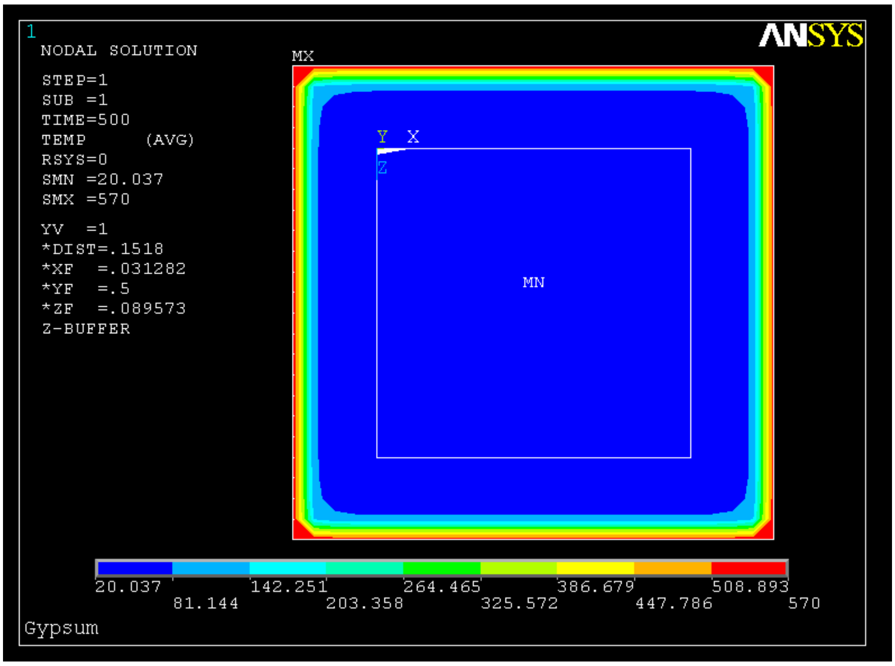


Fig. 5.15 Temperature distribution for the column cross section after 500 second of fire exposure.

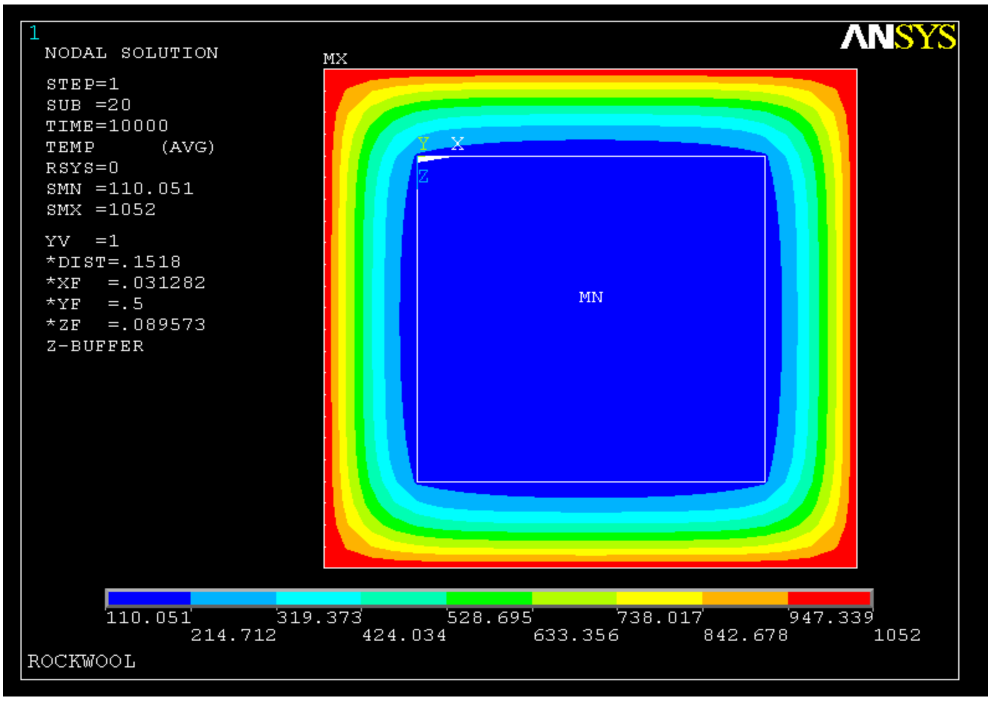


Fig. 5.16 Temperature distribution for the column cross section after 10,000 second of fire exposure

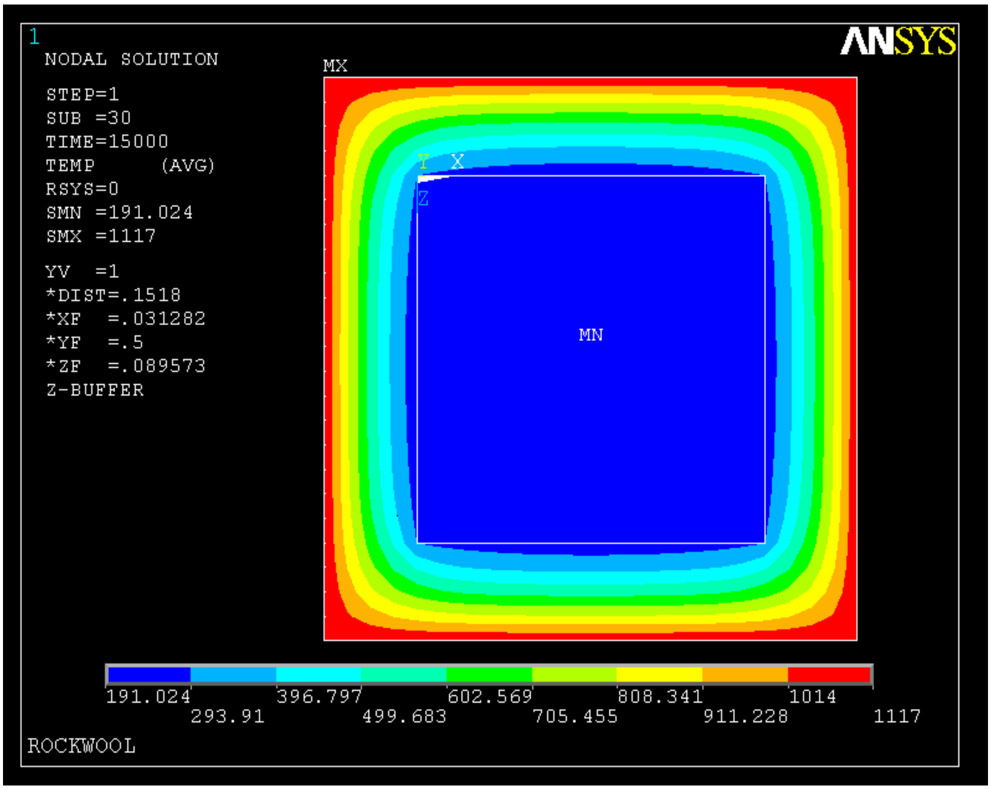


Fig. 5.17 Temperature distribution for the column cross section after 15,000 second of fire exposure

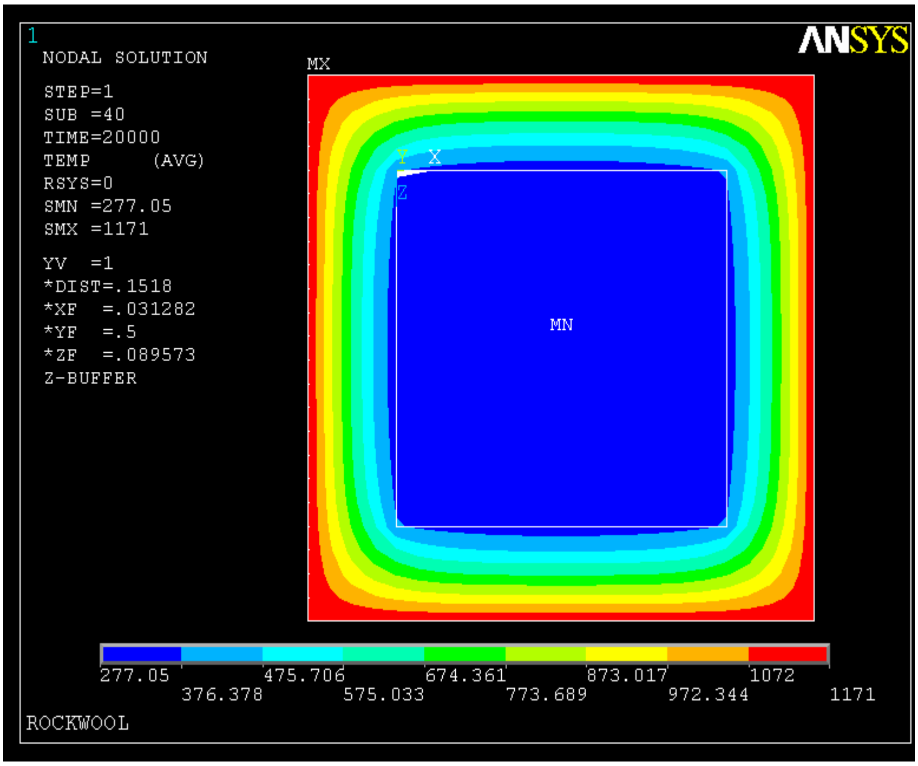


Fig. 5.18 Temperature distribution for the column cross section after 20,000 second of fire exposure

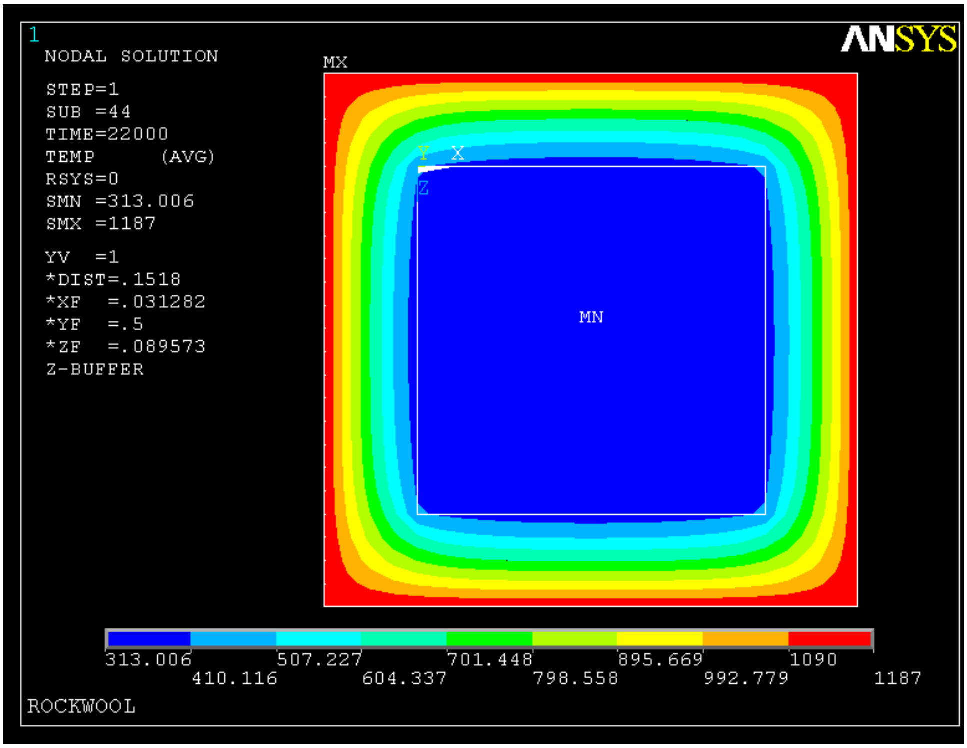


Fig. 5.15 Temperature distribution for the column cross section after 22,000 second of fire exposure and the final step

Based on the previous argument, it can be concluded that the finite element model results for temperature under the insulating material shows very good agreement and conservative results with the experimental results.

5.4.3 Fire Exposure

The Fire Resistance Rating (Fire Endurance) is a measure of the elapsed time during which an assembly continues to exhibit fire resistance under specified conditions of test and performance.

The fire endurance of RC columns has traditionally been defined in terms of their load-carrying capacity during exposure to a standard fire. The standard fire is defined by ASTM E119[25]. This curve can be approximately expressed using the following equation:

$$T_f = 20 + 750\left(1 - e^{-3.79533\sqrt{t}}\right) + 170.41\sqrt{t} \qquad \text{-----------------------------(5.13)}$$

Where: t = time in hours

T_f = Fire temperature in °C

5.4.4 Finite Element Model Verification for fire exposure

For further validation of the model, it was compared to results reported in other research study[74-76]. The experimental program consisted of fire endurance tests on two full-scale square RC columns: one un-strengthened RC column (SQ1) and one FRP-wrapped and insulated RC column (SQ2). Both columns were 3810 mm long and reinforced internally with conventional reinforcing steel. Details of the two columns are given in Table (5.1)

Table (5.1) Details of the Columns used in "Bisby et al "experimental study

Name	*Dim (mm)*	*f'c (MPa)*	*FRP Wrap* [a]	*Supplement Insulation*	*Ultimate Capacity (kN)*	*Fire Endurance (hr:min)*
SQ1	406	38.4	None	None	2418	4:22
SQ2	406	52	SEH	38mm VG + 0.25mm EI-R[b]	3093	4:16

[a] SHE – Tyfo SEH Glass/Tyfo S epoxy , applied in three layers

[b] VG/EI-R – Fyfe Company's Tyfo VG/EI-R ia a patented two component fire protection system developed specifically for fire protection of Tyfo FRP wraps.

Column SQ2 was strengthened (confined) with an externally-bonded circumferential FRP wrap. The FRP strengthening system consisted of three layers of Fyfe Company's Tyfo SHE unidirectional glass/epoxy FRP system (SEH) with a Tyfo S epoxy adhesive/saturant/matrix.

Column SQ1 was not provided with any supplemental fire protection insulation, since conventional RC columns generally display adequate fire endurance without extra measures. However, the FRP-wrapped RC column, SQ2, was provided with a unique two-component fire protection system consisting of Fyfe Company's Tyfo VG insulation in combination with Tyfo EI-R paint. VG insulation is a spray applied cementitious plaster which has low thermal conductivity = 0.082 watt / m / ^{o}c and is thermally inert up to temperatures in excess of 1000^{O}C. The Tyfo VG insulation was spray-applied directly onto the surface of the FRP wrap, without any mechanical anchorage between the FRP and the insulation. Tyfo EI-R was applied by trowel to the exterior of the Tyfo VG insulation as a sealant and surface hardening agent. Column SQ2 was protected with 38mm of VG and a nominal coverage of 0.13mm of EI-R.

During fabrication of the specimens, thermocouples were installed within the concrete and on the internal reinforcing steel at column mid-height for measuring temperatures at various locations across the cross section. Column SQ2 was also instrumented with thermocouples to record the temperatures at the EI-R-VG interface, the VG-FRP interface, and the FRP-concrete interface as shown in figure (5.20)

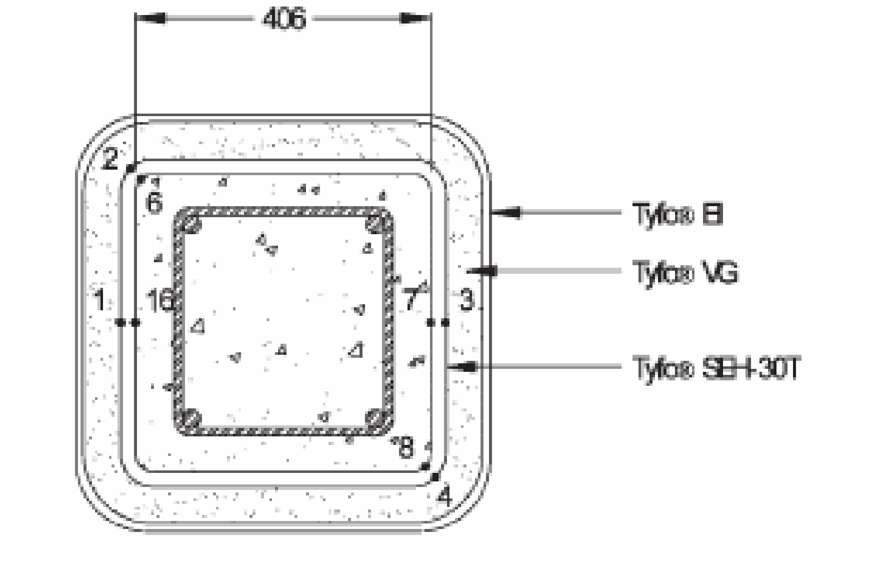


Fig. 5.20 Thermocouple locations in Column SQ2 at mid-height

Figure (5.21) shows temperatures recorded at various locations in Columns SQ2 during exposure to fire. The figure show that that the temperature of the FRP wrap remained below 100^{o}c for about 30 minutes due to the provision of the extremely effective VG/EI-R insulation system on the column. During the tests, the columns were exposed to heat according to the CAN/ULCS101[26] standard time-temperature curve, which is equivalent to the ASTM E-119[25] Standard.

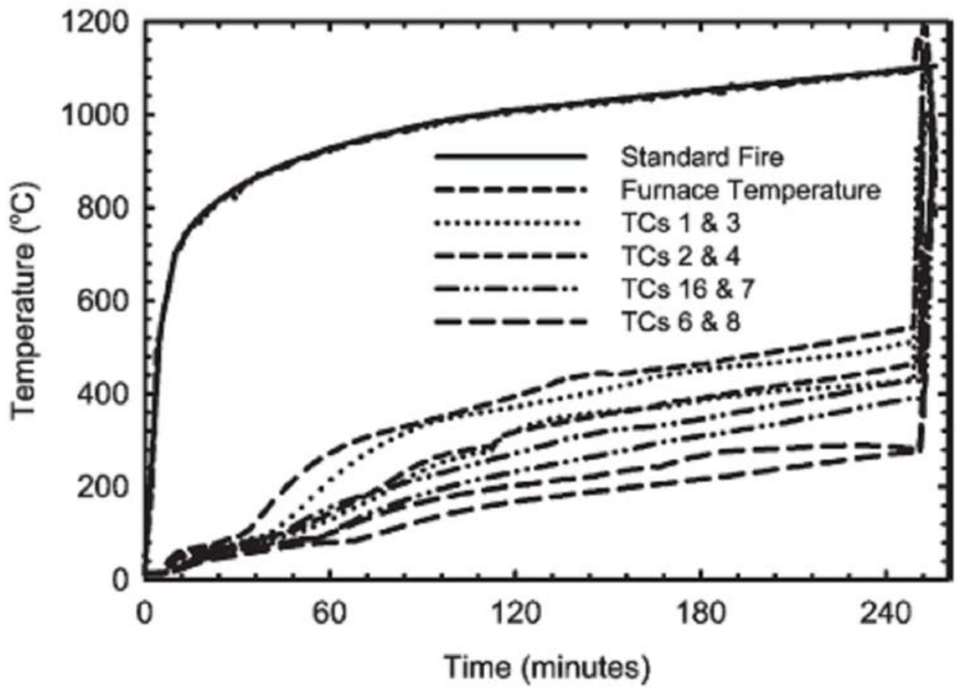


Fig. 5.21 Temperatures recorded at various locations in Column SQ2 as a function of fire exposure time.

Applying the proposed finite element model on the previously mentioned experimental research study to investigate the variation of temperature gradient with time on the CFRP surface and beneath the used insulating material, as shown in figure (5.22), the model have perfect correlation with the experimental readings and agree well to the test results.

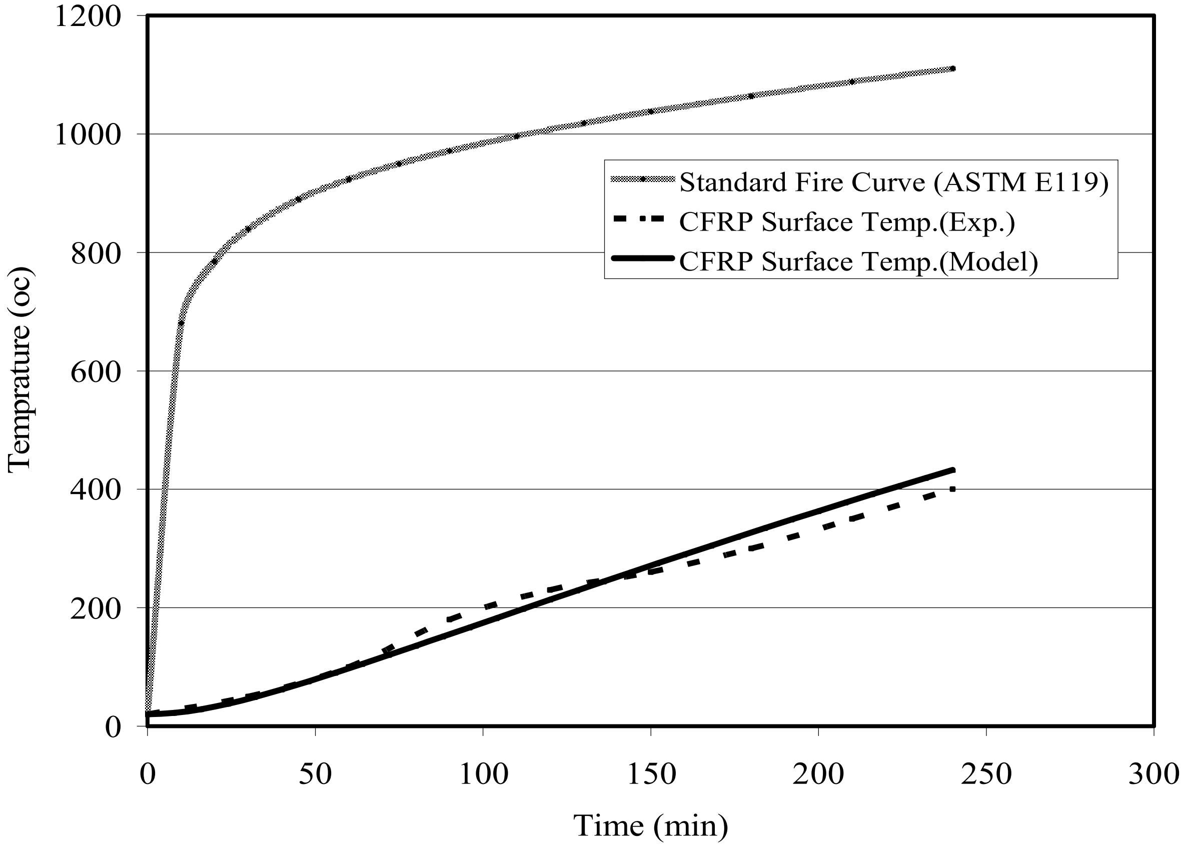


Fig. 5.22 Comparison between Experimental and Theoretical temperature at CFRP surface under fire exposures

More affirmation for the validity of the finite element model have been done by comparing another experimental research were conducted at the National Research Council of Canada (NRC) to investigate the behavior of FRP wrapped R.C. columns under exposure to the standard fire[77]. The experimental program consisted of fire endurance test on two full scale circular R.C. columns, having 400mm diameter and 3810mm long. Both columns were instrumented by thermocouples and strain gauge at the column mid-height, and insulated by supplement fire insulation called Tyfo VG/EI which consisted of Tyfo VG insulation in combination of EI coating, with approximate thickness 30mm and 60mm

Figures (5.23) and (5.24) shows the correlation between experimental and analytical temperature at CFRP surface for 30mm and 60mm insulation thickness, also confirmed the validity of the model in giving accurate and conservative results in circular columns like square columns cross section.

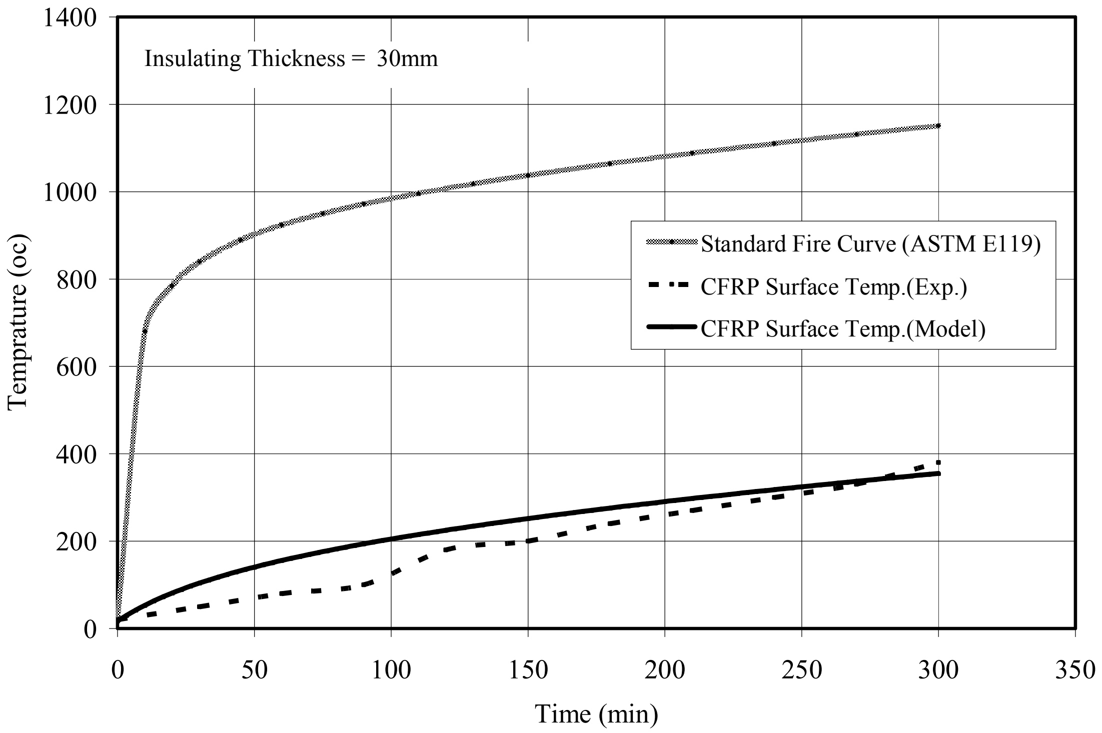


Fig. 5.23 Comparison between Experimental and Theoretical temperature at CFRP surface under fire exposures for Circular columns insulated by 30 mm Tyfo VG.

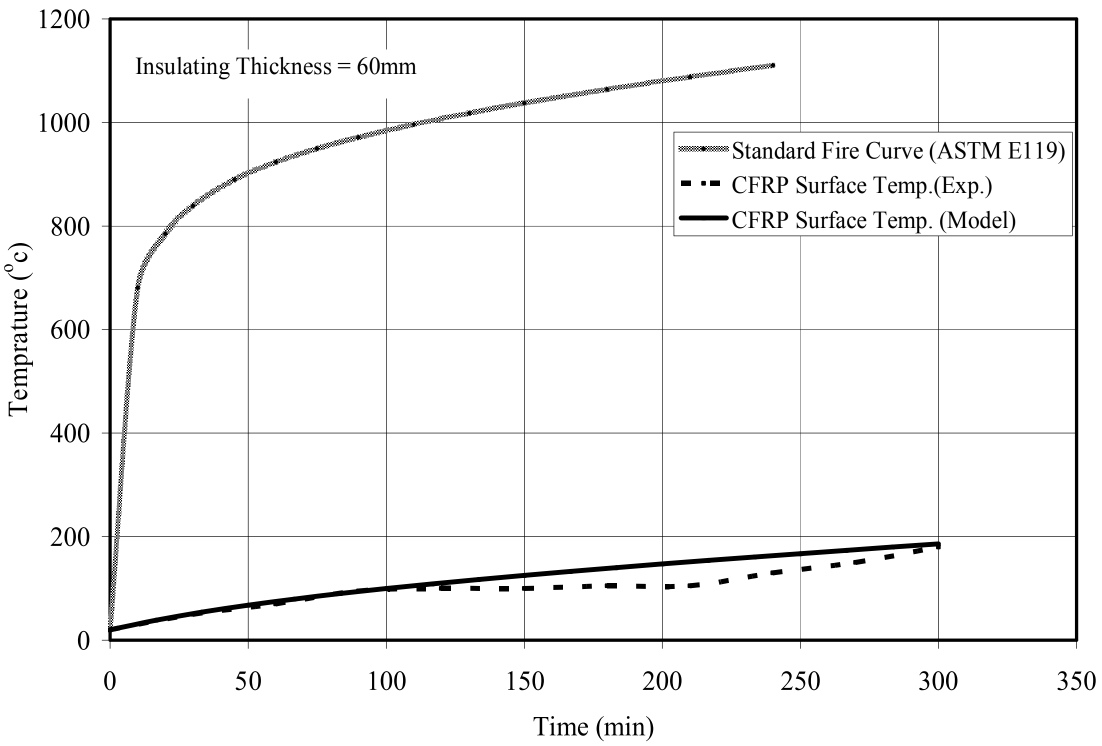


Fig. 5.24 Comparison between Experimental and Theoretical temperature at CFRP surface under fire exposures for Circular columns insulated by 60 mm Tyfo VG 60 .

5.4.5 Insulating thickness effectiveness under fire exposure

Based on the previous verified finite element model, it can be concluded that the effect of insulating material thickness is varied according to the used insulating material. Figures (5.25) to (5.33) show the temperature under the insulating material for different depths 10, 20, 30, and 40 mm from the surface of the insulating material.

It is clearly shown that increasing the insulating thickness for Ceramic fiber, Rock wool, Cement don't greatly effect the fire endurance, and the time-temperature curves for all depths were nearly close to each other. On the other hand Gypsum, Sikacrete 213f, Perlite, the time-temperature curves were parallel and equidistance to each other, which indicate the role of increasing insulation material thickness for those materials

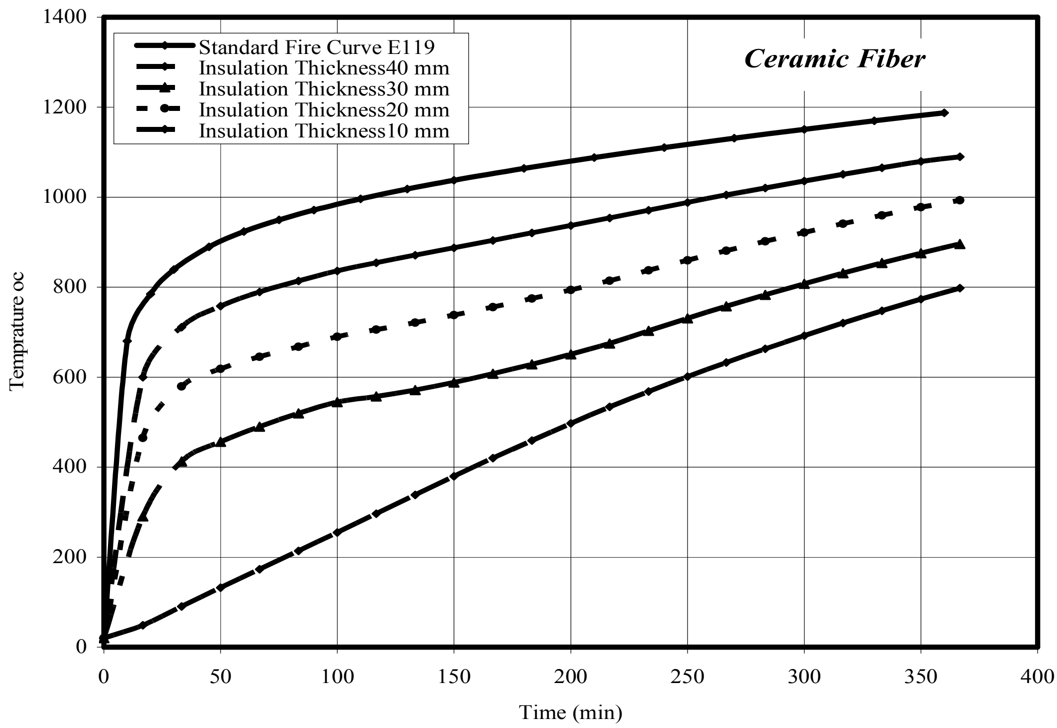


Fig. 5.25 Time versus temperature curves under fire test for Ceramic Fiber

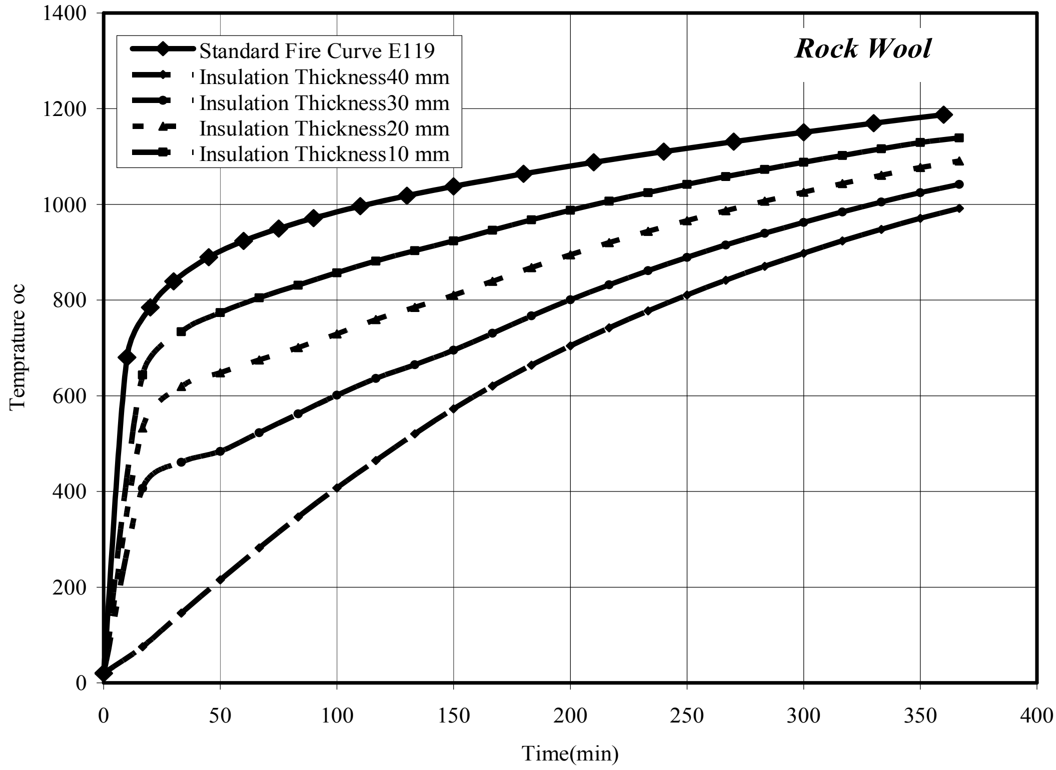


Fig. 5.26 Time versus temperature curves under fire test for Rock wool

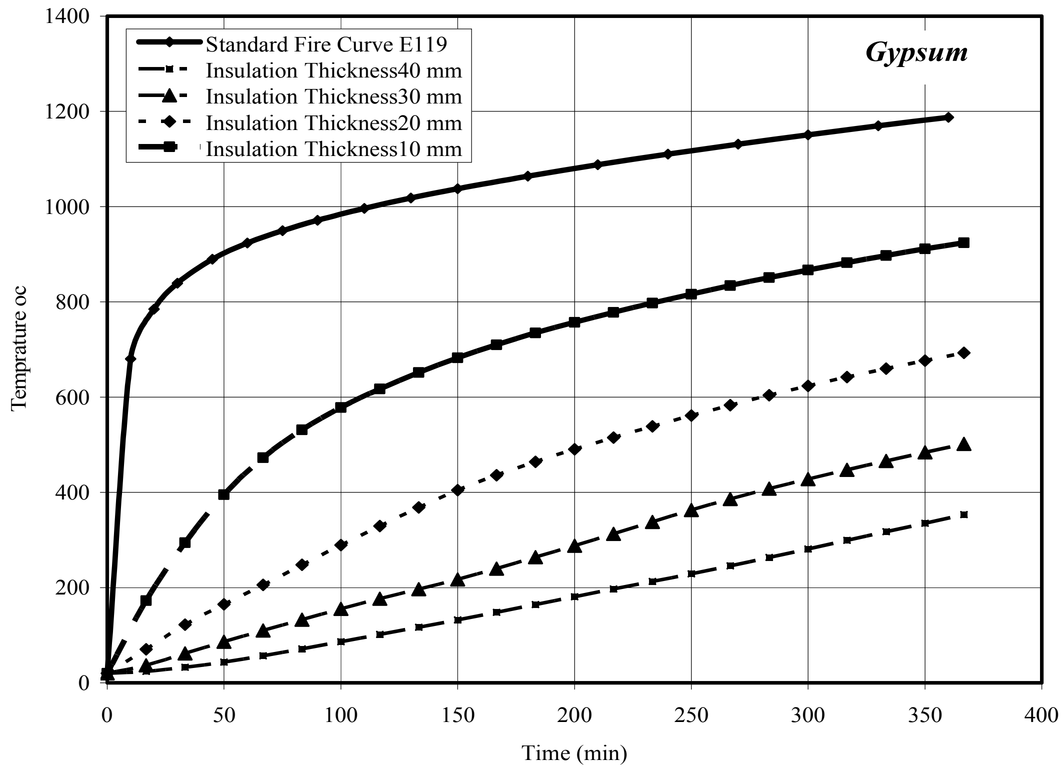


Fig. 5.27 Time versus temperature curves under fire test for Gypsum

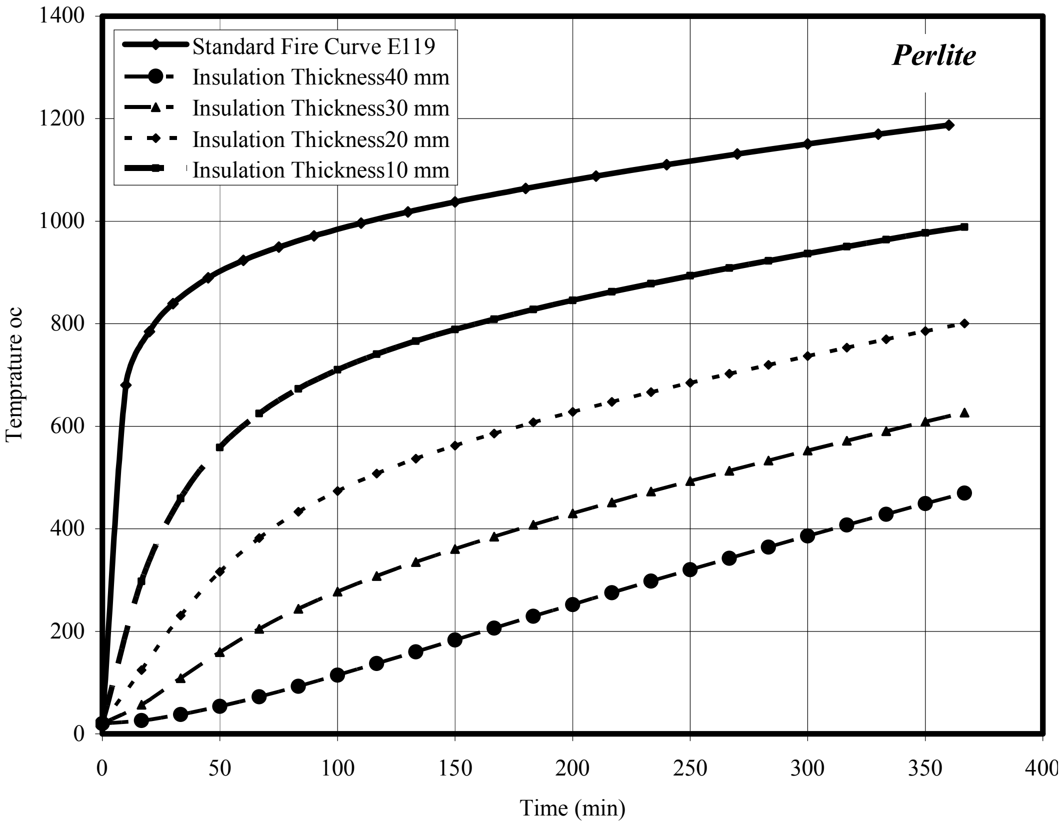


Fig. 5.28 Time versus temperature curves under fire test for Perlite

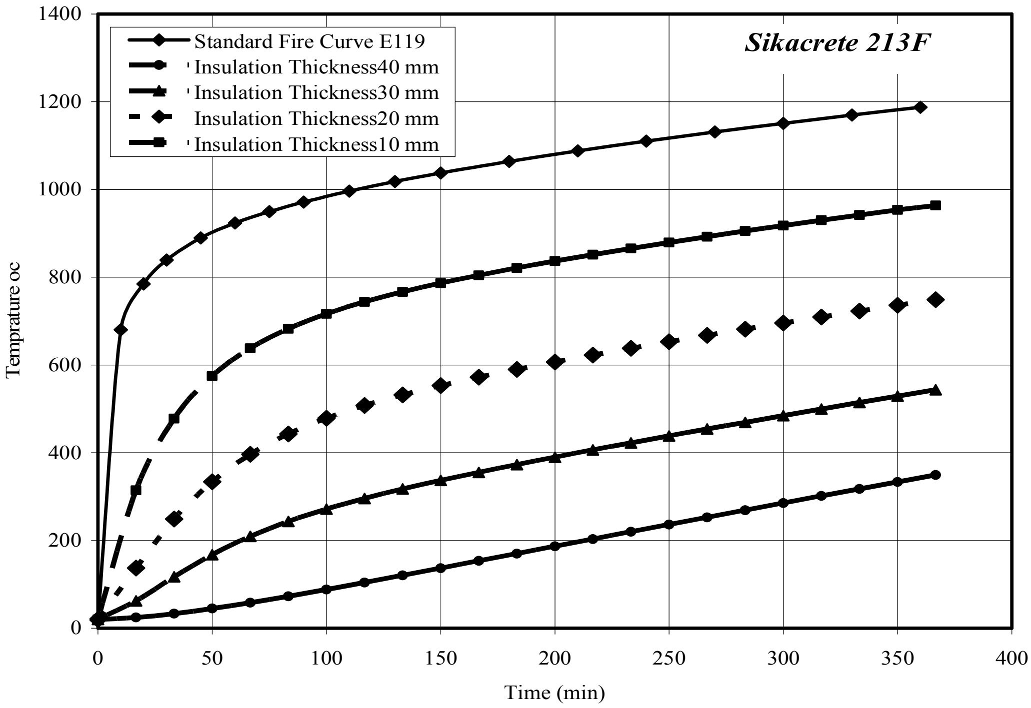


Fig. 5.29 Time versus temperature curves under fire test for Sikacrete 21f F

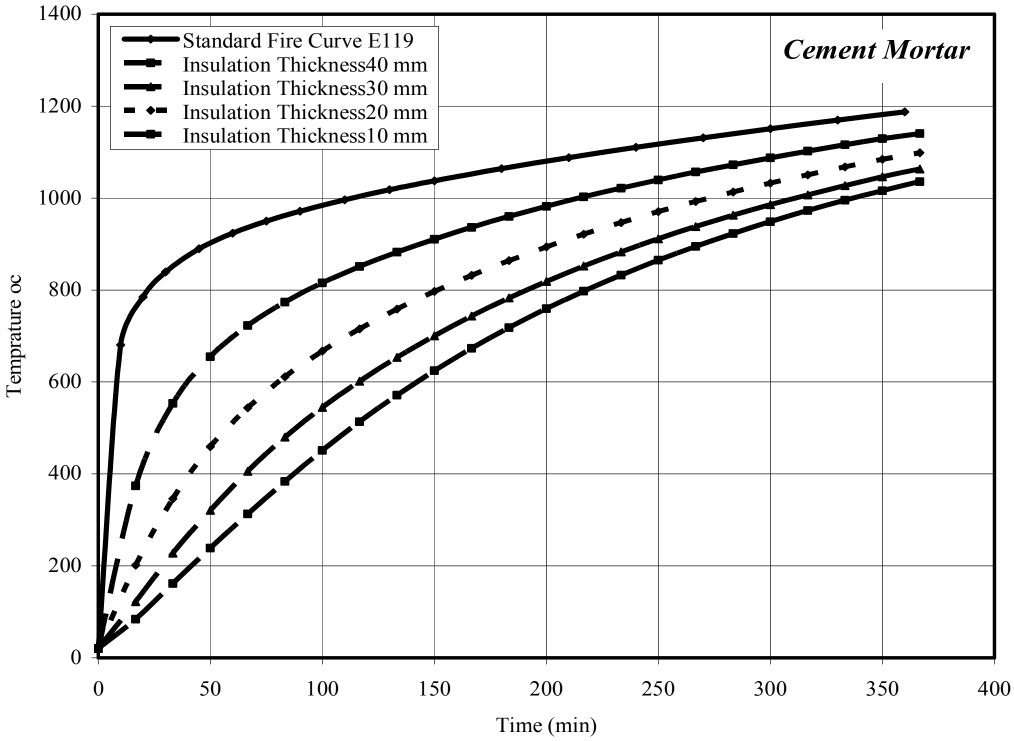


Fig. 5.30 Time versus temperature curves under fire test for Cement Mortar

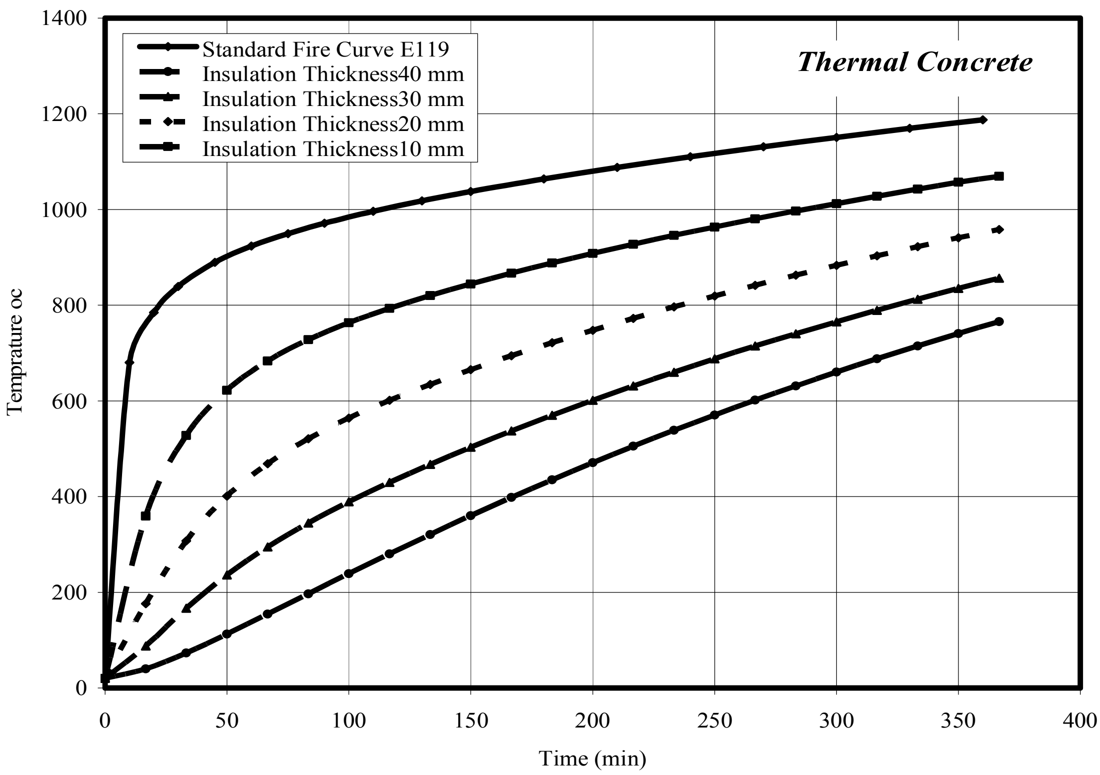


Fig. 5.31 Time versus temperature curves under fire test for Thermal Concrete

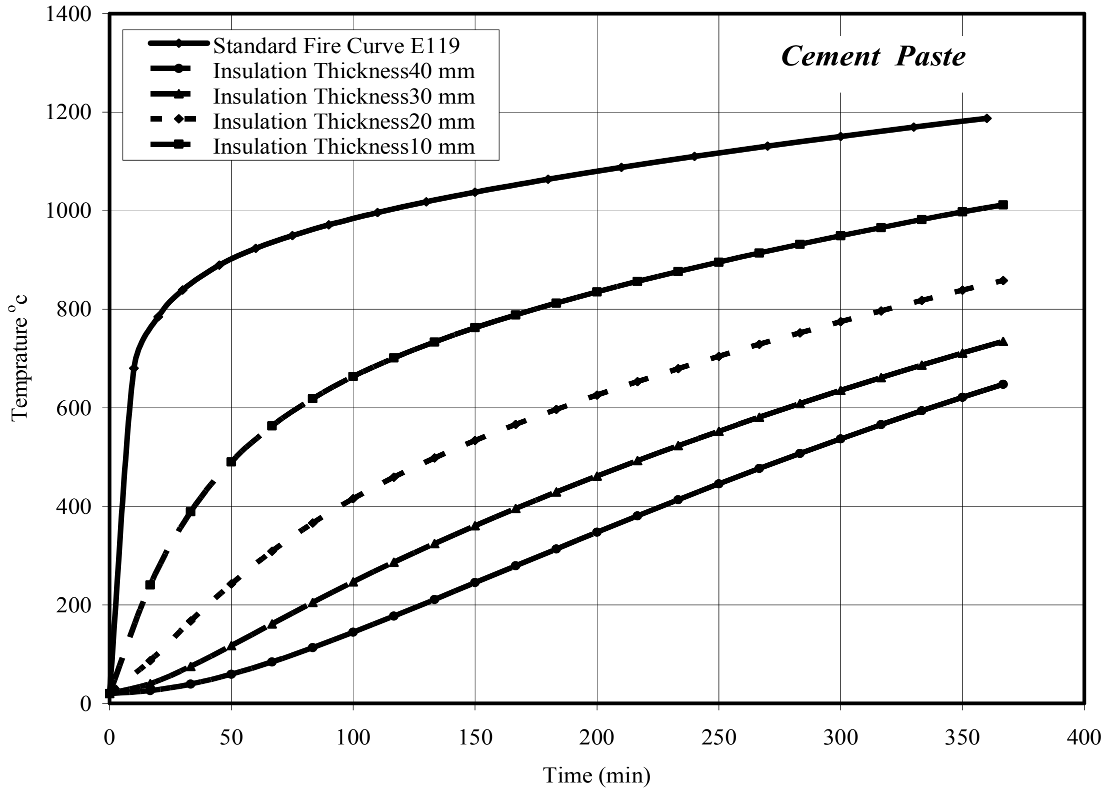


Fig. 5.32 Time versus temperature curves under fire test for Cement Paste

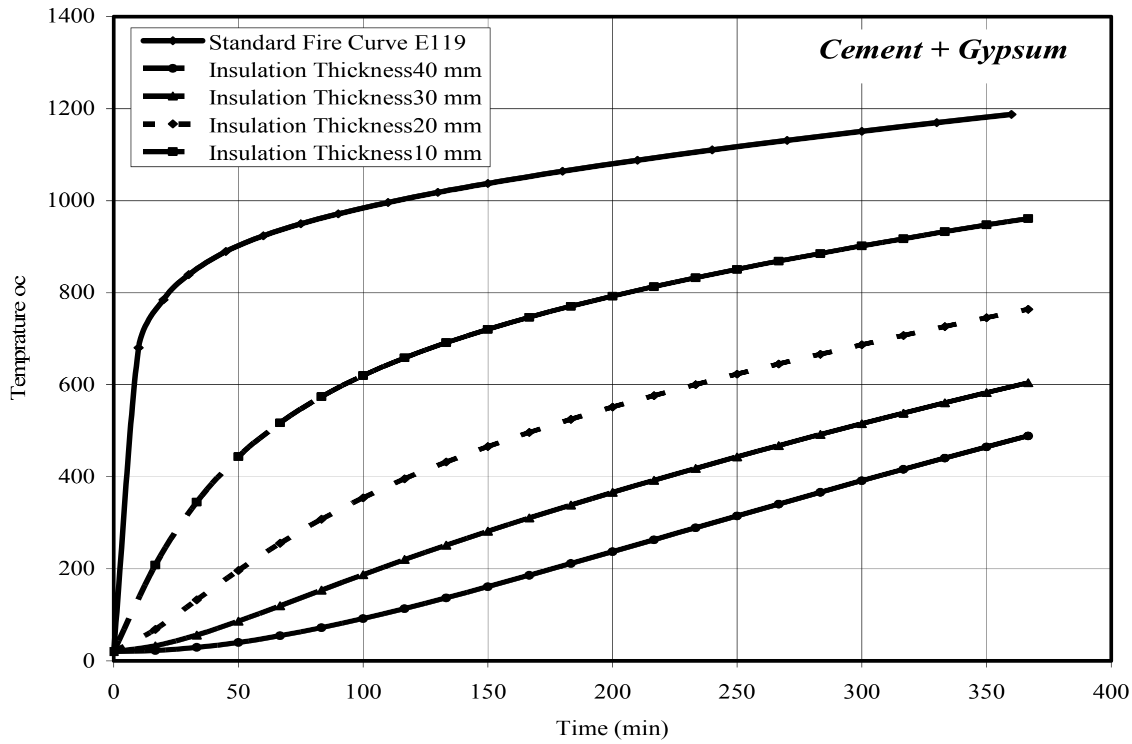


Fig. 5.33 Time versus temperature curves under fire test for Cement + Gypsum

In accordance with other previous study, no deterioration in the CFRP confinement effectiveness occurs for constant exposure to temperature 100°c till 24 hours. Accordingly, fire endurance for each insulating material can be concluded till the temperature reach 100°c at the CFRP surface for different insulation thicknesses, as shown in figure (5.34). It is clearly shown that the relation between fire endurance and insulating material thickness is not linear except in cement mortar and cement paste. Moreover, Perlite and Sikacrete213 don't offer large fire endurance in small thicknesses till 30mm and behave very well when thickness becomes 40mm, also fibrous insulating material don't offer any fire endurance when thickness less than 30mm.

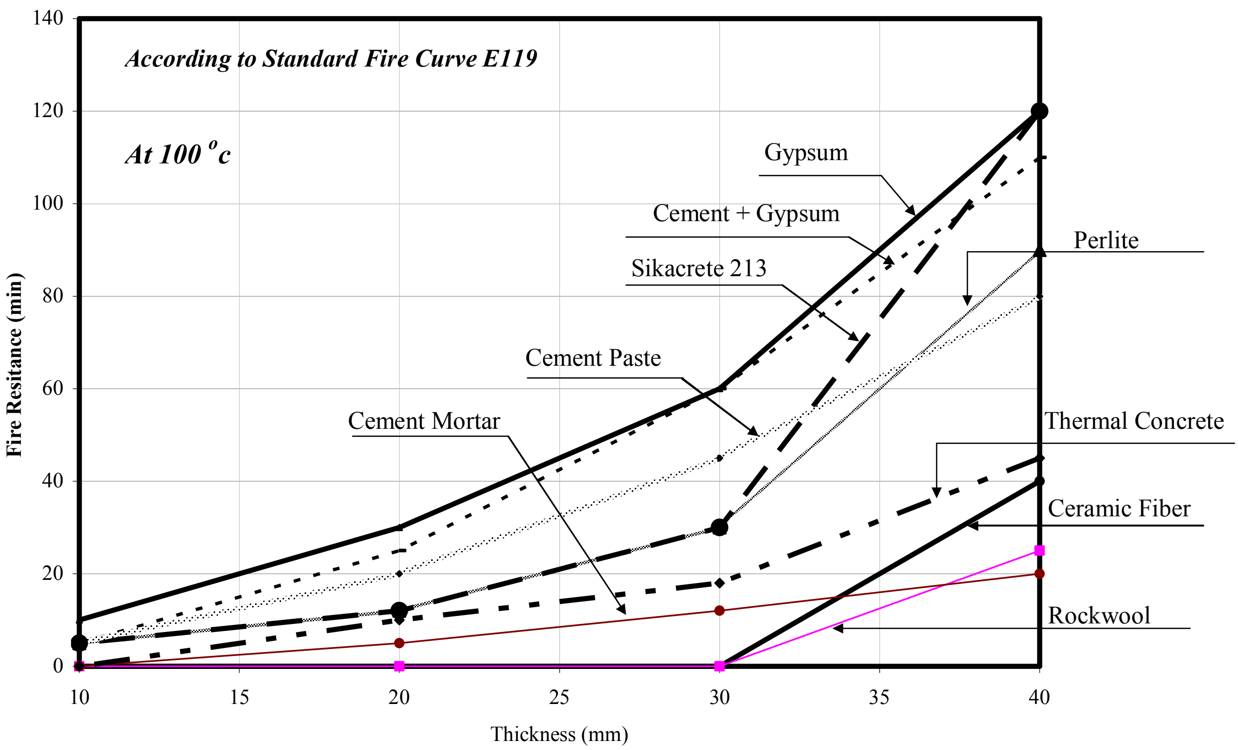


Fig. 5.34 Time versus thickness for the used insulating material to reach 100°c

At temperature level 200°c, the CFRP confining system lose 13% of its confinement effectiveness for constant exposure for 4 hours while it lose 20%,24.6%, and 33.6% for 8, 12, and 24 hours respectively. Accordingly, the relationship between the times for each insulating material till the temperature reaches 200°c at CFRP surface and their thickness can be derived by the FEM, as shown in figure (5.35). The relation between time and thickness for all insulating material at temperature 200°c having the same behavior for temperature 100°c but with increasing the fire endurance time.

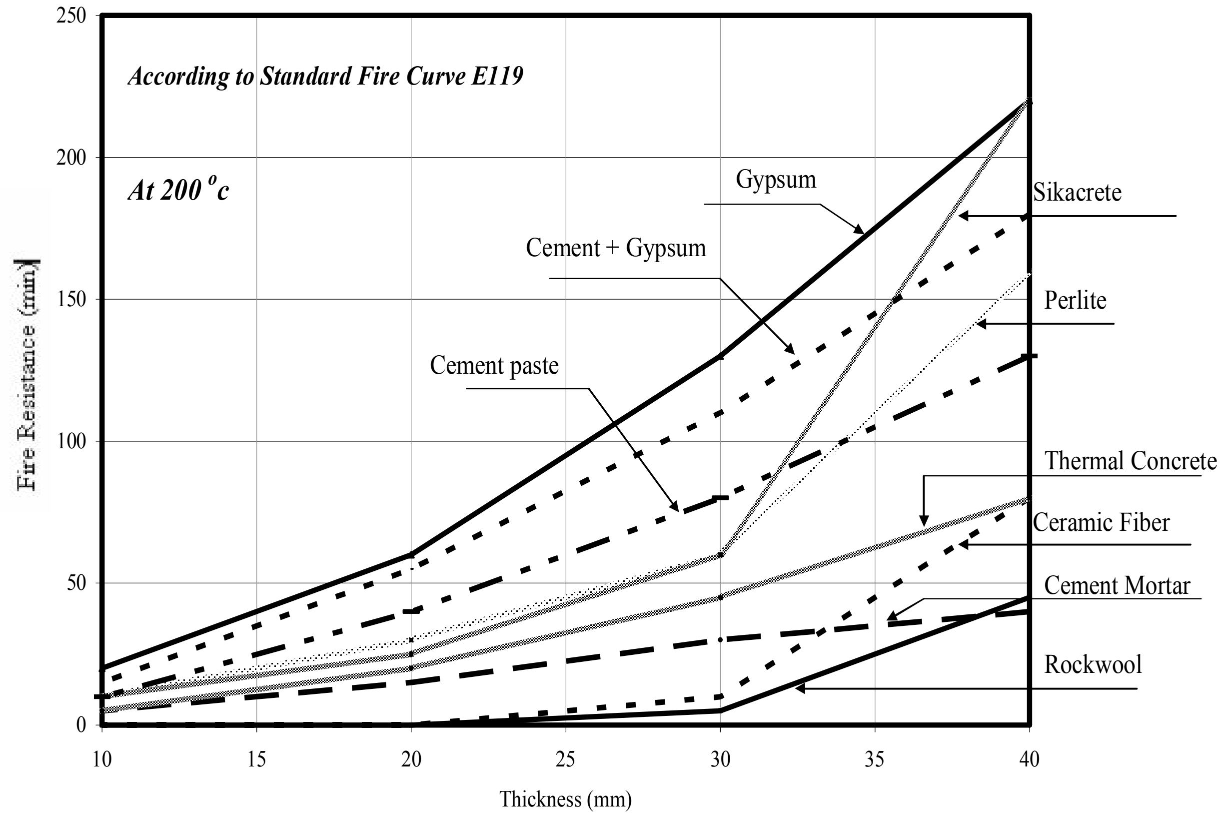


Fig. 5.35. Time versus temperature curves under fire test for various insulating thickness

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6-1 SUMMARY

The main objectives of this research is to investigate the effect of elevated temperature on square R.C. columns confined by one layer of carbon fiber-reinforced polymer (CFRP) and insulated by supplemental thermal insulation material applied to the exterior of the CFRP wrap.

The experimental investigation divided into two major portions; first, diagnose the effect of different levels of elevated temperature and various durations on the structural behavior for the R.C. columns confined by CFRP, the deterioration CFRP sheets, the bond between CFRP sheets and concrete surface. Second; find a proper treatment for the elevated temperature problem associated with CFRP confined R.C. column; using varies kinds of insulating materials, measure of their thermal endurance at different temperature levels and for what extent the used insulating can decrease the rate of heat transfer toward the CFRP surface.

In order to fulfill these objectives, a comprehensive experimental program consisting of 19 R.C. square columns were tested thermally using an electric furnace which constructed to serve this experimental program, subsequently, tested under a monotonic axial compression load. The experimental study has been conducted to investigate the effect of different temperature levels "100^{o}c, 200^{o}c, 250^{o}c, 300^{o}c, and at 350^{o}c" and durations "4, 8, 12, and 24 hours" on the structural performance of R.C. square columns. Furthermore, evaluate the effectiveness of nine different thermal protection materials in increasing the thermal endurance and decrease the heat transfer rate to reach CFRP surface. This experimental work was performed at the Material Laboratory of Faculty of Engineering - Alexandria University in cooperation with College of Engineering – Arab Academy for Science, Technology, and Maritime Transport.

This research developed a finite element thermal model conducted on insulated square R.C. columns confined by CFRP sheets and subjected to elevated temperature. The model simulates the transient heat transfer through different insulating material in accordance to the furnace heating rate. The ultimate goal of this anylatical approach is to provide design recommendations and guidelines that can be suggested for protecting R.C. confined by CFRP using different insulating materials. Moreover, model predicts the temperature distribution at different interfaces of the insulating material and concrete specimen accurately.

The thermal endurance for each insulating material has been validated with the experimental program according to the furnace heating rate. On the other hand, the model have been developed to simulate the rate of heat transfer through insulating material in accordance with the standard fire curve, this leads us to compute the fire endurance and the critical time that the insulated CFRP confining system can be affected by fire exposures. For further validation of the model, it was compared to results reported in other research studies which examine the columns under standard fire.

Comparing with all available published test results to date the correlation between the predicted and measured temperature is fairly accurate for the entire time-temperature history. Finally, employing the validated FEM approach, a parametric study is carried out to predict the effect of insulation thickness on their fire endurance.

6-2 CONCLUSIONS

FRP materials are sensitive to elevated temperature and experience severe deterioration of strength, stiffness, and bond properties at elevated temperature. ACI 440 R-06 states that no information is currently available on the specific behavior of the bond between unprotected externally FRP materials and concrete at high temperatures. This gap of knowledge is primary factor preventing the widespread application of FRP. The performance of fire-exposed FRP systems can be improved by the use of barrier treatments or coatings. These treatments function either by reflecting radiant heat back towards the heat source, or by delaying heat penetration to the FRP through their isolative and/or ablative properties

Some questions to be considered include what level of heat exposure requires replacing the system, and how effective are the available fire proofing system to prevent heat damage.

The tests results obtained in this study indicated that the use of thermal insulating material improves the thermal endurance effectiveness for the insulated columns but to different extents. This beneficial effect was tremendous with respect to granular insulating material rather than fibrous insulating materials. According to the structural effectiveness, no significance deterioration in the CFRP confinement effectiveness occurs for exposure at constant temperature 100oc until 24 hours. While at 200oc the CFRP confinement effectiveness depended mainly on the exposure duration, it lost only 13 % for exposure for 4 hours, and 20 %, 24.6 %, and 33.3 % for 8, 12, and 24 hours respectively. On the other hand, no significant loss of column ductility has been measured at this temperature level. Results also indicate that, there is a large difference between the loss in CFRP effectiveness when exposed to 300oc for 4 hours and 8hours, as it lose 42 % of its load capacity while it loss all of the confinement effectiveness at 8 hours. Moreover, based on the thermal finite element approach, it can be used to compare the thermal endurance for different insulating material under standard fire exposure and conduct a parametric study for the factor effecting their thermal endurance like thickness, thermal conductivity, specific heat, etc. under the fire exposure

The conclusions conducted from the study reported here can be divided to three categories: structural performance for specimens, thermal endurance for insulating material, and the anylatical model proposed.

6.2.1 Structural Performance for R.C. confined by CFRP under exposure to elevated Temperature

1. The deterioration of the CFRP confinement effectiveness does not depend only on temperature level but it depends mainly on exposure duration and the heating rate.
2. No deterioration in the CFRP confinement effectiveness occurs for exposure at constant temperature 100^{o}c till 24 hours
3. At temperature level 200^{o}c, the CFRP confining system lose 13% of its confinement effectiveness for constant exposure for 4 hours while it lose 20%,24.6%, and 33.6% for 8, 12, and 24 hours respectively. On the other hand, no significant loss of column ductility have been measured at this temperature level
4. The CFRP confinement effectiveness for columns tested at 250^{o}c has been decreased by 30.4%, 39.1%, and 44.9% for constant exposure to this level of temperature for 4, 8, and 12 hours respectively. On the other hand the column loses all its effectiveness for continues exposure for 24 hours and behave like the unconfined column.
5. There is a large difference between the loss in CFRP effectiveness when exposed to 300^{o}c for 4 hours and 8hours, as it lose 42.1 % of its load capacity when exposed to temperature 300^{o}c for 4 hours while it loss all of the confinement effectiveness at 8 hours
6. All columns tested at 350^{o}c lose all of the CFRP confinement effectives and their failure mode govern by de-bonding between the CFRP sheets and concrete surface during the loading test for U-350-4 column or before beginning of the test for T.C-350-8 specimen.

7. The only one side of the column that subjected to 350^{o}c for 8 hours govern all column specimen to loss the CFRP effectiveness while the other three sides subjected to 200oc only.

6.2.2 Thermal Endurance of Insulated R.C. columns confined by CFRP sheets

1. All the insulating material used in this research, does not eliminate heat transfer but it merely reduce it and increase the heat transfer time till reach to the CFRP surface for all tested temperature levels.
2. The ultimate temperature can safely subjected to columns confined by CRFP without any loss of the strengthening system capacity is 100^{o}c, that leads us to conclude that the thermal endurance at this temperature level according to the furnace heating rate for the tested insulating material is about 4.2 hours for sikacrete213f, 3.4 hours for all of Gypsum, Perlite, Cement + Gypsum, and cement paste, and about only one hour for thermal concrete, Cement mortar, Ceramic fiber, and Rock wool.
3. Despite of Ceramic fiber and Rock wool having the lowest thermal conductivity among the other granular thermal insulating materials, they offer insignificant thermal endurance at 100^{o}c, due to lake of internal moisture content that help to maintain the temperature on CFRP surface steady at 100^{o}c for an interval of time and help in increasing its thermal resistance
4. Although Cement mortar and Thermal Concrete having moisture content 40%and30% respectively, they don't govern any thermal resistance at 100^{o}c, this is related to absence of internal moisture after reacting with cement and thermal concrete.
5. Thermal endurance after second cycle of heating sikacrete213f decrease by 350%,due to absence of moisture by evaporation in the first cycle as it reach 100^{o}c after 55min only, while it take 245 min during the first cycle.
6. Thermal endurance of the insulating materials at 200^{o}c is quiet different than 100^{o}c, Sikacrete-213f has the superior behavior they reach 200^{o}c in 5.6 hrs, while Cement + Gypsum, Perlite, and Gypsum reach it about 4.5 hrs, and Thermal concrete in 3.2 hrs, and all of other insulating material" Ceramic fiber, Rockwood, sikacrete213f "2nd cycle", and Cement mortar reach 200^{o}c in 1.9 hrs only.
7. The overall behavior of the insulating material at 250^{o}c resembles their behavior at 200^{o}c. The thermal endurance for sikacrete213f reached 400min till heat transfer through this material and reaches CFRP surface at 250 ^{o}c, the thermal endurance of

other insulating material less than Sikacrete213f by 21%, 29%, 48%,90%, and 230% for Cement + Gypsum, Perlite, Thermal Concrete, Siakcrete213f "2nd cycle", and Cement mortar respectively.

8. Thermal concrete and Cement paste have thermal endurance of 320min to reach 300 ^{o}c for CFRP surface at average furnace temperature 665^{o}c, and 720 respectively. While cement mortar is less than thermal concrete by 113% with thermal endurance 150min and average furnace temperature 520 ^{o}c only.
9. Although Rock wool, Ceramic fibers don't offer great thermal endurance in all tested temperatures, but they don't preserve heat for a long duration after finishing tests. On the other hand most of the granular insulating material can store the heat after finishing tests and switched off the furnace for 24hrs.

6.2.3 Modeling the thermal behaviour of FRP-strengthened reinforced concrete Columns under elevated temprature

1. Increasing the thermal and fire endurance for R.C. columns confined by CFRP greatly effected by type of the used insulating material; its thermal conductivity, specific heat and density rather than increasing the material thickness.
2. Comparing with all available published test results to date; the proposed analytical approach for the transient temperature transfer and heat distribution on the column cross section gives acceptable and conservative results.
3. The thermal endurance at 100^{o}c according to the standard fire curve for the tested insulating material with 40 mm thickness is about 2 hours for (sikacrete213f, Gypsum and Cement + Gypsum), 1.5 hours for (Perlite, and cement paste) and about only 20 min to 40 min for (thermal concrete, Cement mortar, Ceramic fiber, and Rock wool).
4. The thermal endurance at 200^{o}c according to the standard fire curve for the tested insulating material with 40 mm thickness is about 3.7 hours for (sikacrete213f, Gypsum and Cement + Gypsum), 2.5 hours for (Perlite, and cement paste) and about only 40 min to 80 min for (thermal concrete, Cement mortar, Ceramic fiber, and Rock wool).
5. Increasing the insulating thickness for Ceramic fiber, Rock wool, Cement don't greatly effect in increasing the fire endurance, and the time-temperature curves for all thickness (10,20,30,and 40mm) were nearly close to each other. On the other hand Gypsum, Sikacrete 213f, Perlite, the time-temperature curves were parallel and

equidistance to each other, which indicate the role of increasing insulation material thickness for those materials

6. It is clearly shown that the relation between fire endurance and insulating material thickness is not linear except in cement mortar and cement paste.
7. Perlite and Sikacrete213 don't offer large fire endurance in small thicknesses till 30mm on the contrary they behave very well when thickness becomes 40mm
8. Fibrous insulating material (Rock wool and Ceramic fiber) have negligible fire endurance when thickness less than 30mm.
9. The relation between time and thickness for all insulating material at temperature 200^{o}c having the same behavior for temperature 100^{o}c but with increasing the fire endurance time.

6-3 RECOMMENDATIONS FOR FUTURE WORK

As is evident in this research, while a number of significant conclusions have been drawn from research conducted to date, a great deal of further research is required before rational and realistic fire design recommendations for FRP wrapped R.C. columns can be suggested with confidence. Some of the most important recommendations for future research into the thermal and fire behavior of FRP-strengthened reinforced concrete columns include

- Further full-scale fire endurance testing of FRP-wrapped reinforced concrete columns is required both to ensure repeatability of the experimental results conducted in this research to date, and to provide additional validation data for the numerical fire simulation models.
- Full scale fire tests should be conducted on FRP-strengthened reinforced concrete members to investigate a variety of important issues, including: member type, strengthening scheme (externally bonded versus near surface mounted), load intensity, combined axial and bending loads, fiber type, matrix type, etc.
- Pre-loading for confined R.C. columns while the columns subjected to elevated temperature.
- Examine the bond between the FRP sheets and concrete surface using different standards tests
- Development of a structural analytical model is needed to predict the effect of elevated temperature on the structural deterioration of R.C. columns confined by CFRP and the decrease in the ultimate load capacity and ductility for the columns.
- A more complete understanding of the variation in thermal properties with temperature, and the movement of moisture within the pores of insulation materials,

and its effect on thermal properties, is essential for accurate modeling of insulated members in fire.

REFERENCES

[1] Kodur, V.K.R. "Spalling in high strength concrete exposed to fire - concerns, causes, critical parameters and cures," *Proceedings: ASCE Structures Congress*. Philadelphia, (2000)

[2] Kodur, V.K.R., and Sultan, M.A. "Effect of temperature on thermal properties of high-strength concrete", Journal of Materials in Civil Engineer, ASCE, March/April, 15(2), 101-107(2003).

[3] Khoury G.A., "Effect of fire on concrete and concrete structures", *Progress in Structural Engineering and Materials*, 2 (2000), 4, pp. 429-447

[4] Bazant, Z.P. & Kaplan, M.F., Concrete at High Temperatures, Longman, London, UK (1996)

[5] Gosain, Narendra " Effects of Fire on Concrete" Concrete International journal (2006)

[6] Phan, L.T., Lawson, J.R., and Davis, F.L."Effect of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete", Materials and Structures (RILEM),March, 34, 83-91, (2001).

[7] Jaesung Lee "Experimental Studies and Theoretical modeling of concrete subjected to high temperatures" Ph.d thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado,(2006)

[8] Cheng, F.P., Kodur, V.K.R., and Wang, T.C.. "Stress-strain curves for high strength concrete at elevated temperature", Journal of Materials in Civil Engineer , ASCE, Jan/Feb., 16(1), 84-90 (2004)

[9] Kodur, V. K. R.; McGrath, R.; Leroux, P., and Latour, J. C., *Fire Endurance Experiments on High-Strength Concrete Columns*, RD138, Portland Cement Association, Skokie, Illinois, USA, 152 pages (2004).

[10] Saafi, M., Toutanji, H.A., and Li,Z. "Behavior of concrete columns confined with fiber reinforced polymer tubes," *ACI Material Journal*, pp 500-509, (1999)

[11] Toutanji, H, "Stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets,"ACI Material Journal., 96(3), pp. 397-404, (1999)

[12] Xiao,Y., Wu,H. "Compressive Behavior of Concrete Confined by Carbon Fiber Composites Jackets ," *Journal of Materials in civil Engineering, ASCE*, Vol. 12 ,No.2, pp.139-146,(2000)

[13] Nanni, A., Norris, M.S., and Badrofd, N.M. "Lateral Confinement of Concrete Using FRP Reinforcement," ACI Structural Journal, pp 193-209, (1996)

[14] F.Picher, P.Rochette and P.Labossiere, " Confinement of Concrete Cylinders With CFRP" Proceeding of 1st International Conference, Composites in Infrastructure, University of Arizona, Tucson, Arizona, pp.829-841, (1996)

[15] Amir Mirmiran and Mohsen Shahawy, "Behavior of Concrete Columns Confined by Fiber Composites," Journal of Structural Engineering, ASCE, Vol. 123, No.5, pp.583-590, (1997)

[16] Amir Mirmiran , Mohsen Shahawy, Michel Sammaan , Hazem EL Echary, Juan Carlos Mastrapa and Odell Pico, " Effect of Column Parameters on FRP-Confined Concrete, "Journal of Composites for construction, ASCE, Vol 2,No.4, pp.175-185,(1998)

[17] Chirs Cole and Abdeldelil Belarabi, "FRP Jacketed Reinforced Concrete Columns," Center For Infra Structure Engineering Studies, Department of Civil Engineering, University of Missouri-Rolla, May (2001)

[18] Azadeh Parvin and Wei Wang, "Behavior Of FRP Jacketed Concrete Columns Under Eccentric Loading," Journal of Composites for construction, ASCE, Vol 5, No.8, pp.146-152, (August 2001).

[19] Yung C. Wang and Jose I. Restrepo, " Investigation of concentrically loaded reinforced concrete columns confined with Glass Fiber Reinforced Polymers jackets," ACI Structural Journal, pp 337-385, (May –June 2001)

[20] Abdelhady Hosny,Hamdy Shahin,Amr Abdelrahman and Tamer El-Afandy, " Uni-axial Tests on Rectangular Columns Strengthened With CFRP " Proceeding of Structural Composites For Infrastructure Applications Conference, Aswan, Egypt, (2002).

[21] Adel El-Kurdi, Shafik Khoury, Aly Eldarwish, Ahmed Khalifa,& Alaa Morsy, "Behavior of axially loaded columns strengthened with carbon fiber reinforced polymers" Proceeding of Alexandria International Conference for Structural and Geotechnical Engineering, Alexandria, Egypt, (2003).

[22] Sorathia, U., Dapp, T., & Beck, C., "Fire Performance of Composites," Mat. Engrg., 9, pp 10-12, (2003).

[23] Kodur, V.K.R." Fire resistance research needs for high performing Materials" NRC/National Academy of Sciences, Washington, D.C., pp. 1-7(2003)

[24] Bisby, L.A.; Williams, V.R.K.; Kodur, V.R.K." Fire Performance of FRP Systems for Infrastructure" A State-of-the-Art Report, Research Report 179, Queen's University, Kingston and National Research Council, Ottawa (2005)

[25] ASTM, Test Method E119-01, ASTM, West Conshohocken, PA, USA, 21 pp (2001)

[26] CAN/ULC, CAN/ULC-S101-M89, ULC, Scarborough, ON, Canada, 49 pp (1989).

[27] Bisby, L.A., Green, M.F. and Kodur, V.K.R., ''Fire Endurance of FRP-Confined Concrete Columns,'' ACI Structural Journal, Vol. 10, No. 6, pp. 883–891,(2005)

[28] ACI Committee 440, "*Guide for the design and construction of externally bonded FRP system for strengthening concrete structures*," American Concrete Institute, Farmington Hills, Michigan, (2002).

[29] James Milke, Venkatesh Kodur, Christopher Marrion "An Overview of Fire Protection in Buildings" Federal Emergency Management Agency, Appendix A

[30] Concrete Reinforcing Steel Institute, "*Reinforced Concrete Fire Resistance*", CRSI, (1980).

[31] T. T. Lie and B. Celikkol " method to Calculate the Fire Resistance of Circular Reinforced Concrete Columns" ACI Materials Journal, Volume 88, Issue 1, pp 84-91,(1991)

[32] Kodur, V.K.R.; Wang, T.C.; Cheng, F.P." Predicting the fire resistance behavior of high strength concrete columns" Cement and Concrete Composites, v. 26, no. 2, pp. 141-153,(Feb. 2004)

[33] William Grosshandler, " Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings, National Institute of Standards and Technology, USA, (2002)

[34] Ian A. Fletcher, Stephen Welch José L. Torero, Richard O. Carvel, Asif Usmani " The Behavior Of Concrete Structures in Fire" Edinburgh research Publications (2007)

[35] Benmarce, A. & Guenfoud, M. “Behavior of axially restrained high strength concrete columns under fire”. Construction & Building Materials, (2005).

[36] A. Y. Elghazouli, B. A. Izzuddin "Failure of Lightly Reinforced Concrete Members under Fire. II: Parametric Studies and Design Considerations" Journal of Structural Engineering. Volume 130, Issue 1, pp. 18-31 (2004)

[37] Venkatesh Kodur and Richard Mcgrath" Fire Endurance of High Strength Concrete Columns" Volume 39, Number 3,pp.73-87 (2003)

[38] Fardis, M.N. and Khalili, H. "FRP-encased concrete as a structural material". Magazine of Concrete Research, 34(121), pp. 191-202 (1982).

[39] Tanano, H., Masuda, Y., and Tomosawa, F."Characteristics and Performance Evaluation Methods of Continuous Fibre Bars" State of the Art Studies on Fire Properties and Durability of Continuous Fibre Reinforced Concrete in Japan. In Fibre Reinforced Polymer Reinforcement for Reinforced Concrete Structures. Edited by A. Nanni, C.W. Dolan, and S.H. Rizkalla. American Concrete Institute, Detroit, Michigan, pp. 523-531.(1999)

[40] Sorathia, U., Dapp, T., and Beck, C."Fire Performance of Composites". Materials Engineering, September, pp. 10-12 (1992).

[41] Sorathia, U., Ohlemiller, T., Lyon, R., Riffle, J., and Schultz, N Chapter 9: Effects of Fire. In Gap Analysis for Durability of Fiber Reinforced Polymer Composites in Civil Infrastructure. American Society of Civil Engineers, pp. 100-121(2001).

[42] Bakis, C.E. "FRP Reinforcement: Materials and Manufacturing. In Fiber-Reinforced-Plastic (FRP) Reinforcements for Concrete Structures": Properties and Applications. Edited by A. Nanni. Elsevier Science Publishers B.V., pp. 13-58, (1993).

[43] Bank, L.C "Properties of FRP Reinforcements for Concrete. In Fibre-Reinforced-Plastic (FRP) Reinforcements for Concrete Structures: Properties and Applications". Edited by A. Nanni. Elsevier Science Publishers B.V., pp. 59-86(1992).

[44] Rostasy, F. "Fiber Composite Elements and Techniques as Non-Metallic Reinforcement of Concrete". Brite Project 4142/BREU – CT 91 0515, Evaluation of Potentials and Production Techniques of FRP, Technical Report Task 1 .(1992).

[45] Sumida, A., Fujisaki, T., Watanabe, K., and Kato, T "Heat Resistance of Continuous Fiber Reinforced Plastic Rods". In The Fifth Annual Symposium on

Fibre-Reinforced-Plastic Reinforcement for Concrete Structures (FRPRCS-5). Edited by C. Burgoyne, Thomas Telford, London, pp. 557-565.(2001)

[46] Dimitrienko, Y.I. "Thermomechanics of Composites under High Temperatures" . Klewer Academic Publishers, London, 347 pp.(1999)

[47] Katz, A., Berman, N., and Bank, L.C." Effect of Cyclic Loading and Elevated Temperature on the Bond Properties of FRP Rebars". In Durability of Fibre Reinforced Polymer (FRP) Composites for Construction. Edited by B. Benmokrane and H. Rahman. Avantage Inc., Sherbrooke, PQ, pp. 403-414. (1998).

[48] Katz, A., Berman, N., and Bank, L.C"Effect High Temperature on the Bond Strength of FRP Rebars". Journal of Composites for Construction, ASCE, 3(2), pp. 73-81.(1999)

[49] Katz, A., and Berman, N "Modeling the effect of high temperature on the bond of FRP reinforcing bars to concrete". Cement and Concrete Composites, 22, pp. 433-443.(2000)

[50] J.C.P.H Gamage, R. Al-Mahaidi* and M.B. Wong "Effect of Insulation on the Bond Behavior of CFRP- Plated concrete elements "Proceedings of the International Symposium on Bond Behavior of FRP in Structures (2005)

[51] AS1530.4. "Methods for fire tests on building materials, components and structures", Fire-resistance tests of elements of building construction, Standards Australia, (4), 6-43. (1997).

[52] Gamage, J.C.P.H., Wong, M.B. and Al-Mahaidhi, R."Bond performance of CFRP plated concrete members at elevated temperatures", the Australian Structural Engineers Conference, Newcastle, Australia. (2005)

[53] Kodur, V.K.R. & Bisby, L.A., Evaluation of fire endurance of concrete slabs reinforced with FRP bars, J. Structural Engineering, ASCE, 131, 1, pp. 34-43 (2005)

[54] Williams, B., Bisby, L., Kodur, V., Green, M. & Chowdhury, E., Fire insulation schemes for FRP-strengthened concrete slabs, Composites Part A: Applied Science & Manufacturing, pp. 1151-116, (2006)

[55] NEFCOM Corporation. Technical Leaflet 3: "Fire resistance of concrete slabs reinforced by NEFMAC", NEFCOM Corp., Tokyo, Japan, 11 pp.(1998)

[56] Tanano, H., Masuda, Y., Kage, T., Fukuyama, H., Nishida, I., and Hashimoto, T." Fire Resistance of Continuous Fibre Reinforced Concrete". In Non-metallic (FRP) Reinforcement for Concrete Structures. Edited by L. Taerwe. E&FN Spon, London, UK, pp. 368-375.(1995)

[57] Sakashita, M. " Deflection of Continuous Fiber Reinforced Concrete Beams Subjected to Loaded Heating". Non-Metallic (FRP) Reinforcement for Concrete Structures, Japan Concrete Institute, Vol. 2, pp. 51-58.(1997)

[58] Deuring, M., Brandversuche an nachtraglich verstarkten Tragern aus Beton. Report No. 148'795, Swiss Federal Laboratories for Materials Testing and Research, Dubendorf, Switzerland, 1994.

[59] Blontrock, H., Taerwe, L., and Vandevelde, P." Fire Tests on Concrete Beams Strengthened with Fibre Composite Laminates". Third Ph.D. Symposium, Vienna, Austria, 10pp.(2000)

[60] Noureddine Benichou, Mark Green, Luke Bisby, Ershad Chowdhury, Brea Williams, and Venkatesh Kodur " Fire Performance of FRP-Strengthened Concrete Systems" SFPE-SAC Fire Science & Technology Conference, Al Khobar, Saudi Arabia, Nov. 17-18, (2008)

[61] ACI 440.XR (to replace 440R) "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures". American Concrete Institute, Farmington Hills, MI (2006).

[62] Bisby, L.A., Green, M.F. and Kodur, V.K.R., ''Fire Endurance of FRP-Confined Concrete Columns,'' ACI Structural Journal, Vol. 10, No. 6, pp. 883–891 (2005)

[63] Saafi, M., & Romine, P., "Effect of Fire on Concrete Cylinders Confined with GFRP," Durability of FRP Composites for Construction (CDCC '02), Montreal, PQ, Canada, pp 512-521(2002)

[64] Douglas B. Cleary, Christopher D. Casino, and Rosie Tortorice "Effect of Elevated Temperature on Fiber Composite Used to Strengthen Concrete Columns" Journal of Reinforced Plastics and Composites, Vol. 22, No.10(2003)

[65] Jack.P.Holman " Heat Transfer" Ninth Edition, Mc-Graw-Hill Series in Mechanical Engineering, International Edition (2002)

[66] Egyptian Code of Practice, "Building Code Requirements for Design and Construction for Reinforced Concrete Structures (Laboratory Test Manual for Concrete Material)," (2003)

[67] S. M. Cramer, O. M. Friday, and R.H. White, G. Sriprutkiat " Mechanical Properties of Gypsum at elevated temperature" Proceedings of the Fire and Materials Conference (2003)

[68] Bénichou, N.; Sultan, M.A.; MacCallum, C.; Hum, J. "Thermal Properties of Wood, Gypsum and Insulation at Elevated Temperatures" Institute for Research in Construction , National Research Council of Canada, IRC Internal Report (2001)

[69] AsaroRobert J. ; Lattimer Brian ; Ramroth William "Structural response of FRP composites during fire" journal for Composite structures , vol. 87, no4, pp. 382-393 (2009)

[70] Yu Bai, Thomas Keller "Modeling of mechanical response of FRP composites in fire "Composites Part A: Applied Science and Manufacturing, Volume 40, Issues 6-7, Pages 731-738, (2009)

[71] Venkatesh Kodur,, Aqeel Ahmed, Monther Dwaikat" Modeling the Fire Performance of FRP-strengthened Reinforced Concrete Beams" COMPOSITES & POLYCON 2009, American Composites Manufacturers Association, Tampa, FL USA(2009)

[72] Mark Green "Modelling the Heat Transfer and Structural Behaviour of Plain and FRP Confined RC Rectangular Columns in fire" FRPRCS-9 Symposium (2009)

[73] ANSYS, Inc. Release 11.0" manual book" Documentation for ANSYS(2008).

[74] Chowdhury, E.U.; Bisby, L.A.; Green, M.F.; Bénichou, N.; Kodur, V.R." Fire behaviour of FRP wrapped square reinforced concrete columns, 9th IAFSS, Karlsruhe, Germany, pp 1-8, (2008)

[75] Bisby, L.A., Green, M.F. & Kodur, V.K.R., Modeling the behavior of fiber reinforced polymer confined concrete columns exposed to fire, J. Composites for Construction, volume 9, issue1, pp. 15-24,

[76] Bisby, L.A., Green, M.F. and Kodur, V.K.R., ‘‘Fire Endurance of FRP-Confined Concrete Columns,’’ ACI Structural Journal, Vol. 10, No. 6, 2005, pp. 883–891, (2005)

[77] Bénichou, N.; Kodur, V.K.R.; Bisby, L.A.; Chowdhury, E.U.; Green, M.F." Results of fire resistance experiments on FRP-strengthened reinforced concrete columns" Report no. 2, National Research Council of Canada, (2007)