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Evaluation of fire resistance of plastering applied to reinforced concrete

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EVALUATION OF FIRE RESISTANCE OF PLASTERING APPLIED TO REINFORCED CONCRETE

BY

Engy M. Samy Serag

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Construction Engineering

Under the supervision of

Dr. Ezzat H. Fahmy **Dr. Mohamed Nagib Abou-Zeid**

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ABSTRACT

Concrete is one of the most resistant construction materials to heat and fire. It is known to retain heat for a relatively long time, thus limiting crack propagation from penetrating deeply. Furthermore, it can be repaired if exposed to fire for a limited time. However it loses its strength dramatically when exposed to elevated temperatures for long duration. With the increase in the use of concrete in structures, a demand arises to assess the fire resistance of concrete structural members and to develop means of improving the fire characteristics of these elements. One of the methods to increase the fire resistance of a building is to coat the structural elements with fire retardant plasters to delay failure.

This work presents results of an experimental investigation aimed at evaluating the fire resistance of reinforced concrete columns coated with variable thicknesses of materials that has potential for fire resistance. Four types of coating materials were investigated namely; Perlite, Vermiculite, Rock wool, and conventional cement plaster. The tested columns had three various dimensions, four coating materials, and three coating thickness. Each column was loaded at half its working load and was simultaneously subjected to fire from four sides in a specially prepared furnace. The time needed to reach a specific temperature specified by ASTM-E119 and the post-fire strength were recorded.

The results show the impact of the type of coating and column size on the fire resistance characteristics of the reinforced concrete columns in terms of time, and temperature. Relationships reflecting time-temperature correlation at the concrete surface and the coating thickness for each type are presented. On the whole, Perlite yielded superior results than the rest of the three coating materials with the conventional cement paste as the least effective fire protective coatings. The resistance to fire seems to enhance upon increasing coating thickness although de-bonding took place when applying large coat thickness. Further work needs to be conducted involving new materials and techniques, and involving micro-structural analysis of concrete and coating layers.

Keywords: (fire resistance, concrete, columns, coating, Perlite, Vermiculite, Rock wool)

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CHAPTER I

INTRODUCTION

1.1 Background

Fire safety is a major concern in any construction; it is required primarily to protect souls, property and community. Fire protection reduces damage to property and equipment in addition to its contribution in reducing insurance costs. Among other safety requirements, most codes require certain time or period before the structural element loses its strength. This time is required to allow people to evacuate and firemen to perform their tasks.

With current technology, the collapse of a member subjected to the effects of a fully developed fire may be delayed a few minutes, a few hours or indefinitely (Gosselin, Guy C., 1987). Among other construction materials, concrete can resist heat, however it loses its strength dramatically when exposed to elevated temperatures for long duration. One of the methods to increase the fire resistance of a building is to plaster the structural elements with fire retardant plasters that delay their failure.

1.2 Causes of Fire Hazards

According to Hosny and AboElmagd, the major fire causes are the following (Hosny and AboElmagd, 1994):

1. Society cultures: In Egypt, 70% of the death from fire occurs due to domestic fires, 30% only due to industrial fire. This shows the lack of awareness in the society of how to have fire protection, and how to maintain the equipment (Air Condition (AC), ovens, and heaters.) to prevent the causes of fires (Hosny and AboElmagd, 1994).

2. Exits and Escape routes: There should be more care to have escape routes with clear signs, and easy to open. What occurs is that most of the escape routes are closed, and if not people store things behind them. Almost 602 people died in Chicago year 1905 when fire occurred in a theatre, and the escape routes were not clear, and the others were closed. Another accident was in New York City in 1911 where a fire occurred in a company and 145 worker died because the escape routes were closed. (Ross, 1984)

3. Carelessness: The carelessness has entered into our lives to a great extent. The smokers who leave through their cigarettes in the basket full of papers, or who through it from a window, the lack of maintenance in the wires and cables in the streets the HVAC, all that lead to major fire disasters. The codes, however it needs some awareness, and continuous maintenance, to at least minimize the causes of fire can't treat this carelessness (Hosny and AboElmagd, 1994).

4. Weak codes: The Egyptian code for fire is following the British standards This means that it is not related to the Egyptian construction materials, which might differs in their components and behavior than the British Construction materials. In addition, specifications are poorly worded and fire protection products are not well known for the engineers, architects and contractors .

5. Change of function: Any change in the function of the building should be accompanied by a change in the fire protection system. For instance, A store that has an efficient system in fire protection if changed to a bookstore the fire protection system would be inferior. Also, if old buildings are renovated and AC's are installed to upgrade the ventilation of the building, this would increase the possibility of suffocation especially that there might not be an advanced system of smoke detectors, sprinklers, or escape routes.

6. Advance Architecture: the innovations in architecture, and design give more chances to have buildings of steel frames of longer spans, and larger heights. Also, most of the columns are exposed and not covered with concrete. All these would require a sophisticated system of fire protection (Hosny and AboElmagd, 1994).
7. New building materials: Plastic materials used in the finishes, furniture or the curtains have increased the danger of fire. Upon fire, Polystyrene starts to burn slowly. After that, the rate of burning increased at a very high rate, where rate of heat emission became three times that of wood (Ross, 1984)
8. Schools: The building system of schools here in Egypt does not comply with the fire safety regulations. There are no escape routes, the floors and the furniture are mainly made of wood and the fire alarm systems (if any) is very weak and primitive, the cores and stairs does not have systems that prevents smoke entrapment.
9. Smoke: when the building has an artificial source of ventilation or AC, and when the cores and stairs does not have doors that prevents the smoke from entrapping to higher floors, all that make it easier for hazardous gases to disperse at higher rates, especially if there is not any natural ventilation system. This case has occurred in the world trade center where a bomb exploded in the second floor and people got suffocated in floors higher than the basement by twenty and thirty floors.
10. Loss of strength: reinforced concrete loses its strength significantly at elevated temperatures, and this effect depends mainly on, the degree of temperature of the fire, time of exposure to fire, loading of specimen during fire, type of aggregates, w/c ratio, size of the member and plastering material

1.3 Statement of the Problem

Generally, concrete partially loses its strength at temperature of 200-250°C, but cracks starts to occur at about 300°C where the concrete losses 30% of its compressive strength, and the loss in strength continues with the increase in the temperature. If the temperature does not exceed 300°C the concrete will return most of its strength by time. Table 1-1 below shows the effect of high temperature on both reinforced concrete and steel (Hosny and AboElmagd, 1994).

Table 1.1- Effect of Heat on Reinforced Concrete (Hosny and AboElmagd, 1994)

Characteristics	Temperature	Effect
Compressive strength	<300°C from 500-600°C	Loss of 30% Loss of 60-80%
E(modulus of elasticity)	≈300°C ≈600°C	Loss of 40% Loss of 80-85%
Poisson's ratio	No specific trend	It decreases with increase in temperature
Cracks	Surface cracking 290°C Deeper cracking 540°C	Perpendicular to face and Internal May resemble large scale shrinkage cracking (Random cracks due to difference of thermal expansion of concrete, and steel.)

1.4 Work Objective and Scope

The objective of this work is to evaluate the fire resistance of plastering applid to reinforced concrete performance model columns. The main parameters in this investigation are, specimen dimension, type of plastering material and its effectiveness and plastering thickness

Four different plastering materials are experimented: Perlite, Vermiculite, Rock wool and conventional Cement plaster

To meet this objective, an experimental program was designed involving one concrete mixture with different plastering material, and three size columns, 100x100x1000 mm, 100x200x1000-mm and100x300x1000 mm. So as to evaluate the effect of the columns dimensions exposed to fire on the fire resistance of columns For each plastering material, three plastering thicknesses will be used namely, 15, 25 and 35 mm to evaluate the effect of the plaster thickness in fire resistance. The mixture is prepared with gravel as coarse aggregates, sand as fine Aggregates.

Columns will be tested in a special furnace under sustained loading until the unexposed surface reaches 140°C + ambient, which is the failure criterion according to ASTM-E119 "Standard Methods of Fire Test of Building Construction and Materials".

The fire resistance of each column that corresponds to the thickness applied, and the type of plaster applied will be determined through the experimental program.

After the concrete structurally failed according to ASTM-E119 standards, columns will be loaded to determine the percent loss in strength after fire exposure.

CHAPTER II

LITERATURE REVIEW

2.1 Fire Growth

For any fire to spread, heat must pass from one part to another to cause ignition of the combustible gases. There are three basic mechanisms of heat transfer, and all of them are common in building fires:

1. Conduction: " Mode of heat transfer within solids, and although it does occur in liquids and gases" usually masked by convection".
2. Convection:" involves the movement of the medium and is therefore, restricted to liquids and gases".
3. Radiation: " a form of heat transfer which does not require an intervening medium between the source and receiver" (Lie, T.T., 1991)

There is major difference between the behavior of fire in open and closed spaces. Any Architect should understand such difference and especially understands the behavior and the stages of fire in the enclosed spaces, as this is the most common one. As shown in the Figure 2.1, the presence of a ceiling over the fire has a major effect as it increases the radiant heat that goes back to the surface of the fuel. The presence of walls as well increases such an effect, provided there is a good ventilation (Lie, T.T., 1991).

In the presence of ventilation, and fuel, an enclosed fire will go through several stages after ignition:

a. Growth
b. Stability
c. Cooling

The plotting of the temperature of a fire against time from ignition will give a " fire growth curve" as shown in Figure 2.2.

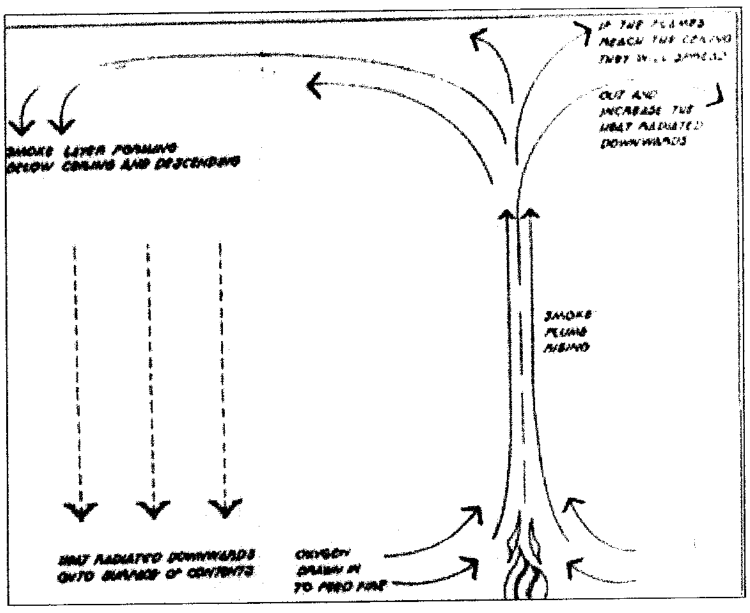

Figure 2.1- Standard Compartment Fire (Lie, T.T., 1991)

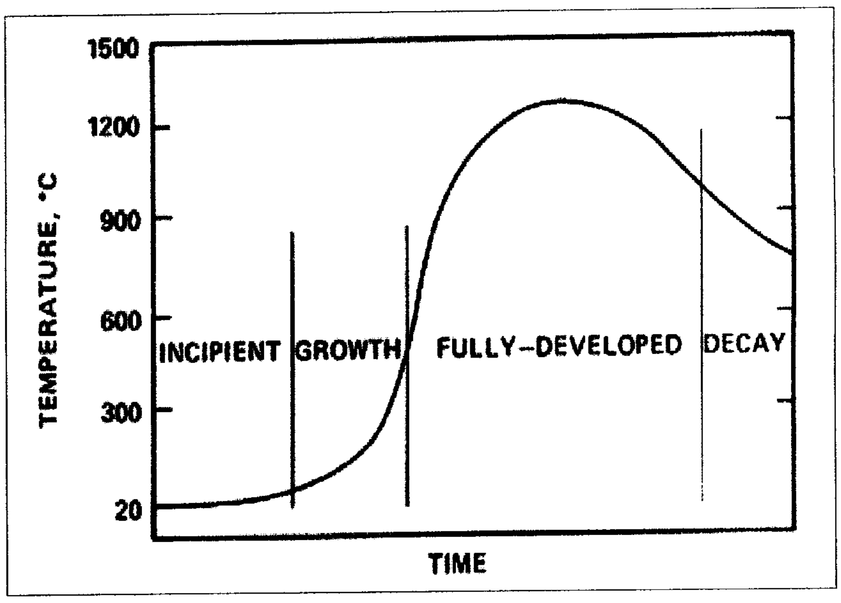

Figure 2.2- Standard Fire Growth Curve (Lie, T.T., 1991)

The growth period stays from the moment the ignition starts to the time when all the combustible materials within the enclosures are alight. First, the vapors that goes out by the fuel will be burning near the surface from which they are generated, and usually there is enough oxygen from the ventilation to enhance such burning. The duration of the growth period depends upon many factors, however a dangerous moment is reached when the flame reaches the ceiling. As the flame spread out under the ceiling, the radiant heat goes back to the surface will increase dramatically. This usually occurs (in a domestic sized room with typical furniture) when the temperature at the ceiling reached approximately 550°C. The remaining combustible materials will now reach their fire point in a short time within 3-4 seconds and ignite. Such sudden transition is known as the "flashover" and such a phenomenon represents the start of the stable phase of the fire. (Lie, T.T., 1991).

In the case where there is not enough oxygen due to lack of ventilation in the room in the growth stage, the flashover will fail to occur. The fire can decay at such a point or will continue to burn without visible flame.

At the stable phase of an enclosed fire, the flame occur allover the enclosure. The volatiles are mixing with the air entering and the rate of burning will be determined through the level of ventilation available, and the amount of fuel. This stage is of high significance to the Architect, as the maximum temperature will be attained. Thus the fire resistance of any element will have to encounter both the maximum temperature that will be reached, and the length of time which will be likely to stand without failure. Once all the available fuel is consumed, the stage of decay takes place.

Combustion only takes place if oxygen is present; thus many extinguishing agents operate by limiting the amount of oxygen available to the fire (e.g. carbon dioxide, foam, sand) (Lie, T.T., 1991).

The main products of combustion are heat, smoke and light. Light does not constitute a danger to the building; however, heat and smoke are specifically hazardous and must be designed against (Lie, T.T., 1991).

2.1.1 Heat

Smoke damage can be a severe one but it can never be a reason for collapse of any building, however, extreme heat can destroy a building.

As mentioned before, concrete is a fire resistant material because it is made from inorganic materials that is a good heat insulator. However, as the reinforced concrete relies on the steel for its tensile strength, the steel has to be protected from heat to avoid its reaching its critical temperature. The amount of heat produced is considered as a measure to determine the fire severity, and the heat produced depends mainly upon the fuel and the ventilation available.

The quantity of fuel within a building is known as the fire load, and such factor is hard to determine due to the multiplicity of the materials to be involved. For instance, the fuel load of a large distributive warehouse is larger than that of a sports center of similar size. (Lie, T.T., 1991)

2.1.2 Smoke

A small percentage of the fire victims' die indirectly from the heat generated that might cause collapse, but the majority dies from the smoke either by the inhalation of toxic gases, or by carbon monoxide poisoning. It is as well important to determine the rate of smoke production. It mainly depends on the size of the fire (in particular, its perimeter and the height of the rising smoke column) and the intensity of the fire (in particular, its heat output) (Lie, T.T., 1991).

2.2 Fire Safety

The role of structural fire protection can be expressed by one or more of the following fire safety objectives: Delaying collapse indefinitely (in essence, prohibiting it) is not always necessary (Gosselin, Guy C., 1987)

- provide sufficient time for occupants on the floors above the fire floor to be able to escape to a safe area
- Support the fire separations necessary to control the overall size of the fire and prevent conflagration;
- Minimize potential damage to adjacent properties.

The term 'sufficient' in the first objective is highlighted to indicate that the required degree of fire resistance will vary according to design factors. For instance, small buildings where people can escape fast upon fire occurrence, do not require a sophisticated protection against collapse, and their design will satisfy safety conditions. The idea of weather to provide fire protection for such buildings or not depends mainly on the economics of the situation (i.e. comparing the capital and business investment value to the cost of providing the structural fire protection).

In larger buildings, or in ones where occupants may need some time to escape, and where the collapse is required to be delayed for the fire fighters to have a chance to extinguish the fire, structural fire protection is required.

In a case of a fully developed fire, the safety of the people within the room is no longer an issue. The average temperature would reach 500°C and rise quickly to a peak level of 800°C to 1200°C as shown in Figure 2.2. In addition, the amount of vaporized fuel and products of combustion caused from burning of one piece of furniture (i.e. upholstered chair) could fill a space equivalent to 15,000 m^3 warehouse in a time of twenty minutes. Thus according to Gosselin, Guy C, 1987, a more logic safety objective is to contain fire and the superheated products of combustion, to the area of origin. Thus another solution is to let the fire spread to other portions of the floor or other stories in the building provided precaution measures were taken to prohibit its entry into areas declared as safe, isolated zones for the use of people occupying the building. This is illustrated as controlling the movement of fire in the "fire safety concepts tree" shown in Figure 2.3 (Gosselin, Guy C., 1987).

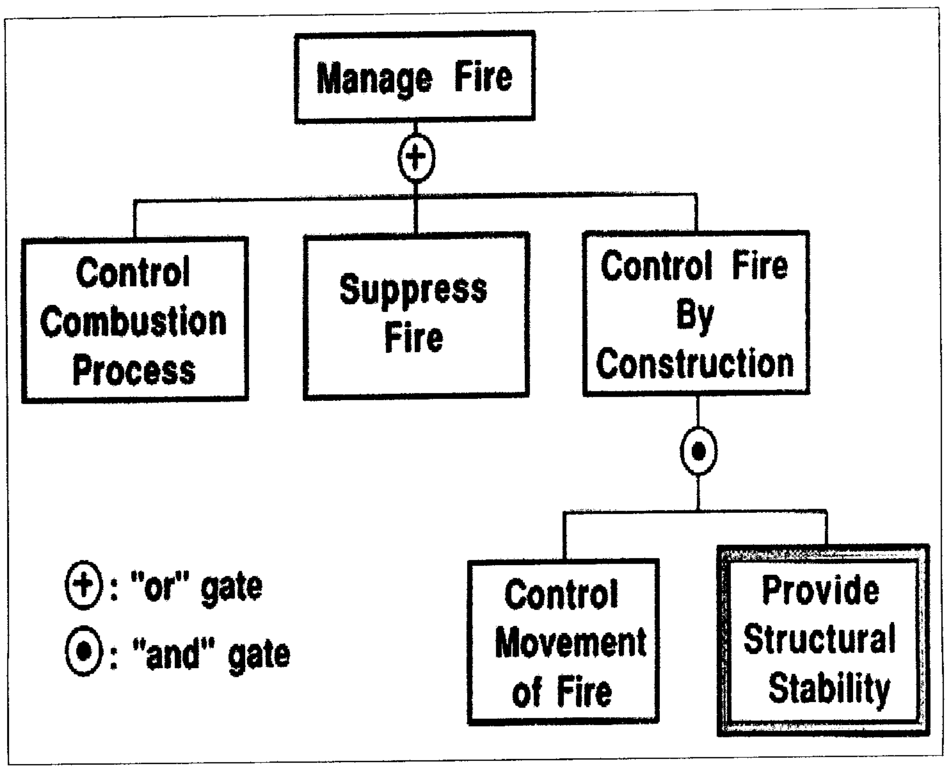

Figure 2.3- Control Movement of Fire element, Manage Fire sub-branch of Fire Safety Concepts Tree.

Such tree takes into consideration the fact that the control of fire by construction objective can be obtained only if both movement of the fire is controlled (by barriers such as fire separations) and structure stability is provided. This is shown in by the *and* gate shown in the tree above theses two elements of the tree. Thus, one of the fire safety objectives of the structural fire protection is to ensure that rated fire separations can perform their fire barrier function for a certain period of time. Thus it is clear that all the factors that contribute to the assessment of the fire resistance rating considered for the fire separations (relative mobility and alertness of the occupants, anticipated combustible loads, specific occupancy hazards…etc.) apply as well to the rating of the supporting structural members. This is important as it would not be logic to allow a two-hour rated floor assembly to be supported by unprotected beams and columns that can collapse in a short period of time i.e. twenty minutes after the flashover in the compartment directly below the floor assembly. (Gosselin, Guy C., 1987)

2.3 Thermal Properties of Concrete

2.3.1 Heat of Hydration:

When water is added to cement, an exothermic reaction takes place, and a considerable amount of heat is released over a period of time. The heat evolves is measured in calories per unit weight of cement. When the amount of such heat, heat capacity of the paste, mortar are known, the resulting temperature rise can be calculated, assuming no heat loss to the surroundings. Many studies have been performed on the hydration reaction, and it was shown that all the components of the cement are anhydrous, and when comes in contact with water they are attacked at various rates and different times. There is an agreement that the tri-calcium aluminate (C_3A) is the largest contributor to the elevated heat, followed by tri-calcium silicate (C_3S) and tetracalcium aluminoferrite (C_4AF) with about equal contributions, and finally dicalcium silicate (C_2S) (Scanlon, John M. and Mc. Donald, James E., 1994).

2.3.2 Thermal Conductivity (K):

Thermal Conductivity, a measure of the ability of a material to conduct heat, is defined as the ratio of the rate of heat flow to the temperature gradient. In normal metric use, the number of kilocalories passing between opposite faces of a 1-m cube per unit of time when the temperature difference is 1°C. It s measured according to ASTM C-177.

The main factors that influence the thermal conductivity are, water content, density, and temperature. Other factors like cement type and content, entrained air, water/cement (w/c), and age have minor or negligible effect on the thermal conductivity.

The amount of free water in concrete, regardless of its density, has a significant effect on the thermal conductivity. Though water is considered a poor conductor of heat as compared to rock, its thermal conductivity is as many times larger as in air. The values of the thermal conductivity of water are shown in Table 2.1 below (Scanlon, John M., and McDonald, James E., 1994).

Table 2.1- Thermal Conductivity of Water (Scanlon, John M., McDonald,James E., 1994).

Water Temperature(°C)	Conductivity (W/mk)
20	0.59
0	0.56
-18	2.3
-59	2.6
-101	3.3
-157	5.2

Thermal conductivity of concrete varies with the moisture content as shown below in Table 2. 2

Table 2.2- Typical Variations in Thermal Conductivity with Moisture at Normal Temperatures (Scanlon, John M., McDonald,James E., 1994)

Moisture Content	Conductivity(W/mk)
Quartz Gravel Concrete	
Moist	3.3
50% relative humidity	2.7
Dry	2.3

As for the density of insulating light weight concrete with densities less than 960 kg/ m^3 that may have been aerated, or may contain very light weight porous aggregates, have thermal conductivity values shown on Table 2.3. (Scanlon, John M., and McDonald, James E., 1994).

Table 2.3- Thermal Conductivity of Insulating Concrete(Scanlon, John M., McDonald,James E., 1994)

Density(kg/m^3)	Thermal Conductivity(W/mk)
Aerated	
320	0.07
480	0.11
640	0.14
800	0.20
960	0.26
Vermiculite	
400	0.10
Expanded Shale	
825	0.17

At elevated temperatures, up to 750°C, thermal conductivity of cement paste mortars, and concrete decrease in a uniform constant manner. Such decrease is attributed to the disruption of the inter crystalline bonds in the aggregates caused by excessive thermal expansion. At about 400°C, the value of the thermal conductivity is 0.56 W/mk for cement paste. Above temperatures of 400°C, gradual disintegration of fully hydrated cement paste occurs that decreases the thermal conductivity (Scanlon, John M., and McDonald, James E., 1994).

2.3.3 Specific Heat (c):

Specific heat capacity reflects the amount of thermal energy needed to raise the temperature of 1kg of a material by 1 degrees Kelvin. As mentioned before, concrete has water in its content at early stages before drying, and upon heating, water will start to evaporate.

Several studies were performed on the effect of temperature increase on the specific heat capacity of concrete. It shows that the specific heat capacity increases with the increase in temperature and this is explained that at 100°C, water will evaporate and the amount of energy needed to raise 1kg of concrete by 1 degree Kelvin will be higher. Studies carried out on the effect of various types of aggregates, gravel, limestone and lightweight aggregates on the specific heat capacity of concrete, showed that it has a minor effect. (Collet, Y., and Tavernier, E., 1976).

2.3.4 Thermal Diffusivity (α):

It is a measure of a material ability to conduct heat energy in relation to its thermal storage capacity. Also it provides some information about the rate at which thermal energy can travel through the material. (Mosalamy, Usama, 2002).

Thermal diffusivity is defined numerically as the thermal conductivity divided by the product of specific heat and density, or $\alpha=\kappa/c\rho$. Both thermal conductivity and diffusivity are affected by changes in the moisture content, and thus derived thermal diffusivity values will be based on thermal conductivity and density that corresponds to the condition of the concrete used. (Scanlon, John M., McDonald, James E., 1994) Materials that have large thermal diffusivity respond more to thermal heat efflux than those of lower ones do. Studies have been performed on dense and lightweight aggregates and they showed that as the temperature increases, the thermal diffusivity decreases, and after 600°C, the difference between the thermal diffusivity of various types of aggregates became considerably small. The Beaureau of reclamation reported thermal diffusivity values of neat cement pastes ranging from 0.0012 to 0.0016 m^2/h (Harmathy, T.Z., 1970).

2.3.5 Thermal Expansion:

The coefficient of the thermal expansion reflects the expansion per unit length of material produced when the temperature is raised 1°C.

The actual thermal expansion is the net result of two actions occurring simultaneously. The first is a normal expansion of anhydrous solids. Second there is a hygrothermal expansion or contraction associated with the movement of internal moisture from capillaries or from gel pores. Up to 100°C, the paste has achieved its natural expansion, and at higher temperature starts to shrink, continuing to do so to about 500 to 600°C. At this level, only the original dry ingredients remain.

As the aggregates constitute 80 to 85% of the concrete, its thermal properties usually affect the concrete behavior. For instance, quartzite and other siliceous aggregates have high thermal expansion, and concrete containing such aggregates has a value of thermal expansion of 13X10^{-6}/°C. Cement paste constitute only 15 to 20% of the concrete volume but its thermal expansion coefficient (9 to 22X10^{-6}/°C) is several times more than that of aggregates. Generally, the coefficient of thermal expansion increases with the decrease in the in the w/c (Scanlon, John M., McDonald, James E., 1994).

2.3.6 Thermal Resistance (R):

It is the property of the material, which enables it to with-stand the passage of the heat through it due to a temperature difference two opposite surface of the material and it is calculated as follows:

$$R=(1/h_{eo}) + \sum (T_i/k_I) + (1/h_{ai}) \qquad (2.1)$$

Where,

R =thermal resistance

h_{eo} = external heat transfer coefficient =25

T_i = Thickness of plaster material in meters

K_i = thermal conductivity that corresponds to the thickness in w/mk

h_{ai} = internal heat transfer coefficient =8

2.4 Heat Transfer Analysis

Concrete is a porous material, with its pores filled with water and air. Surface heating of the concrete at elevated temperature during fire, not only results in deterioration of its properties like elastic modulus, yield strength, tensile and compressive strength, but also in moisture migration. In the presence of liquid water, heat evolved from fire to the concrete, causes the evaporation of liquid water. If the evaporation rate of the liquid water is higher than the vapor migration rate, pore pressure will build up. The combination of the raised pore pressure, thermal stress developed due to increase of the temperature, external restraint and the reduction of the strength due to high temperature may cause surface spalling of the concrete. The spalling will accelerate the heat transfer process, which will cause stripping away of the concrete layers and exposure of new layers to fire. (LY Li, J A Purkiss and R T. Tenchev, 2001)

The main issues in the prediction of the concrete spalling are the moisture migration and the thermal stresses developed on account of the temperature gradient. Based on experimental results, Bazant *et al*, 1978,1997) developed a model in which the mass of liquid water and that of gaseous mixture were treated together as a single variable, namely " water content". Thus the phase change between water and water vapor need not to be considered in the model. The relationships between water content and pore pressure for given temperatures are determined experimentally, and thus the temperature and water content can be solved directly from heat and mass transfer equations.

As for the pore pressure, recorded results obtained vary from less than 1Mpa to higher than 8 Mpa (Tenchev, R.T., Li, L. Y., and others, 2001). Experimental data on the pore pressure are scattered due to the variation in the materials properties such as permeability, porosity, and the level of water saturation.

Experiments conducted at higher temperatures showed that the movement of both liquid water and gaseous mixture on account of the pressure gradient becomes the control transport mechanism. (England, G.L. and Sharp, T.J., 1971, Bazant, Z.P., 1975). When concrete is exposed to heat, liquid water evaporates, and local pore pressure built up. The movement of both liquid water and gaseous mixture leads to release of water vapor from the boundaries. Continuos heating of one of the surfaces provides continuos evaporation and drying of regions near the surface. In deeper regions, the concrete stays wet, and actually gains moisture from re-condensation. The dry-wet interface, or the evaporation front that separates the two regions, penetrates into the surface with further evaporation. Realizing that, L Y, J A Purkiss and R T Technev, 2002, developed a computer model that is able to predict the distribution of pore pressure within the concrete during fire, and the effect of various material parameters on it. The model considers the heat transfer and the mass transport of liquid water and gaseous mixture.

His model was applied on a concrete wall of thickness 100mm, one side is exposed to room temperature and the other side to fire, and the temperature (T), and time (t) follows the standard furnace curve:

$T(t) = T_0 + 345 \log((2t/15)+1)$ ....(2.2)

Figure 2.4 shows the typical distribution of temperature, pore pressure and contents of liquid water and gaseous mixture in a unit volume of concrete at 5, 10,20, and 40 min. As expected, the temperature rises with time, and for a given time, it decreases with the distance from the fire-exposed surface. The pore pressure, at a given time, is found to display a single wave. The peak value of the pressure increases with time, and the corresponding position penetrates from the fire-exposed surface into the concrete. The increase in the peak pressure is rather rapid in the first 20min and there after becomes very slow. The length of the pressure wave is also found to increase with time, which indicates that the pressure spreads out with time. The mass distribution of liquid and gaseous mixtures shows that the liquid water disappears very quickly when the temperature is around 200°C. Such disappearance is due to both transportation and evaporation. Transportation is demonstrated by the increase in liquid water on the wet side of the dry-wet interface, although this is partly due to the re-condensation of the water vapor transferred from the dry zone. Evaporation is illustrated by the huge increase in the gaseous mixture on the dry side of the interface. The peak pressure is found almost on the dry -wet interface. The spread of the gaseous mixture into the wet zone seems to be limited by the increase in the liquid water near the interface, which obstructs the travel of gaseous mixture.

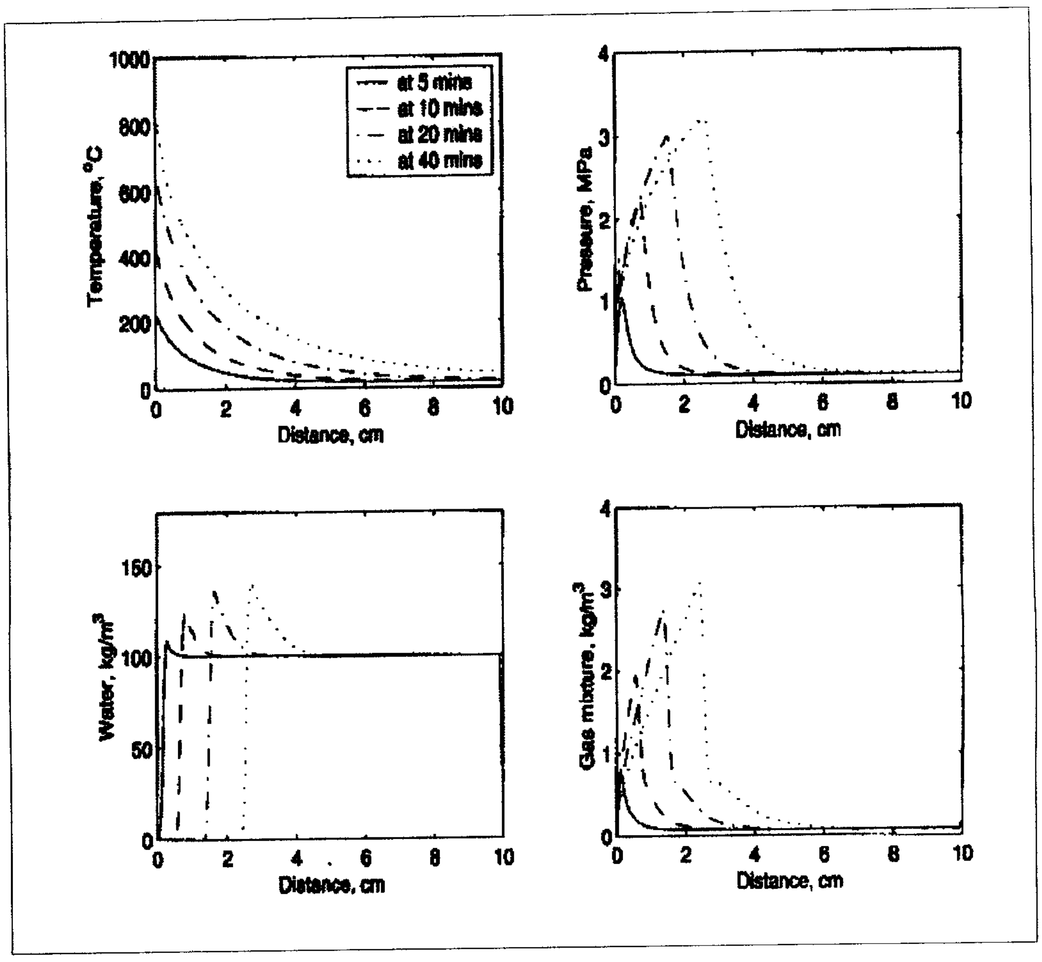

Figure 2.4- Distribution of Temperature, Pore Pressure, and Liquid Water and Gaseous Mixture Contents Before 40 min (LY Li, J A Purkiss and R T Tenchev, 2001)

As illustrated in Figure 2.5 as the time increases, the peak value of the pressure wave seems not to significantly increase. Because of the rise of temperature within the concrete, liquid water continues to evaporate at the dry-wet interface, which moves further into the deeper region of the concrete with time.

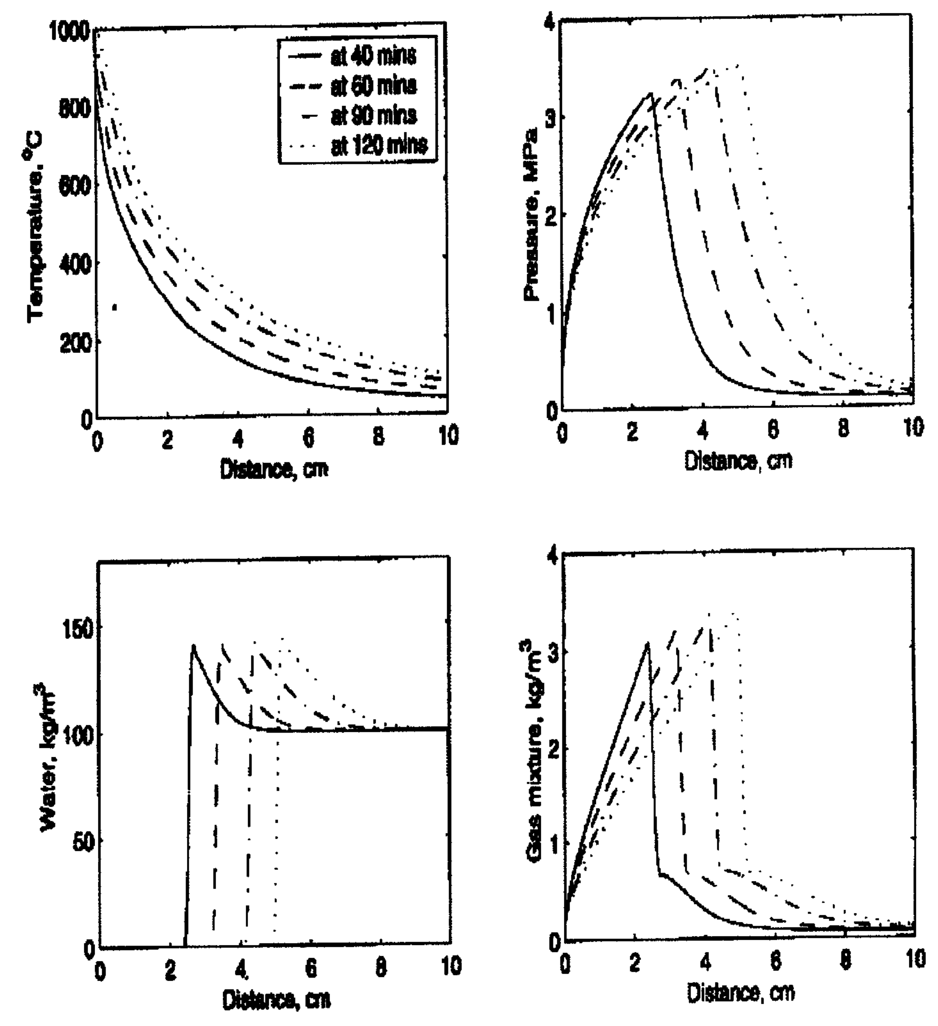

Figure 2.5- Distribution of Temperature, Pore Pressure, and Liquid Water and Gaseous Mixture Contents After 40 min (LY Li, J A Purkiss and R T Tenchev, 2001)

Figure 2.6 shows the influence of permeability on the profiles of temperature, pore pressure, and contents of liquid water and gaseous mixture. The increase in permeability Figure (2.6a), or the decrease in permeability Figure (2.6b) by a factor of 5, has no effect on the temperature profiles, but a great influence on the pore pressure profiles. Increasing the permeability as in Figure 2.6a accelerates the transportation of liquid water into the wet zone, which reduces the water source to be evaporated, and thus results in lower pore pressure. Comparing Figure 2.6a and b with Figure 2.4 shows that reducing the permeability by a factor of 5 can almost double the pore pressure.

Figure 2.7 shows the influence of the initial volume fraction of liquid water on the profiles of temperature, pore pressure and contents of liquid water and gaseous mixture. The increase or decrease in the initial water content (by 20%) is found to have some influence on the pore pressure profiles but very little influence on the temperature profiles. The greater the initial liquid water content, the higher is the pore pressure

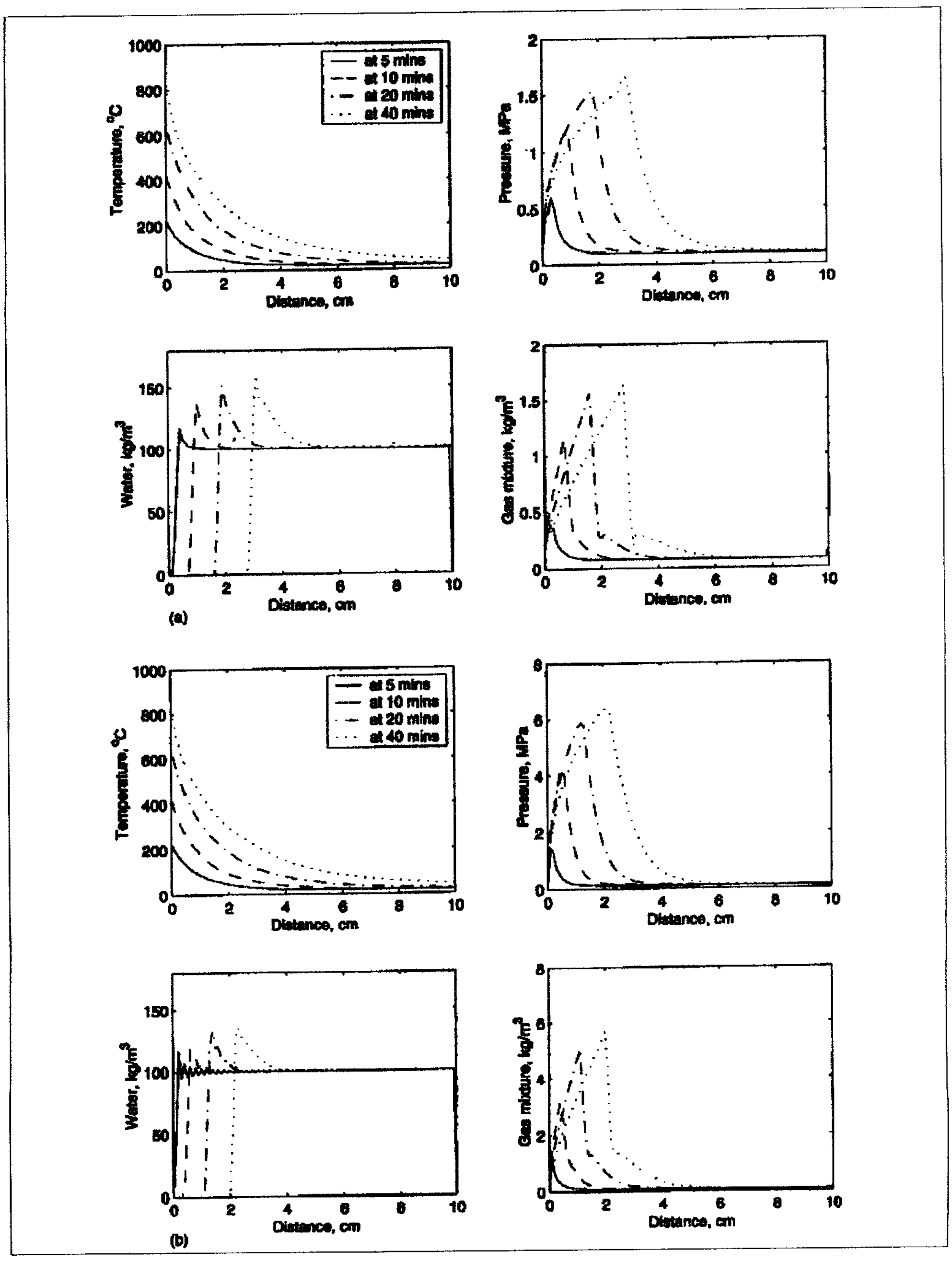

Figure 2.6- Distribution of Temperature, Pore Pressure, and Liquid Water and Gaseous Mixture (a) increased permeability; (b) reduced permeability (LY Li, J A Purkiss and R T Tenchev, 2001)

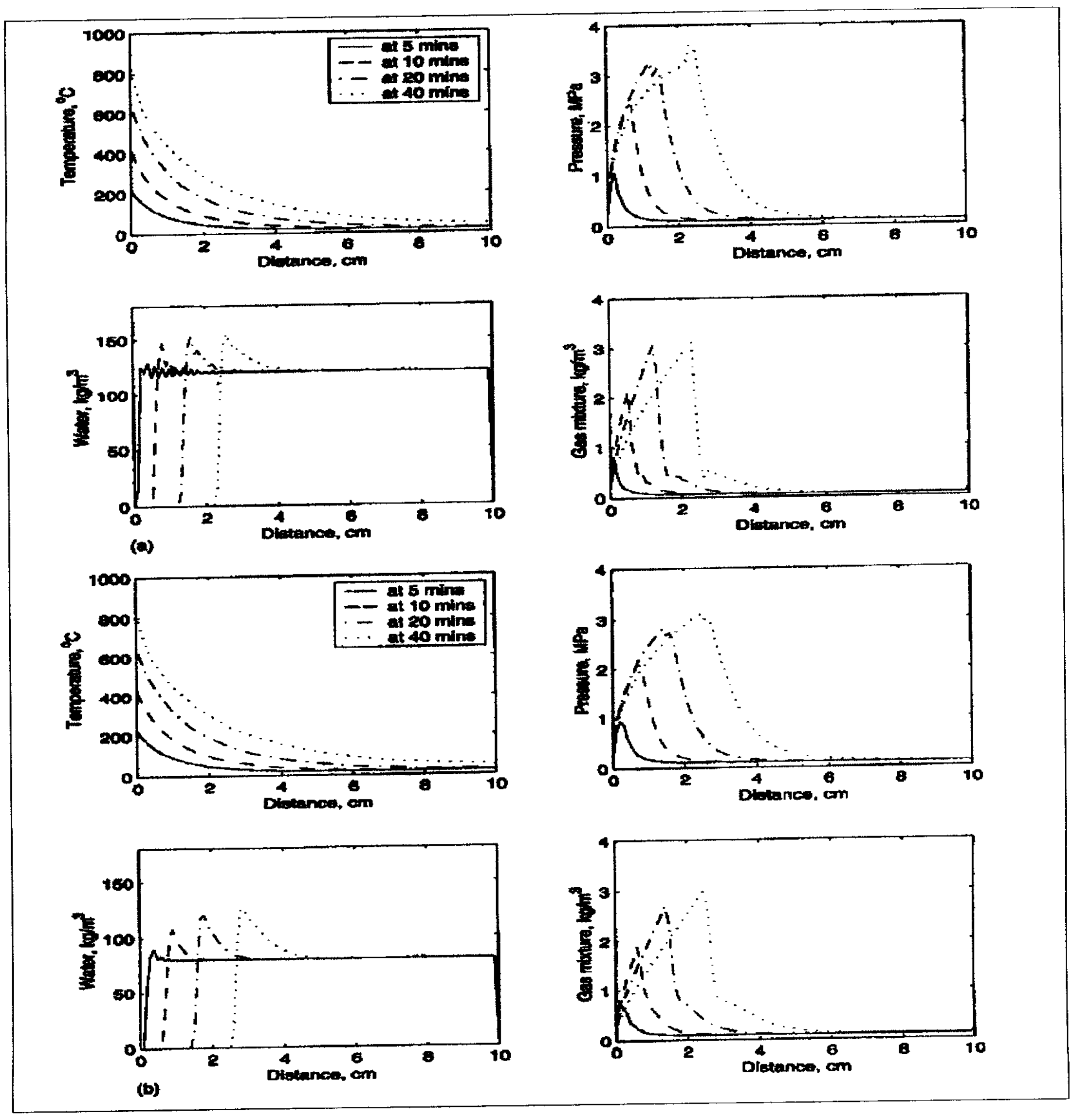

Figure 2.7- Distribution of Temperature, Pore pressure, and Liquid Water and Gaseous Mixture (a) increased initial water content; (b) reduced initial water content(LY Li, J A Purkiss and R T Tenchev, 2001)

2.5 Effect of Heat on Steel Reinforcement:

The loss in the steel reinforcement tensile strength is one of the main reasons for the deflection that occurs during fire, in addition to the loads that exists as compared to the design load. As the existed load increased more than the design load, as the deflection increase more during fire.

Joint committee of Institution of Structural Engineering and Concrete Society published the results of studies performed on studying the properties of steel at high temperatures. They showed that if the steel reinforcement is heated up to 660°C, it recovers its full normal strength when cooled to room temperature again. However if heated to 800°C, then on cooling to room temperature, full strength won't be regained. Also, steel losses half its modulus of elasticity when the temperature reaches 500-600°C, but it returns it back if the temperature does not exceed 700°C.

This is important because, before the introduction of limit state design concepts, when permissible stress was used as a basis for design, the maximum stress allowed in a member was about 60% of its room temperature strength. This led to the commonly held assumption that 550°C was the highest or "critical" temperatures that steel structure would withstand before collapse. The time it will take for these temperatures to be reached in a concrete member depends on the thickness of the cover protecting the steel (Gosselin, Guy C., 1987)

Table 2.4 and Figure 2.8 below summarizes the effect of high temperature on the steel reinforcement (Kong, F.K., 1983)

Table 2.4- Effect of Heat on Steel Reinforcement (Hosny and AboElmagd, 1994).

Characteristics	Temperature	Effect
Yield strength	Cold worked high tensile ≈550 ≈700	Loss of 40-50% Loss of 80%
	Mild steel and hot rolled high tensile ≈550	Loss of 30-40%
	≈700	Loss of 70%
Ultimate Strength	≈400 ≈700	Loss of 20% Loss of 80%
E	≈480	Loss of 20%

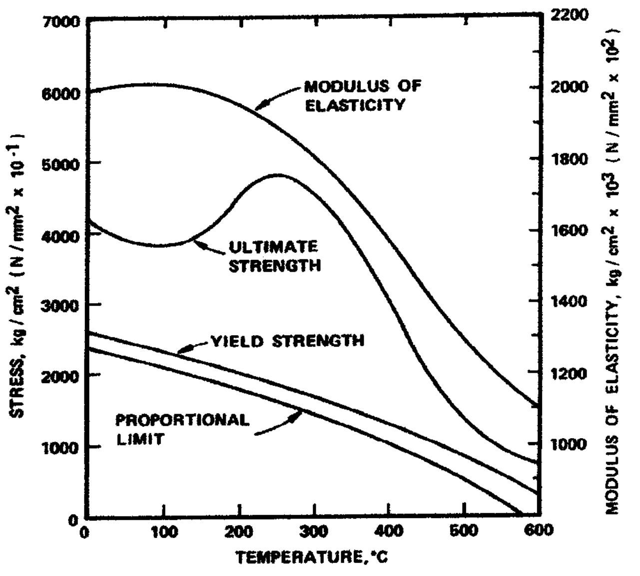

Figure 2.8- Strength and Deformation Characteristics of a Mild Structural Steel (St37) as a Function of Temperature (T.T., Lie, 1991)

It is as well very important to take into account the studies performed on the Egyptian reinforced bars. Elibiari and salah Eldin, 1989 conducted experiments on the Egyptian reinforced bars and came with the following conclusions:

One. The yield and ultimate strength for grade (24/35), grade (36/52) and grade (40/60) of heated steel bars at different temperature up to 1200°C and cooled either by air or by water was still within the limits of Egyptian specifications.

Two. The heated steel bars of grade (40/60) lost almost 50% of their yield strength at 1200°C from that at normal temperature than that when cooled in air. The ultimate strength of the same heated bars remained constant until 600°C for air and water-cooling, and then it decreased to 61% at 1200°C for air-cooling.

2.6 Analysis of Fire Resistance:

Several researches have been undertaken, and it was shown that there are three different ways of determining the fire resistance ratings of structural members and assemblies and they are as follows:

1st. Testing approach: it is performed by conducting fire test on a loaded specimen in accordance with a nationally recognized standard such as ASTM E-119 method "Standard Methods of Fire Test of Building Construction and Materials", or by looking up published listings of test results and conforming with the specifications of a tested assembly.

2nd. Design approach: makes use of the empirical equations that correlate the results of the fire tests for specific combinations of construction material/protection material. This approach has been common recently due to the high cost of the full-scale tests, and through such equations, researchers can extend the importance of test results.

3rd. Rational Design approach: currently, scientists at the fire research section of the institute for Research in Construction and other institutions are developing theoretically based approaches, often referred to as "Rational design procedures" which rely on structural mechanics, and heat transfer principles to assesses structural response under fire conditions

2.6.1 Testing Approach

- ***History of Fire Testing (Early fire tests):***

The first trial in the testing of fire for buildings goes back to the 19th century. The recorded experiments were in Germany in the eighties and in Britain in the nineties of this century. The experiments have started and increased since then, which led to the setting of the first standards in the beginning of the 20th century.

Edwin Sach of England, and Professor Ira Woolson in the United States were of the pioneers in the fire-testing field. The fuel they used was mainly wood with a little pitch added. The temperature was measured using thermocouples connected to indicating potentiometers. In early tests of Columbia university, it was found that one cord of wood allow enough fuel for a one hour test in small buildings (G. W. Shorter, 1964)

The first trials in testing were headed towards the fire proofing systems, and the experiment conducted by the office of the Associated Architects by the end of the 18th century on two floor fire proofing systems was considered one of the first on such field. The reinforced concrete was not known at that time until the 70's of that century. By the end of that century, experiments were conducted to test the resistance of the reinforced concrete slabs, when the Engineers realized the superiority of the concrete in the fire resistance, after that experiments were conducted on steel columns covered with concrete to resists the fire.

- ***Development of Fire Resistive Tests***

Until 1903, every lab was using its special specifications to test fire, and it was mainly the maximum temperature that can be reached for duration that differs from one experiment to another. Then the British Fire Prevention Committee set the first specifications for such experiments, and they were published in the International Fire Prevention Congress in London 1903. These specifications consist of Tables that specify the duration at which the fire-resistive materials can sustain at a temperature of 982°C, and they were categorized into three main categories:

- The first stage: materials that offer complete protection from fire
- The second stage: materials that offer partial protection from fire
- The third stage: materials that offer temporary protection from fire.

In 1918, a time-temperature curve was prepared in a conference sponsored by the American society for Testing materials in the United States, through a committee on Fireproofing, the National Fire Protection Association and a committee on Fire-resistive construction. The curve was proven through series of experiments of burnout tests conducted by the National Bureau of Standards under the direction of Mr. S. N. Ingberg, a U.S. National Bureau of standards testing Engineer. There was a problem that the standard fire resistance test is not representing the real-world fires. It differs in its degree of severity according to type and geometry of combustible load, which can burn and is present in the compartment, the availability of the fresh air (door and window openings) and the thermal properties of the finish materials available during the fire. The Figure below, 2.9 illustrates the above problem through a comparison of typical compartment fires (A and B) and Standard fire exposure. (Gosselin, Guy C., 1987)

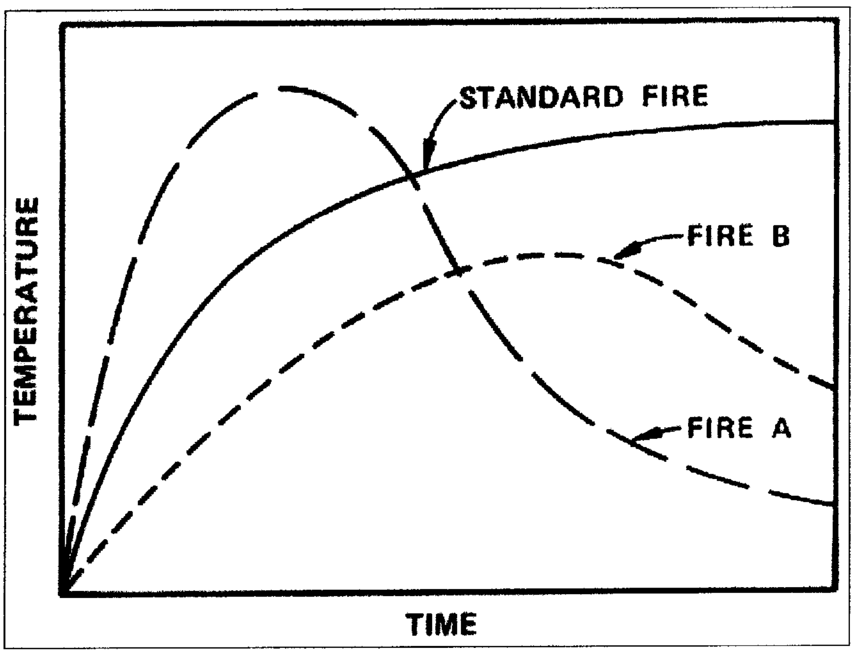

Figure 2.9- Comparison of Typical Compartment Fires (A and B) and Standard Fire Exposure (Gosselin, Guy C., 1987)

In 1928, Ingberg solved the problem, that the standard fire resistance test is not representing the real-world fires, by trying to develop a relationship between the "Standard fire" and the real fire. He conducted a series of full-scale room burns with the combustible content that is related to a typical office, record storage, and residential occupancies. According to such tests, at which the room temperatures were recorded as a function of time, Inberg proposed the equal area hypothesis to be able to perform a comparison between the severity of fire to that of a standard fire of specified duration. Such hypothesis ,illustrated in Figure 2.10 , stated that "test fires can be considered similar if the areas under their respective temperature-time curves above a baseline are equal".

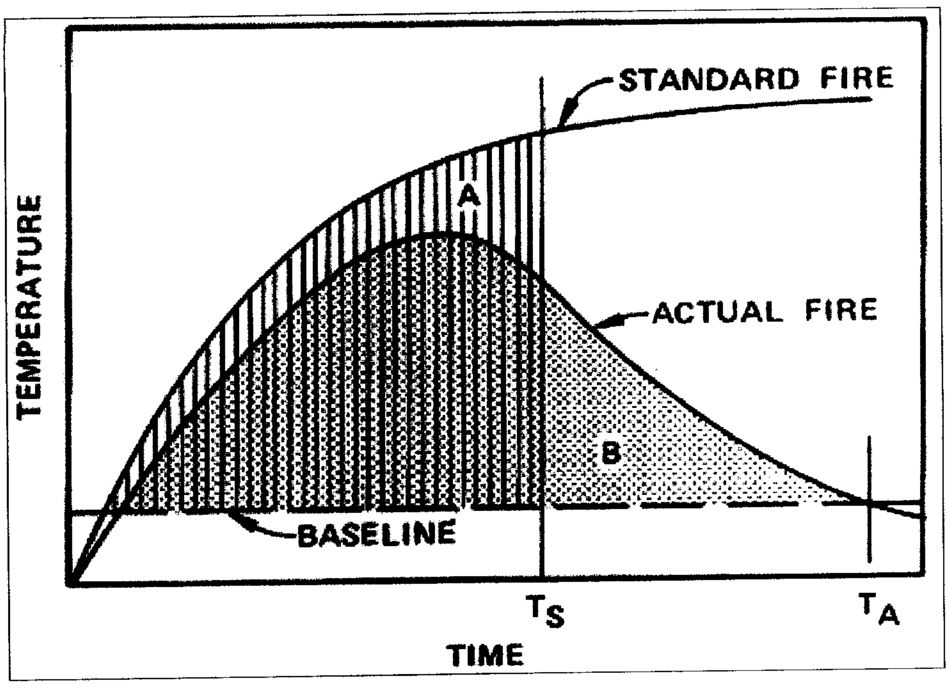

Figure 2.10- Ingberg's hypothesis - equal fire severity if area A = area B

Although it has been shown not to be scientifically correct, Ingeberg rule of thumb relationship between combustible load and equivalent duration of standard fire exposure presented a convenient method to determine the fire resistance required to withstand a complete burnout in a fire compartment. Such an ideas was adopted by code authorities in 1930's and 40's following the gathering of information about combustible loads in residencies, offices, schools, hospitals, stores and manufacturing establishments. (Inberg, S.H., Dunham, J.W. and J.P.Thompson, 1947)

However, the code committee discovered that fire load data was only one item in the fire safety equation. Other factors such as the height and the area of the building, the ability of the occupants to evacuate the building without assistance quickly, the degree of awareness of the fire conditions and fire fighting capabilities, also has a great impact on life safety and affect the decision regarding the level of the fire resistance to be considered in different types of buildings. (Gosselin, Guy C., 1987)

Other tests were conducted that formed a relationship between fire load (is "the quantity of combustible material per square foot of floor area") and the duration of a fire corresponding to a fire resistive building exposure (G.W. Shorter, 1964).

- ***Current Testing Approach:***

In the United States, fire resistance requirements specified in the building codes are expressed in terms of fire endurance ratings of a building's structural members. The ratings are determined according to the American Society for Testing and Materials (ASTM) E119 test method "Standard Methods of Fire Test of Building Construction and Materials". An ASTM-E119 rating is defined as "the length of time a member of a structure can withstand exposure to standard fire without critical loss of its load bearing capacity". The standard fire is defined in the ASTM-E119 document in terms of a specified temperature-time history as shown in Figure 2.11 below.

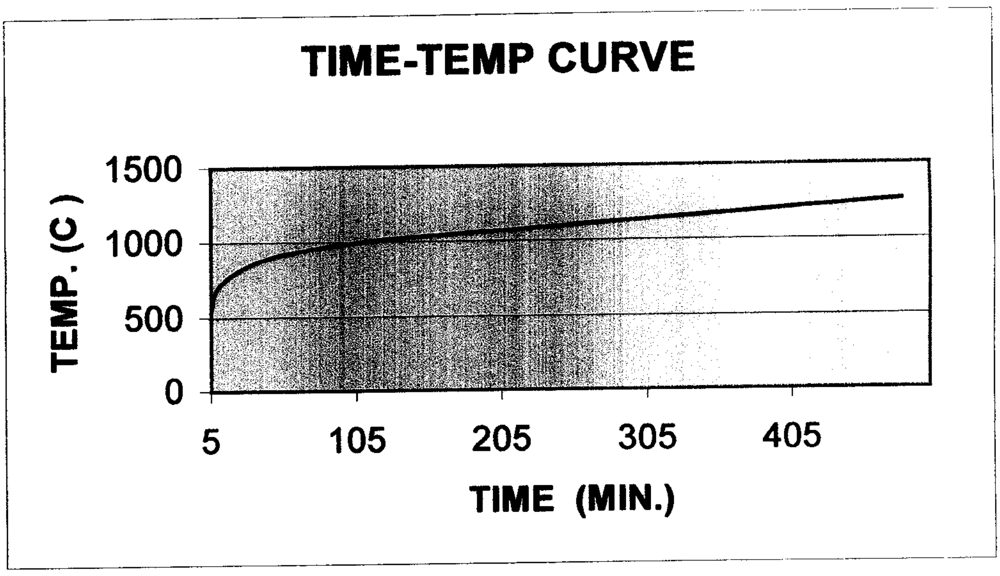

Figure 2.11- ASTM Time-Temperature Curve

The ASTM curve has a steep section at the start, reaching 538°C in 5 min, and leveling off until it reaches 927°C in 1 hour. The curve then increases at the rate of approximately 150°F per hour. The steep section of the time-temperature curve represents the case in a rapidly increasing fire. The flat part of the curve is concerned with the duration of the fire and is related to the amount of combustible materials available in occupancy. As shown in the curve, the test stops at a point in the flat portion, whereas a time-temperature curve of a typical fire would have a portion catering to the fire extinguishing, or the fire decay period. However, for the evaluation of the building constructions, such case is neglected. (Shorter, G.W., 1964)

Structural elements are rated according to ASTM E-119 by testing them in a furnace, where they are exposed to the standard fire environment shown above. According to Gilvary, Kenneth R., *and et al.* 1997, it is difficult for a furnace to follow the ASTM E-119 time-temperature curve exactly, therefore; the code allows for some variations from such curve. This is one of many reasons that can cause scattering in results from one test to another.

As stated in ASTM E-119 for structural column conditions during testing, the columns have to be vertical in the furnace, as shown in Figure 2.12 during the fire exposure. Through out the fire endurance test, the column is exposed to fire from all the four sides and is loaded with a superimposed load to stimulate a maximum load condition. This load shall be the maximum load condition allowed under nationally recognized structural design criteria unless limited design criteria are specified an a corresponding reduced load is applied.

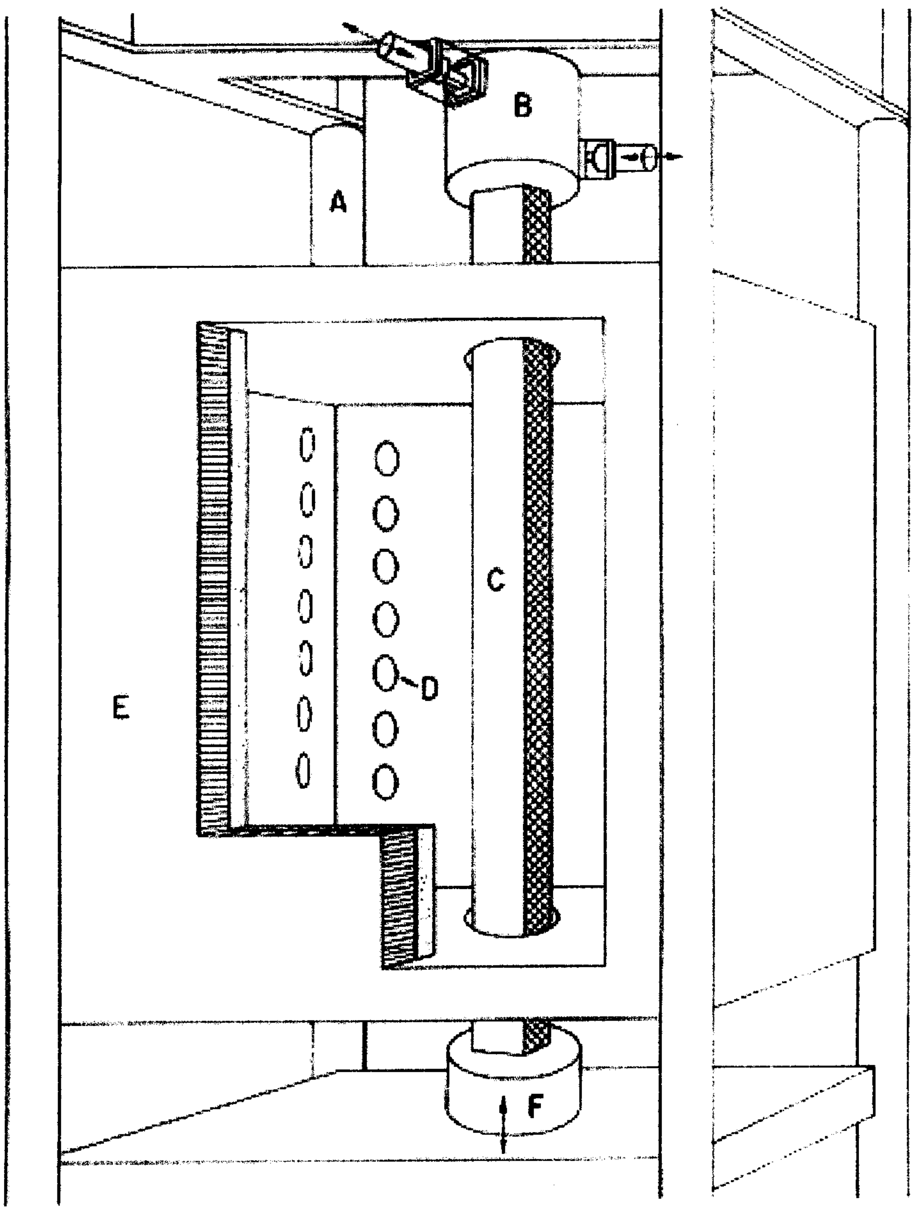

Figure 2.12- Schematic of Column Furnace. A - Restraint Frame, B - Transverse Loading Head, C - Test Column, D - Burner, E - Insulated Furnace Shell, F- Axial Loading arm (Gosselin, Guy C, 1987.)

Although ASTM-E119 ratings are very conservative, such ratings have been successfully used for many decades as the basis for fire-safe design in the U.S.

According to Gilvary, Kenneth R., *and et al.* 1997, the primary problem with ASTM E-119 rating that the standard fire does not accurately simulate real building fires. For example, the temperature of the standard fire is monolithically increasing with time for up to 8 hours. This temperature history as originally recorded from a fire that was continuously fueled with railroad ties. The temperature of a real fire rises to peak then begins to decrease with time. A floor in a typical building will generally burn itself out in about two hours. It is generally accepted that the continuously increasing ASTM E119 would be impossible unless the fire was being continuously fueled.

Fire severity as well as the peak temperature and time to peak of the temperature-history depend on several factors, including:

1. Fire load(amount andtype)
2. Distribution of this fire load.
3. Specific surface characteristics of the fire load.
4. Ventilation
5. Geometry of fire compartment.
6. Thermal characteristics of enclosure boundaries.
7. Relative humidity of the atmosphere(Gilvary, Kenneth R., *and et al.* 1997)

There are three basic types of failure of the test specimen that are specified in ASTM-E119:

1. Temperature rise of more than 140°C above the initial temperature on the side of the specimen not exposed to fire.

The temperature rise criterion ensures that the combustible material piled next to the side of the member not exposed to the fire will not ignite.

The temperature rise limit was originally set at 167°C on the basis of the ignition temperature of a cotton waste. Later was reduced to 140°C when it was observed that the temperature at the back of the wall continue to increase for a while after the test furnace had been shut down.

As mentioned above, the temperature on the unexposed side of the specimen will be measured by thermocouples (Gossilin, Guy C., 1987).

2. Collapse,

This criterion is important especially for load bearing element like beams and columns that do not act as enclosing elements but do support such elements. This is very important especially to fire fighters who enter in a building to extinguish fire (Shorter, G.W. , 1964).

3. Wide Cracks

This is very important as if wide cracks occur, it ill allow hot gases to pass through and ignite combustibles on the side of the element removed from the fire. (Shorter, G.W., 1964)

Other Fire Standards used beside ASTM E119 is the British Standard BS 476 These two fire standard are mainly concentrating on fire Temperature below 1000°C. As shown in Figure 2. 13, the upper and lower boundaries of both standards are close to each other. For fire Temperature above 1000°C, Hydrocarbon Time Temperature Curve is followed as shown in Figure 2.13.

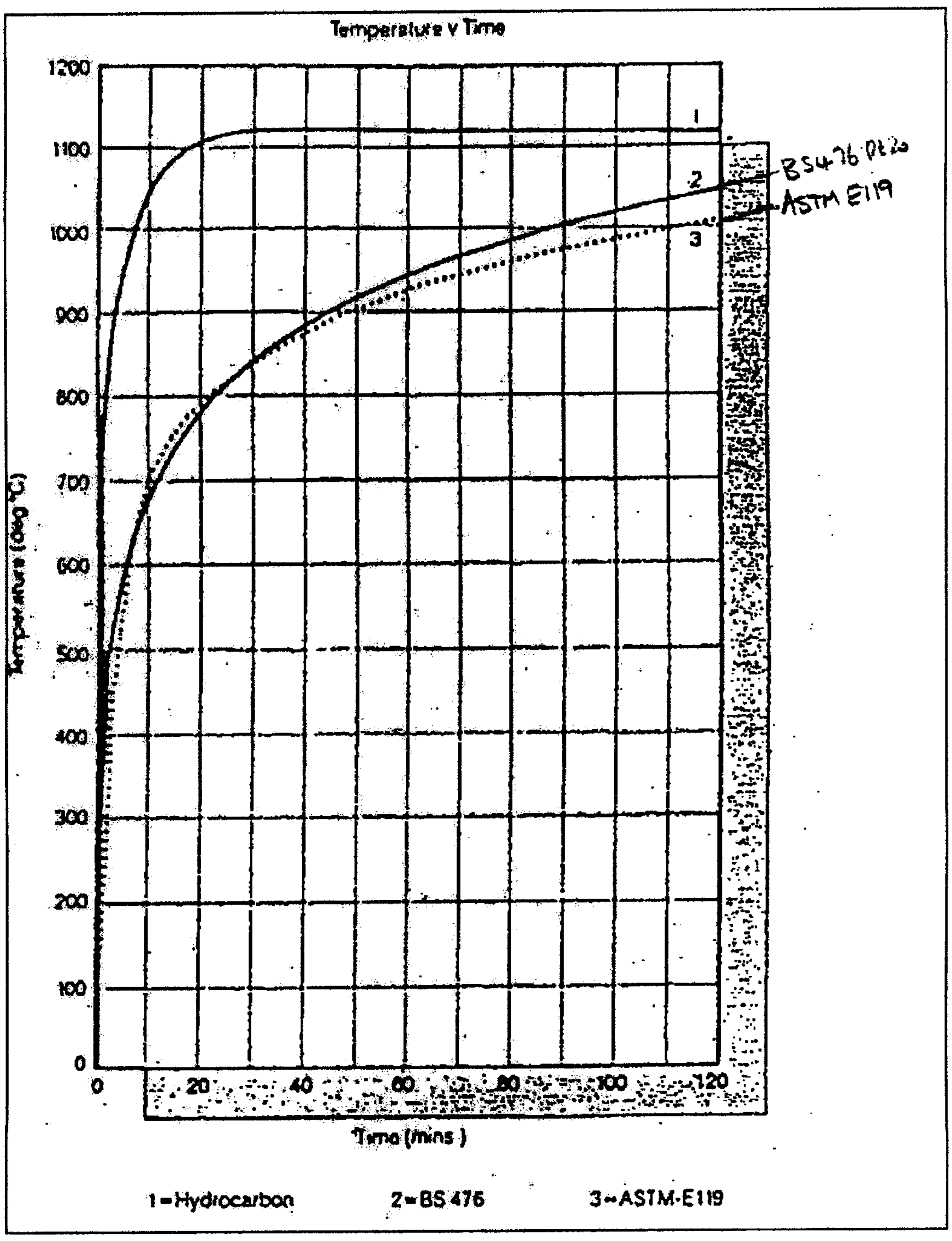

Figure 2.13- Comparison of BS 476 Part B 1972 Revised to BS 476 Part 20 1987, ASTM E119 and a Typical Hydrocarbon Time/Temperature Curve

- ***Major Findings from Testing Approach Experiments***

Several experiments have been conducted in various laboratories to study the effect of various parameters on the fire resistance of concrete columns. Experiments at the University of Ghent and the laboratory of bridges and the University of Liege were carried out and they came out with some observations during test actions. They observed that after failure of the columns, buckling of some individual longitudinal reinforcement occurs between two stirrups. Therefore, decreasing the spacing between stirrups might modify the behavior of column under fire conditions. Several studies have been performed on the effect of load level, dimensions of the cross section, main reinforcement, the concrete cover, and load eccentricity where the following conclusions were drawn:

1. Columns with reinforcement of bars of diameters exceeding 25 mm have revealed smaller values of fire resistance than expected.
2. Spalling of concrete has been observed in many tests, where large cracks along longitudinal reinforcement could often be observed
3. The lowest fire resistance occurs at the columns with the highest load levels.
4. Increasing the length of the column revealed negative effect in terms of fire resistance , due to geometric non-liner effects
5. An increase in the concrete cover gave positive effects in terms of the fire resistance to concrete columns.

Other experiments were conducted as well in the Housing and Building Research Center in Cairo to evaluate parameters that affects fire resistance of concrete columns. A study was carried out to study the effect of the residual strength of RC concrete models contain different types of coarse aggregates (gravel, dolomite, basalt) after exposure to 650°C temperature for various periods of exposure time.

Columns were simultaneously exposed to an elevated temperature of 650°C for varying periods of time (30min, 60min, and 180min). The results showed that the residual capacity of the column decreases with increase in the exposure time to elevated temperature for all three tested concrete types. In addition, the results showed that columns containing basalt sustained 650°C for the longest period (180min) and gave the highest residual capacities among all tested columns. Columns containing dolomite aggregates, came in the second rank, then finally gravel came in the last place. In this experiment, the applied load increases with increase in temperature. This is attributed to the residual thermal expansion of both the specimen and the loading steel plate that is used to transfer the load from the hydraulic jack to the specimen.

Columns in real construction applications, will undergo similar situation in case that the surrounding temperature is raised. The results showed that the gravel specimen subjected to 650°C failed before completing the minimum specified time exposure (30min). The longest exposure duration was 20min. Dolomite concrete specimens completed exposure duration of 30min, and 60min but it did not sustain for 180min. Basalt sustained 650°C for exposure periods up to 180min. All specimens subjected to elevated temperature failed by excessive cracking near the specimen's ends that led to cover spalling then buckling of main reinforcement. Gravel and dolomite concrete specimens failed in similar pattern, whereas the basalt failed in a more violent and sudden pattern. (Abdelrazek, M. and et al, 2001).

The great disadvantage of this method of testing the fire resistance is that designers must accurately follow every essential detail in the tested assemblies for the fire resistance ratings to be applicable in actual construction. Any change in the design requires testing of a new specimen or a detailed engineering evaluation to show that the effect of the modification won't be detrimental of the fire resistance rating of the assembly (Lie, T.T. , 1977).

2.6.2 Design Approach

Empirical equations presenting correlatins of fire resistance test results with important design parameters started to emerge in the late 1960's when test results were sufficient enough and more available to quantify the effects of critical temperatures. Some of the equations were based on theoretical predictions, which were validated by test results.

There are important aspects that need to be taken into consideration while using empirical equations and they are as follows:

- The scope of the database used to validate the empirical relationships.
- The level of confidence in the calculated results.
- The applicability of the established relationships to the specific materials and products used in actual construction.

As for the use of empirical equations, a small database will limit the importance of such equations, as only a limited range of design parameter values will be available to the designer. Applying the equations to design conditions outside the tested range (extrapolation),shouldn't be used unless a complete fire engineering evaluation is performed. To have a thorough and complete level of confidence to use such equations, the number of test results used in the establishment of the empirical relationship should be enough, i.e. ten or twenty results rather than three or four. Care should be taken to ensure that the proposed construction materials, such as the sprayed-on material for protecting a member, are similar to those tested in all conditions such as adhesion, resistance to cracking, or spalling and thermal conductivity. (Gosselin Guy. C., 1987)

Some of these equations for reinforced concrete columns are: (Lie,T.T., and D.E. Allen, 1972):

R
=(t/75f) -1... lightweight concrete; rectangular column..............................(2.3)

=(d/90f) -1... lightweight concrete; round column......................................(2.4)

=(t/l00f) -1... normal weight concrete; rectangular column............................(2.5)

=(d/120f) -1... normal weight concrete; roundcolumn.................................(2.6)

Provided c

= 25 R if R $\leq$ 2hours... ....(2.7)

= 25 + 12.5 R if R $\geq$ 2 hours..(2.8)

Where,

R =fire resistance rating, in hours,

t = smaller dimension of rectangular column, in millimeters

d = diameter of round column, in millimeters,

f = load factor

k = effective length factor

L = unsupported column length, in meters,

P = area of vertical steel reinforcement as a percentage of column area,

c = minimum thickness of concrete cover over vertical steel reinforcement, in millimeters.

These equations takes into account seven design parameters: the size and shape of the column, its effective length, the type of concrete, the percentage of steel reinforcement, the thickness of concrete cover over the steel reinforcement and the degree of over design. The effective length of the column affects fire resistance as 'short' columns fail by crushing of the concrete (compressive failure), whereas longer columns fail by lateral buckling, and different mechanical properties govern each mode of failure. The type of aggregate used in lightweight concrete (e.g., expanded clay, shale or slag) is better in fire resistance to that used in normal weight concrete under elevated temperatures. As a result, lightweight concrete retains more of its strength and has a lower coefficient of thermal conductivity. Experiments showed that columns with heavy steel reinforcement (P greater than 3%) are more stable upon exposure to fire. Also, the thickness of the concrete cover controls the rate at which heat enters into the steel reinforcement. (Gosselin, Guy.C., 1987). Another more general approach was performed by T.T. Lie, 1979. He stated that to predict the fire behavior of the structural member, assessment of various parameters should be performed. Such parameters are: fire temperature, and the strength of the member. Figure 2.14 below summarizes the steps to be taken to determine the fire resistance of a member.

Step 1, determine the fire load: fire load is " the combustible contents on which fire resistance design of the building should be based". Several studies have been performed to determine the fire load of in buildings.

Step 2, determine fire temperature: it can be calculated from a heat balance for the compartment taking into account the heat produced and heat lost to the walls and openings. The most significant factor is the fire load and the dimension of the opening through where air required for combustion of fire load can pass through. Figure 2.15 illustrates how fire load affects the temperature, and. The influence of the opening is illustrated in Figure 2.16. From the Figures, it is shown that the fire load determines the duration of the fire, whereas the openings affect both the intensity and the duration. Thus, from such analysis, a temperature of the fire can be determined for a given building.

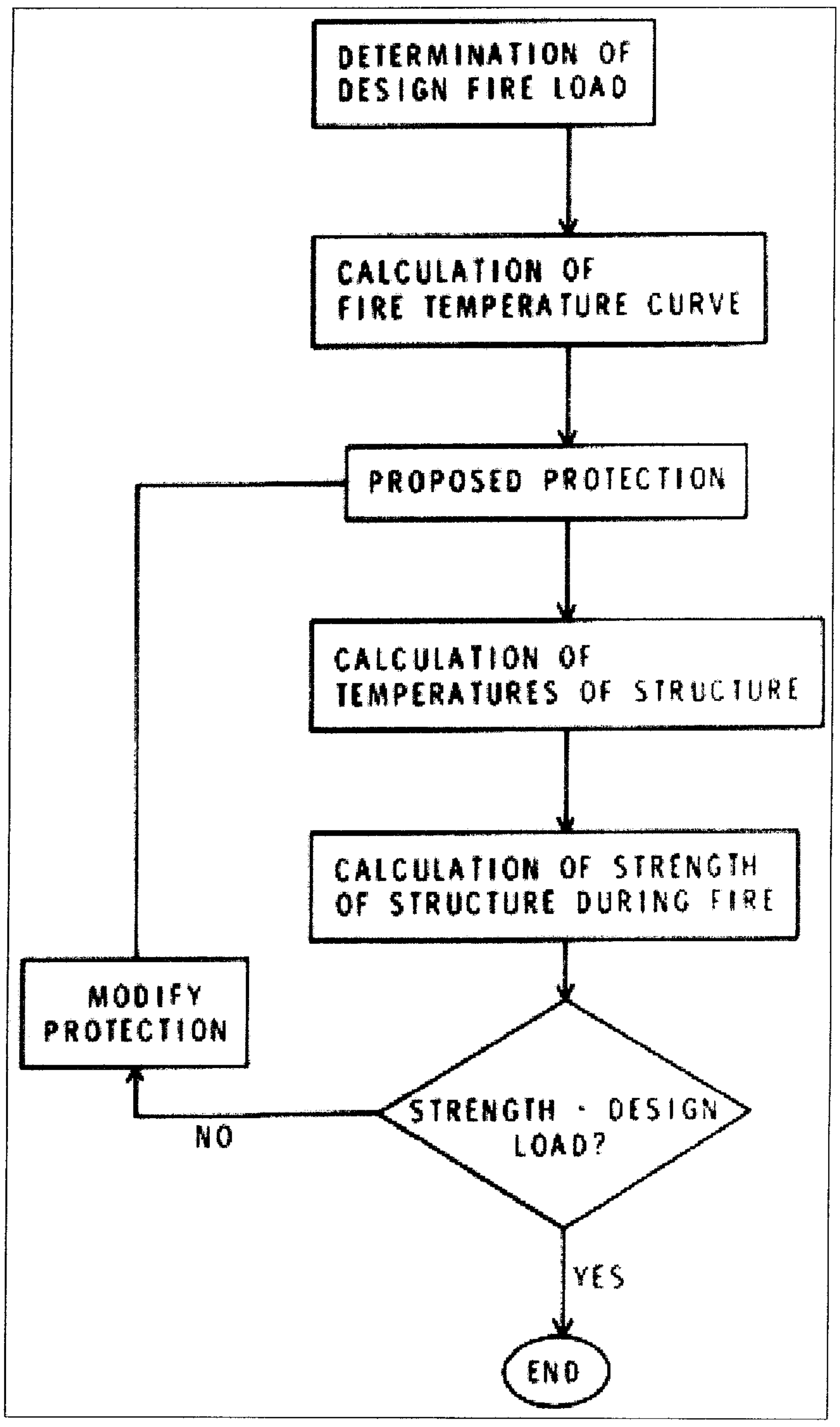

Figure 2.14- Calculation Procedures for Fire Resistance Design (T.T. Lie, 1979)

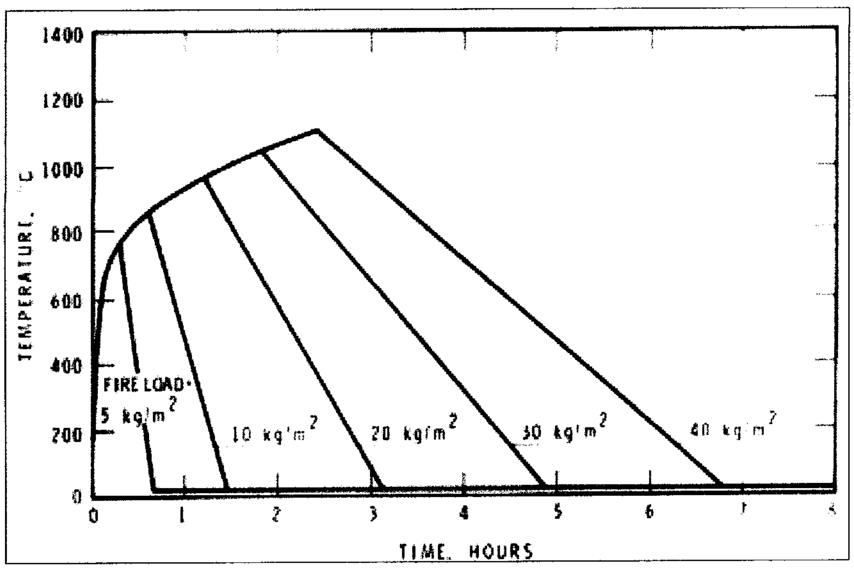

Figure 2.15- Influence of Fire Load on Fire Temperature Course (T.T. Lie, 1979)

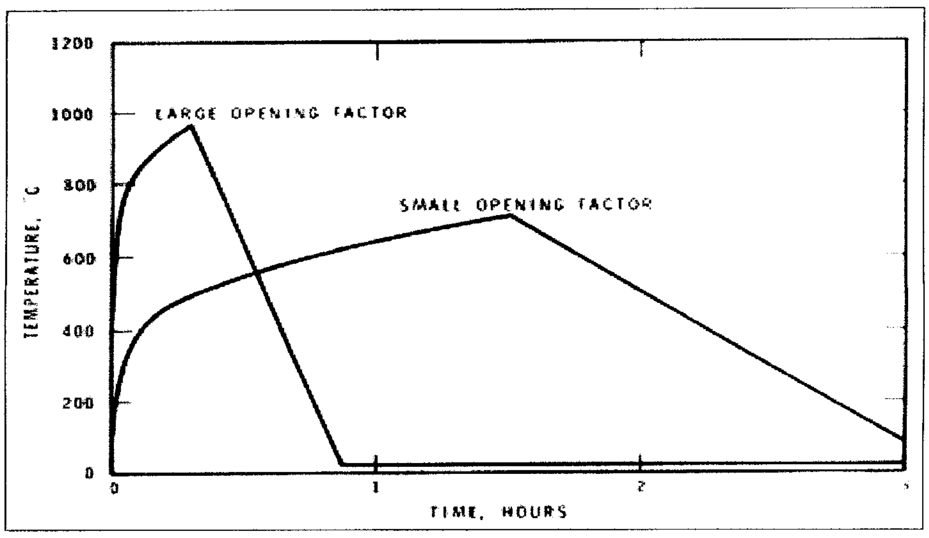

Figure 2.16- Influence of Opening Factor on Fire Temperature Course (T.T. Lie, 1979)

Step 3, determine temperature of the member: heat mostly transferred to the element by radiation. Within the fire exposed surface, the temperature distribution inside the member is known by finite difference method, in which the member's cross section is divided into a number of regions, which may have different shapes such as, square, triangles or layers depending on the geometry of the member.

Step 4, determine strength of the member: as the temperature increases in the fire exposed surface, its strength decreases. If the fire load is enough and the duration of the fire extended to a long time, the member can no longer be able to support the structural load. The fire load that is just sufficient to reduce the strength to this critical point is defined as the critical fire load. The goal of any experiment in such an area is to make the critical fire load for a member high enough to allow it to sustain burn out of the design fire load. This can be performed by selecting the appropriate plaster materials of an adequate thickness. and appropriate dimension of a member (T.T. Lie, 1979).

2.6.3 Theoretical Design Approach:

Recently, researches has been carried out to develop analytical methods for calculating the fire resistance of structural elements and assemblies Procedures are being validated against fire resistance test results for reinforced concrete columns, and floor slabs, and columns protected externally with sprayed-on inorganic materials.

Most calculation steps are limited to relatively simple design cases such as concentric loads, Pinned ends, or statically determinant structures, but experimental work is underway to widen the experience to include fixed or partially fixed ends or eccentric loading for example. (Harmathy, T.Z., 1983).

Most of the rational design methods composed of applying the usual structural mechanics design principles with due consideration assigned to the impact of elevated temperatures on the thermal and mechanical properties of the primary construction materials. Thus, designing for fire resistance depend mainly on three components;

- The nature of the fire severity,
- Heat transmission to the building element
- Evaluation of the strength and deformation characteristics of the structure

Further data on the thermal and mechanical properties of other materials can be obtained, but generally, the database is incomplete. As more studies and experiments are carried out for elevated temperature measurements made for different construction materials, the full advantages of this design approach will obtain more significance in practice. (Harmathy, T.Z., 1983).

2.7 Reduced Scale Reinforced Concrete Subjected to Fire:

Full-scale tests are expensive and require vast resources that are available at major accredited universities. Upon the performance of fire testing on reduced scale structural models, all significant thermo-structural responses have to be taken in consideration. Several researches have been done on fire resistance scale modeling. McGuire, Stanzak and Law, 1975 developed a theoretical fire resistance scaling concept to analyze fire resistance of a structural element. They conducted a thorough experimental investigation on the scaling of various small scale concrete encased steel columns to determine their fire resistance for temperature up to 1100°C. Their experiments revealed that fire resistance beside being simple, did not require knowledge of thermal properties of the materials involved (McGuire, J.H. and et al., 1975). In 1990 Ah Book, M Saed Mirza, and T.T. Lie carried out experiments on small scale models of square reinforced columns exposed to fire and predicted their fire resistance using small scale of 1/2.23 and 1/3.0 models. They used dimensional analysis to represent the variables involved in thermal modeling, the length scale factor S_l which is defined as:

$S_l = l_p/l_m$..(2. 9)

Where:

S_l = scale Factor

l_m = characteristic length of the model = area of the model / parameter of the model exposed to fire

l_p = characteristic length of the prototype = area of the prototype / parameter of the prototype exposed to fire

Where (p) and (m) represents the prototype and the model used. Based on thermal modeling principles they treated two or more physical properties such as thermal diffusivity (α=K/Cρ) where K is the thermal conductivity, C is the specific heat and ρ is the density). Also, they used a temperature scale factor S_θ of a value of 1, which means that in true thermal modeling process, the scaled temperature characteristics, the model thermal stresses and strains will be identical to those in the prototype, and where S_θ is given by:

$S_\theta = (\theta_p / \theta_m)$..(2.10)

Where:

S_θ = temperature scale factor

θ_p = prototyope temperature profile

θ_m = model temperature profile

The rate of fire exposure intensity, which is the variation of temperature of a fire with time, is governed by time scale factor S_t given by:

$S_t = (t_p / t_m) = (S^2_l / S_\alpha)$..(2.11)

Thus, $t_m = (S_\alpha / S^2_l) * (t_p)$..(2.12)

Where:

S_t = time scale factor

t_p = Fire resistance time of the prototype

t_m = Fire resistance time of the model

S_α = Diffusivity scale factor

Studies have shown that the yield and ultimate strengths of the model reinforcement should be close to the yield and ultimate strengths of the prototype reinforcement (Mosalamay, 2002).

Upon fire testing, conducted fire tests should be controlled by the standard time temperature curve of ASTM E-119 shown in Figure 2. 11. If the furnace does not exactly follow the same time temperature profile, ASTM suggested a correction factor, that is developed from the fire load density. It is based on an assumption that the fire resistance of the structure depends mainly on the fire severity. The correction factor is calculated as follows:

$C = 2I (A - A_s) / 3 (A_s + L)$..(2.13)

Where:

C = correction in the same units as I

I = indicated fire resistance period

A = area under the curve for indicated average furnace temperature for the first three fourths of the indicated period

A_s = area under the standard furnace curve for the same part of the indicated period

L = lag correction in the same units as A and A_s {30°C/hr (1800°C/min)}.

If the model furnace time temperature curve is higher than the standard then the calculated resistance period is increased by the amount C and vise versa. Therefore the final fire resistance time of the prototype after correction would be :

$t_m = (S_\alpha / S^2_l) * (t_p)$..(2.14)

$t_p = (S^2_l / S_\alpha)\ t_m +/- (C)$...(2.15)

D.J. O' Connor and Silcock, 1992 performed several studies for the testing of reduced scale structural model. They considered that is essential that both the model and the prototype fire curves have similar temperature inputs, and also suggesting that the equivalent model fire curve must retain a temperature axis same as that of the standard fire curve applied to prototype, thus scaling effect applies only to the time axis. Their studies, based on Buckingham Pi theorem, show that the relation between the model and the prototype fire resistance is as follows:

$t_m = (L_m)^2 / (L_p)^2 * (t_p)$..(2.16)

$t_m = (S)^2 * (t_p)$..(2.17)

$S = L_m / L_p$..(2.18)

2.8 Effective Fire Protective Plasters:

2.8.1 Perlite as Fire Retardant

The demand for protecting structural members from direct attack by flame and maintain the temperature of the load bearing members below the critical point, at which weakening or failure is likely to occur, results in the need for fire protection. Repeated tests have demonstrated that Perlite-gypsum and Perlite- Portland cement plaster are exceptionally effective in blocking flames and retarding the transmission of heat due to:

- The countless air cells in Perlite aggregate make it an excellent insulation. Perlite plasters offers up to 4-6 times more resistance to heat transmission than ordinary sand plaster.
- Perlite-gypsum and Perlite-Portland cement weighs about 60 % less than ordinary sanded plaster.
- When exposed to fire Perlite plaster releases chemically combined water in the form of vapor, which maintains the plaster temperature at about 100°C, until all of the water has been driven off as steam.
- Perlite plaster has low linear thermal expansion compared with sand plaster at high temperatures, which greatly reduces the number and size of cracks, which permit heat and flame to penetrate through the plaster barrier.

Typical mix design is suggested in Table 2.5. The mix is considered as a guide to the application, but minor adjustment in proportions may be required depending upon specific brands of materials and spray guns used. Adequate quality control on the job can be assured by enforcing density and strength requirements.
(http://www.schundler.com/).

Table 2.5- Mix Design for Perlite (http://www.schundler.com/)

Mix Proportions					Thermal and Mechanical Properties		
Cement (kg)	Perlite (L)	Water (L)	AEA (g)	Fiber (g)	Density (kg/m^3)	Compressive strength (kg/m^3)	Thermal Conductivity (W/mk)
50	100	34	100	600	1100 -1200	130-140	0.04

AEA= Air Entrained Admixture

2.8.2 Vermiculite as Fire Retardant:

Vermiculite plasters consist of a blend of expanded vermiculite aggregates with either neat gypsum or Portland cement. When properly mixed with water they can be applied to walls and/or ceiling surfaces for fireproofing.

Vermiculite plasters has 4 times more resistant to heat transmission than sand plaster. Thus permits savings in heating and air conditioning costs and conserves energy.

It is as well fire Retardant /Non-combustible and non-toxic as it provides up to 5-hour fire protection with minimum weight and thickness

It provides protection for columns, partitions, and the undersides of floors and roof assemblies. This protection can be applied with either rough finishes, or in attractive, durable. When exposed to fire, vermiculite plasters release chemically combined water in the form of water vapor, which helps maintain the plaster temperature to below 100°C until all of the water has been driven off as steam. Meanwhile, the insulating action of the vermiculite aggregates delays the release of steam and retards the transmission of heat, thus improving overall fireproofing characteristics.

Unlike ordinary sand plaster which can expand and "explode" during fires and/or when subjected to high temperatures, vermiculite plasters has low linear expansion characteristics which highly reduce the number and size of cracks. By reducing the number and size of cracks through the plaster, the heat and flames of a fire cannot penetrate the plaster surface as easily or quickly (http://www.shcundler.com/, and http://www.vermiculite.org/)

2.8.3 Rock wool as Fire Retardant

Rock wool is made of stone and thus cannot burn. Rock wool resists temperatures higher than 1000°C as shown in Figure 2.18. It can act as a fire barrier, which obstructs the spread of the fire and provides valuable extra minutes to save people, property and reduce the environmental damage (.http://www.rockwool.com/).

Rock wool is an insulation material, light in weight, made up of intermingled vitreous fibers composed of complex silicates. It is available in various forms like Loose Wool, Preformed Mattresses, Slabs and Pipe Sections bonded with thermosetting resin conforming to IS, ASTM, BS, JIS, DIN standards. All the forms of Rock Wool are incombustible, fire retardant, moisture resistant, chemically inert, neither cause nor accelerate corrosion, durable, colorless, friendly to handle and easy to apply. Also it resists the spread of flame to any material which it covers (http://www.minwool.com/)

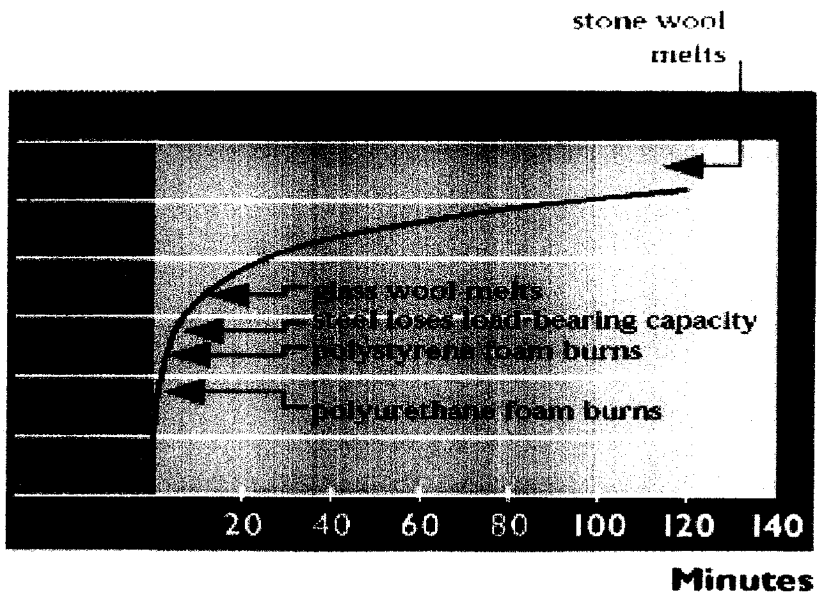

Figure 2.17- Standard Fire Curve (ISO 834) (http://www.rockwool.com/)

CHAPTER III

EXPERIMENTAL WORK

3.1 Introduction:

The experimental work herein is carried out to investigate the effect of plastering materials on the fire resistance of reinforced concrete columns. This involves 72 columns of 3 different dimensions 100x100x1000 mm, 100x200x1000 mm and 100x300x1000 mm. The columns are plastered with four different materials namely; Perlite, Vermiculite, Rock wool and Cement plaster. The thickness of the plastering layer is 15, 25 and 35 mm. The columns are subjected to fire following the ASTM-E119 standard to evaluate their resistance in terms of time. The columns are then loaded to determine the percent loss in strength after the fire

3.2 Materials Characteristics:

Materials used in the experimental work were obtained from local Egyptian sources and are commonly used in most of the construction works in Egypt.

3.2.1 Aggregates:

The aggregates used in this study were natural gravel as coarse aggregates and sand as fine aggregates.

3.2.2 Aggregates Testing:

Sieve Analysis:

This test method was performed according to ASTM C136-92. The maximum nominal aggregate size was 25mm for the gravel. Typical results for the fine and coarse aggregate are presented in Table 3.1 and 3.2.

Table 3.1- Gradation Table for the Fine Aggregate Used

Sieve Size (mm)	% Retained Cumulative	% Passing Cumulative
4.75	0.2	99.9
2.36	0.9	99.1
0.6	11.1	88.9
0.3	84.3	45.7
0.09	96.5	3.5
0.075	99.9	0.1
Pan	100.0	0.0

Table 3.2- Gradation Table for the Coarse Aggregate Used

Sieve Size (mm)	% Retained Cumulative	% Passing Cumulative
37.5	0.0	100.0
25	0.0	100.0
19	11.02	88.98
12.5	48.01	51.99
9.51	85.24	14.76
4.75	99.35	0.65
Pan	0.0	0.0

Specific Gravity (SSD) and Absorption of Aggregates

Bulk Specific gravity based on saturated surface dry (SSD) and Absorption were carried out on coarse and fine aggregates according to ASTM designation ASTM designation C 127-88 and C 128-93 respectively. The calculated specific gravity was 2.71 and 2.61 for the coarse and fine aggregates respectively.

The percent of absorption showed that absorption was 0.6% for the coarse aggregates and 1.14 % for the fine aggregates.

Total Moisture content of Aggregates:

This test method was performed according to ASTM designation C566-89.The moisture content was found to be 0.1% for the coarse aggregates and 1.30% for the fine aggregates.

Unit weight of Aggregates:

The unit weight was determined for both coarse and fine aggregates and was found to be 1732 kg/m^3 for the coarse aggregates and 1304 kg/m^3 for the fine aggregates.

3.2.3 Cement:

Ordinary Portland cement (OPC) Type I complying with ASTM designation C150 was used. Table 3.3 provides typical results of standard testing of the cement used, which were obtained both at the start and towards the end of the experimental work.

Table 3.3- Typical Results of Standard Testing of the Cement Used

Test	Test Standard Specification	Property	Results		ASTM C 150 Limits for Type I
			At start of Work	Towards End of Work	
Cement Fineness (Blaine)	ASTM C 204	Fineness	304 m^2/kg	285.6 m^2/kg	280 m^2/kg
Density	ASTM C 188	Density	3140 kg/m^3	3150 kg/m^3	---
Normal Consistency	ASTM C 187	Appropriate amount of water for paste	27.5%	23.7%	---
Setting Time	ASTM C 191	Initial Setting	3 hrs 25 mins	1hr 40 mins	$\geq$ 45 mins
		Final Setting	4 hrs 52 mins	2 hrs 40 mins	$\leq$ 375 mins
Compressive Strength of cement Mortar	BS 4550	3.day	24.2 MPA	20.1 MPA	12.4 MPA
		7-day	32.5 MPA	27.4MPA	19.3 MPA

3.2.4 Steel Reinforcement and Ties:

Ordinary mild steel with yield strength of 240 MPA was used. The diameters of the bars vary according to the size of the column, but were mainly 6 and 8 mm.

3.2.5 Wire Mesh:

A square galvanized wire mesh 20 x 20 mm complying with British Standards 1369 Part 1 and BSEN 10142 with density ≥ 1.61 kg/m^2 was fixed around the columns by wire of ϕ1mm.

3.2.6 Thermocouple:

Type J, resists fire up to 1000°C, and calibrated according to ASTM standards

3.2.7 Air Entrained Admixture:

Master Builders Micro-Air 100, an ASTM C-260 air-entraining admixture was used. This product is a brown liquid of a specific gravity of 0.9886 and pH of 10.5-12.5. This product creates stable air bubbles that are strong, small and closely spaced, thus decreasing the thermal conductivity of the paste.

3.2.8 Glass Fiber:

Master Builders FIBERS 012 alkali resistance chopped strand fiber produced from 100% coated fiberglass was used. This product is 17 micron in diameter, 12 mm in length, and characterized by its low thermal conductivity. The manufacturer suggests a dosage of 0.5 kg of fibers for every 50 kg of cement.

It provides high assurance against cracking, and minimizes shrinkage in concrete upon heating.

3.2.9 Perlite

Perlite is not a trade name but a generic term for naturally occurring siliceous volcanic rock. Its components are summarized in Table 3.2.When Perlite is heated it expand 4 to 20 times of its original volume. This expansion is due to the presence of 2-6 % of combined water in the core Perlite rock. When quickly heated to above 8700°C the crude rock pops in a manner similar to popcorn. This occurs as the combined water vapor creates countless tiny bubbles in the glass - sealed bubbles, which account for the excellent insulating properties and lightweight concrete. It is classified as chemically inert and has a pH of approximately 7. Table 3.4 shows the physical properties of the Perlite. (http://www.perlite.org/, http://www.schundler.com/)

Table 3.4- Properties of Perlite (http://www.schundler.com/)

Typical Elemental Analysis		**Typical physical Properties**	
Component	Percentage %	Property	Observation
Silicon	33.8	Color	White
Aluminum	7.2	Refractive Index	1.5
Potassium	3.5	Free Moisture, Max.	0.5%
Sodium	3.4	pH	6.5-8.0
Iron	0.6	Specific Gravity	2.2-2.4
Calcium	0.6	Bulk Density	32-40 kg/m^3
Magnesium	0.2	Softening Point	871-1093 °C
Trace	0.2	Fusion Point	1260-1343 °C
Oxygen (by deference)	47.5	Specific Heat	837 J/ kg k
Bound Water	3.0	Thermal Conductivity At 24° C	.04-.06 W/m.k

Thermal and Mechanical Properties of Perlite:

Perlite gives excellent insulating properties at temperature varying from very low to very high. For example, Perlite is one of the best known insulation for manufacture and storage of liquid gases such as Oxygen at temperature as low as (-240 °C. At high temperatures, Perlite begins to soften at about 982 ° C, while fusion of the particles at the exposed surface begins at about 1260 °C. The thermal properties of Perlite are stable for long time and not affected by environment.

The following materials were selected for the Perlite mix:

- Portland Cement type I accordance with ASTM standards C-150
- Perlite Aggregate conforming to the requirements of ASTM Designation C-35

Perlite is available in Egypt for 30 L.E/10 liters.

3.2.10 Vermiculite

Vermiculite is a member of the phyllosilicate group of minerals, resembling mica in appearance as shown in Fig3.1. Vermiculite has a remarkable ability to expand many times its original volume when, heated, a property known as exfoliation. (http://www.schundler.com/)

Figure 3.1- Vermiculite: Unexpanded, Expanded and a Single Particle (http://www.schundler.com/)

The typical sizes, densities and is shown in Table 3.5, The typical chemical formula for Vermiculite is: $\mathbf{(Mg,Ca,K,Fe^{11})_3(Si,AL,Fe^{111})_4O_{10}(OH)_2O4H_2O}$

The typical chemical analysis and physical properties of Vermiculite are summarized in Table 3.6.

Table 3.5- Typical sizes, densities and names of expanded Vermiculite (http://www.schundler.com/)

Sizes (mm)	Densities (kg/m^3)	Size or Grade	
		U.S. System	International
16	56-72	N/A	Premium (6)
8	64-85	1	Large (4)
4	72-90	2	Medium (3)
2	75-112	3	Fine (2)
1	80-144	4	Super Fine (1)
0.5	90-160	5	Micron (0)

Table 3.6- Properties of Vermiculite (http://www.schundler.com/)

Typical Chemical Analysis		Typical physical Properties	
Component	**Percentage**	**Property**	**Observation**
SiO_2	38-46	Color	Gold-Brown
AL_2O_3	10-16	Free Moisture, Maximum	0.50%
MgO	16-35	pH (of water slurry)	7.0-9.5
CaO	1-6	Specific Gravity	2.5
K_2O	6-13	Expanded Bulk Density (normal)	4-10 lb/ft^3
Fe_2O_3	1-3	Mesh Sizes (normal)	2-40 mesh and finer
TiO_2	8-16	Fusion Point	2200-2400F
H_2O	0.2-1.2	Specific Heat	1.08 kJ/kg.k
Other	1-6	Thermal Conductivity	0.27-0.41 $BTU.in/h.ft^2.F$

The following materials were selected for the Vermiculite mix:

- Portland Cement type I in accordance with ASTM standards C-150.
- Vermiculite in accordance with ASTM standard C-332 Group 1.

Vermiculite is available in Egypt for 8 L.E/10 liters

3.2.11 Rock Wool

Rock wool is a mineral wool used as thermo-acoustic insulation and fireproof purposes. It is produced from volcanic Rock "Basaltic Type" according to the international standards. It has the following characteristics:

- Low thermal conductivity.
- Can withstand high temperature exceeds 750 °C and fireproof.
- It is non-combustible, non-aging and water repellent.
- It is inorganic and vermin proof.
- It is free of sulfates and chlorides, thus it is non-corrosive.

Rock Wool is produced in five types namely; Loose Rock Wool as shown in Figure 3.2, Rock Wool Panels "Slabs", Rock Wool Felt, Rock Wool Quilted Mattes, and Rock Wool preformed pipe section. (http://www.jordan rock wool.com/)

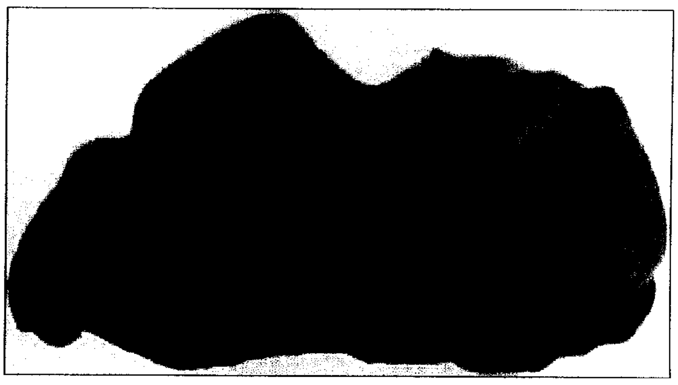

Figure 3.2- Loose Rock Wool (http://www.jordan rock wool.com/)

Loose Rock Wool (RWL)

Technical Specifications:

Loose Rock Wool is the basic product which is used directly as is, long or short (carded) fibers, or to produce the other RW. products. Table 3.7 illustrates the chemical composition and the physical properties of loose rock wool

Table 3.7- Chemical Composition and physical properties of rock wool (http://www.jordan rock wool.com/)

Chemical Composition		**Physical Properties**	
Component	Percentage	Property	Observation
SiO_2	43.54 %	Diameter of Fibers	5-25 Microns
Al_2O_3	15.01 %	Length of fibers	20-200 mm
Fe_2O_3	10.82 %	Water content	0 %
CaO	11.82 %	Loss on ignition	0 %
MgO	4.51 %		
Na_2O	0.14 %		
K_2O	0.00 %		

Thermal Properties:

Loose Rock Wool is used for thermo-acoustic insulation and fire proof in filling irregular cavities, such as Furnaces and Vehicle Exhausts .... etc. Rock Wool is a non-combustible material and can withstand high temperatures; therefore it is used as a thermal insulation and fireproof material. The following

Table, Table 3.8, shows the combustibility and fire rate of rock wool (www.jordan rock wool.com)

Table 3.8- Combustibility and Fire Rate (http://www.jordan rock wool.com/)

R.W Type	Period of subjecting to flame	Results
Mattes with wire mesh	30 min	Mattes did not propagate or catch flame
Mattes	3 Hours	Same as above

The following materials were selected for the Rock wool mix:

- Portland Cement type I in accordance with ASTM standards C-150.
- Rock wool in accordance with ASTM C 764.

Rock wool is available in Egypt for 5 L.E/10 liters

3.3 Preparations of the Test Specimens:

A total of 72 reinforced concrete column specimens were cast, plastered, and tested. All columns are 1000mm long. Columns cross-section, reinforcement, type and thickness of the protective plaster were varied to achieve the work objective.

The mix design of the concrete is shown in Table 3.9. w/c ratio was 0.5 for all mixes. Table 3.10 shows the mix design for Perlite, Vermiculite, Rock wool, and cement plaster respectively.

Table 3.9- Summary of Mix batch by Weight for One Cubic Meter of Concrete

Concrete (m^3)	Cement (kg)	Water (L)	Coarse Aggregates (kg)	Fine Aggregates. (kg)
1	380	190	1150	640

Table 3.10- Mix Designs of Plasters Applied for One Cubic Meter of Plaster Applied

Plaster Type	Cement (kg)	Water (L)	Fiber (g)	Air Entrained Admixture (L)	Fine Aggregates. (kg)
Perlite	450	250	600	3	-
Vermiculite	450	392	600	3	-
Rock wool	450	250	600	3	-
Cement plaster	534.4	213.76	-	-	1603.2

Test specimens were prepared, cast and instrumented in the following sequence:

1. Forms and steel reinforcement were designed according to the Egyptian Code of Concrete and prepared as shown in Table 3.9
2. A supplementary thermocouples was fixed exactly at the center of the column before pouring as shown in Figure 3.3

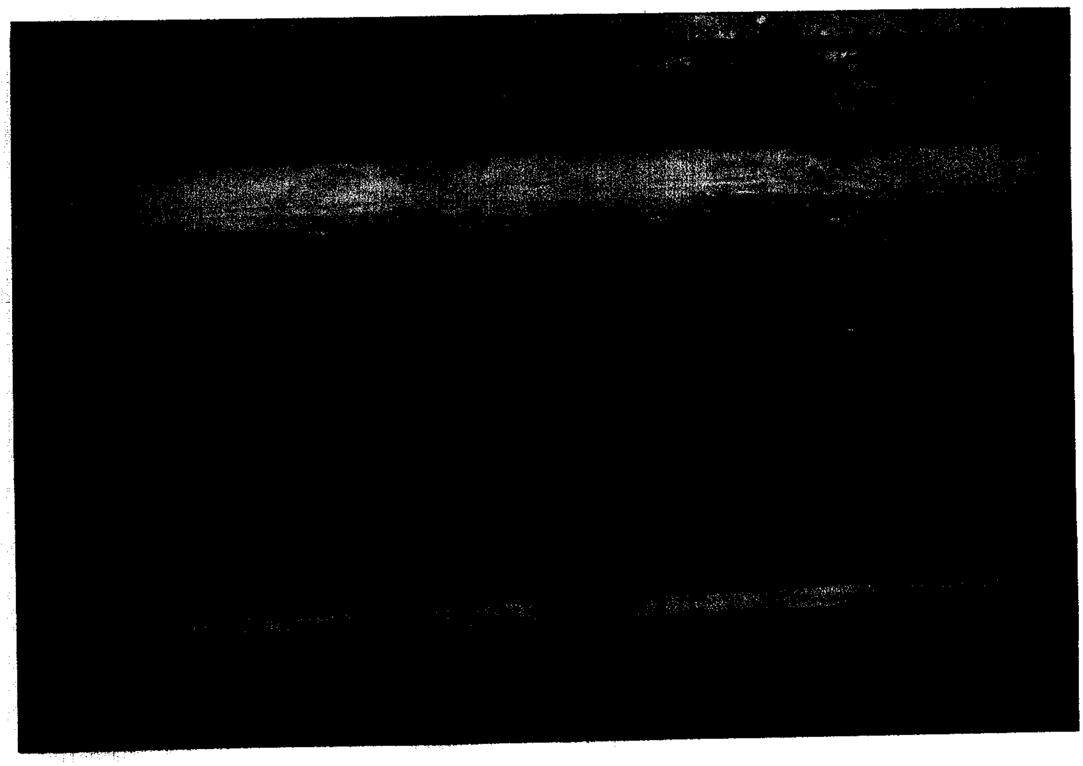

Figure 3.3- Installation of Thermocouple at the Middle of the Column Before Casting

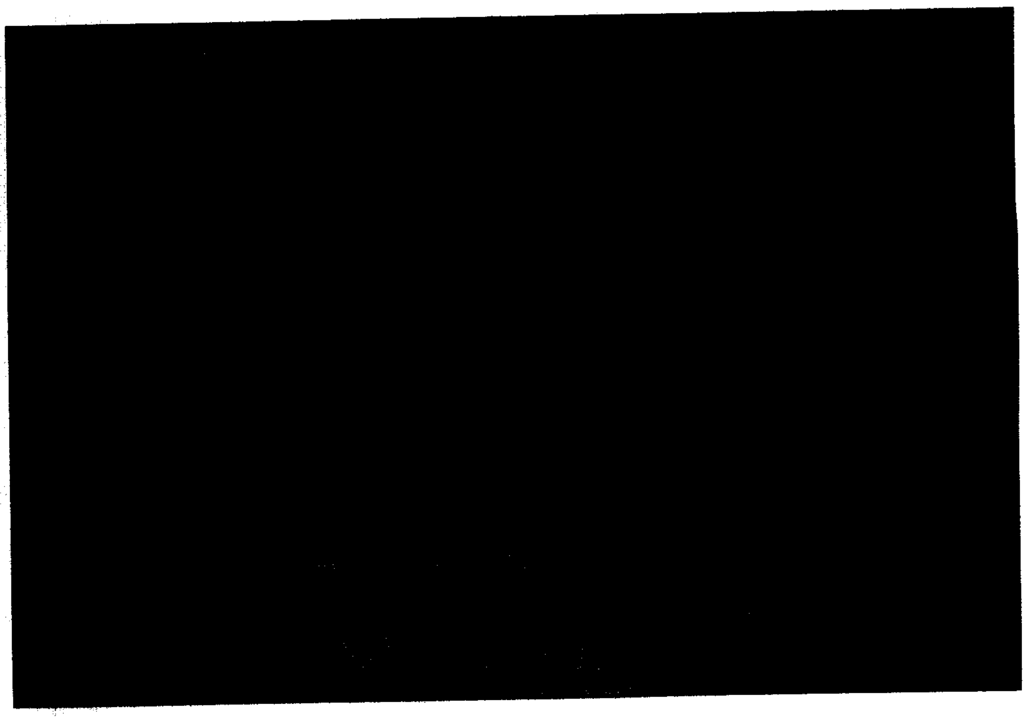

Figure 3.4- Thermocouples After Pouring Concrete

3. Columns were poured in three dimensions as shown in Tables 3.9 and 3.10. Figure 3.5 shows the longitudinal and cross section of the column, and the plaster thickness for each

Table 3.11- Column Sizes and Plaster Thickness

Columns dimension (mm)	100x100x1000			100x200x1000			100x300x1000		
Reinforcement	4Φ 6			4 Φ 8			6 Φ 8		
Design Load (ton)	12.5			24.5			36		
Plaster Thickness (mm)	15	25	35	15	25	35	15	25	35
	Number of Tested Columns								
Perlite Plaster	2	2	2	2	2	2	2	2	2
Vermiculite Plaster	2	2	2	2	2	2	2	2	2
Rock Wool Plaster	2	2	2	2	2	2	2	2	2
Conventional Cement Plaster	2	2	2	2	2	2	2	2	2

Table 3.12- Columns Identification

No.	**ID**	**Plaster Material**	**Column Size (mm x mm)**	**Plaster Thickness(mm)**
1	CP10015	Perlite	100x100	15
2	CP10025	Perlite	100x100	25
3	CP10035	Perlite	100x100	35
4	CP20015	Perlite	100x200	15
5	CP20025	Perlite	100x200	25
6	CP20035	Perlite	100x200	35
7	CP30015	Perlite	100x300	15
8	CP30025	Perlite	100x300	25
9	CP30035	Perlite	100x300	35

10	CV10015	Vermiculite	100x100	15
11	CV10025	Vermiculite	100x100	25
12	CV10035	Vermiculite	100x100	35
13	CV20015	Vermiculite	100x200	15
14	CV20025	Vermiculite	100x200	25
15	CV20035	Vermiculite	100x200	35
16	CV30015	Vermiculite	100x300	15
17	CV30025	Vermiculite	100x300	25
18	CV30035	Vermiculite	100x300	35
19	CR10015	Rock Wool	100x100	15
20	CR10025	Rock Wool	100x100	25
21	CR10035	Rock Wool	100x100	35
22	CR20015	Rock Wool	100x200	15
23	CR20025	Rock Wool	100x200	25
24	CR20035	Rock Wool	100x200	35
25	CR30015	Rock Wool	100x300	15
26	CR30025	Rock Wool	100x300	25
27	CR30035	Rock Wool	100x300	35
28	CC10015	Concrete	100x100	15
29	CC10025	Concrete	100X100	25
30	CC10035	Concrete	100x100	35
31	CC20015	Concrete	100x200	15
32	CC20025	Concrete	100x200	25
33	CC20035	Concrete	100x200	35
34	CC30015	Concrete	100x300	15
35	CC30025	Concrete	100x300	25
36	CC30035	Concrete	100x300	35

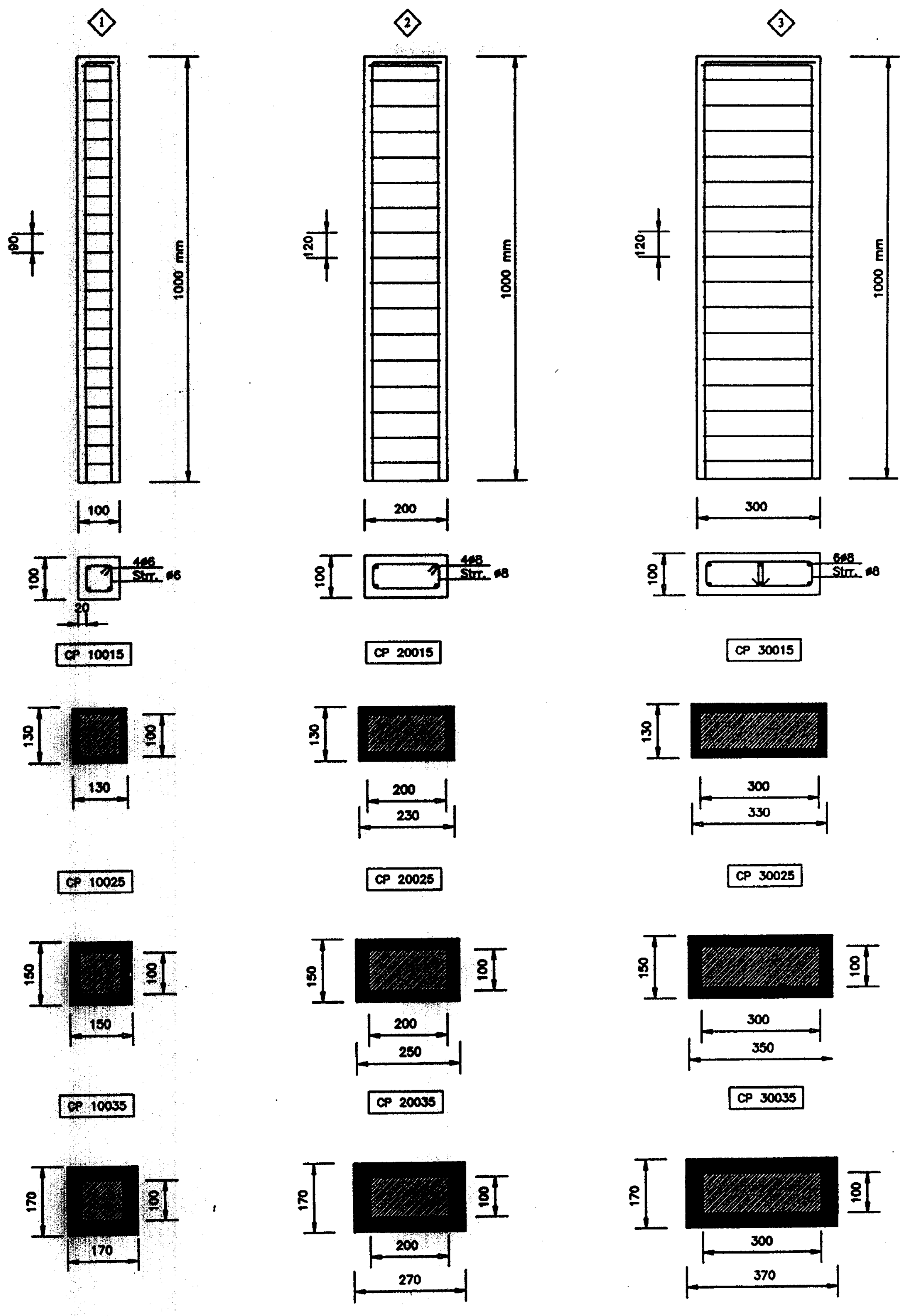

Figure 3.5- Longitudinal and Transverse Cross-Section of the Columns, and the Coat Thickness on Each Column Dimension

4. After columns were cured for 56 days, surface preparation was performed to allow the plaster materials to be homogeneous with the columns as shown in Figure 3.6.

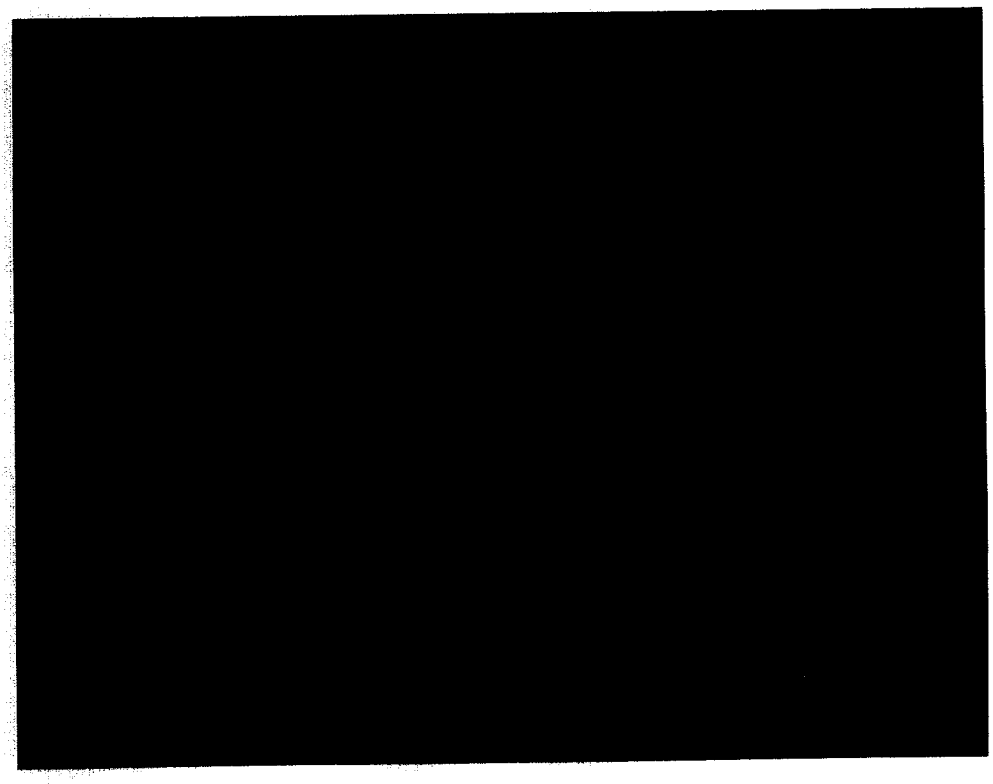

Figure 3.6- Surface preparation of the columns

4. The second thermocouple was fixed on the surface of the concrete columns.
5. Columns were wrapped tightly with a wire mesh of dimensions 20 x 20mm as shown in Figure 3.7.

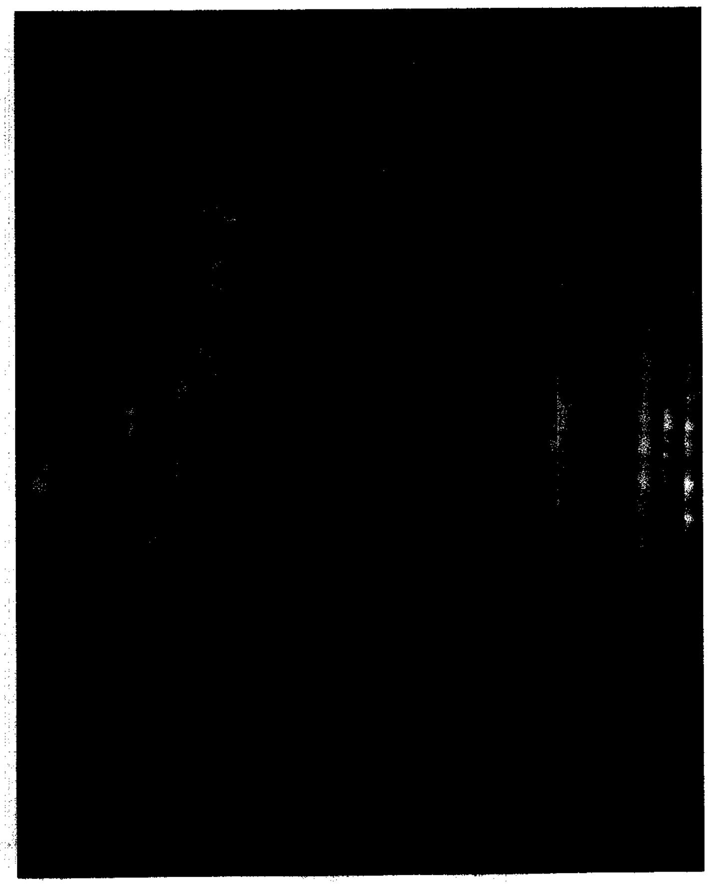

Figure 3.7- Wire mesh Around Column

6. **Plasters were applied manually, with mix designs according to** Table 3.8 in three different thicknesses as shown in Tables 3.9

7. The plaster was applied only on one surface at a time to make sure that accurate thickness of plaster was applied as shown in Figures 3.8, and3.9.

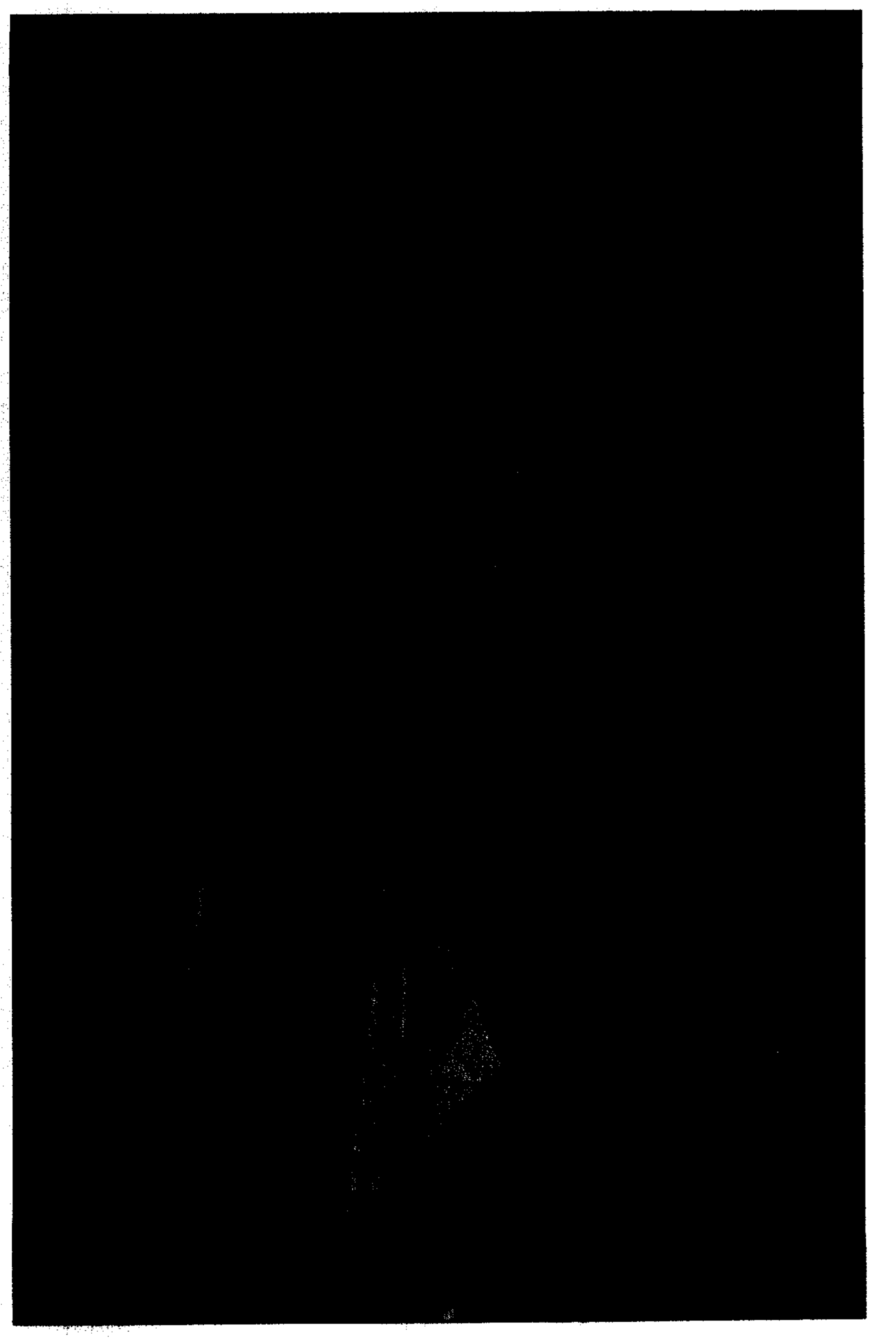

Figure 3.8- Plasters Application

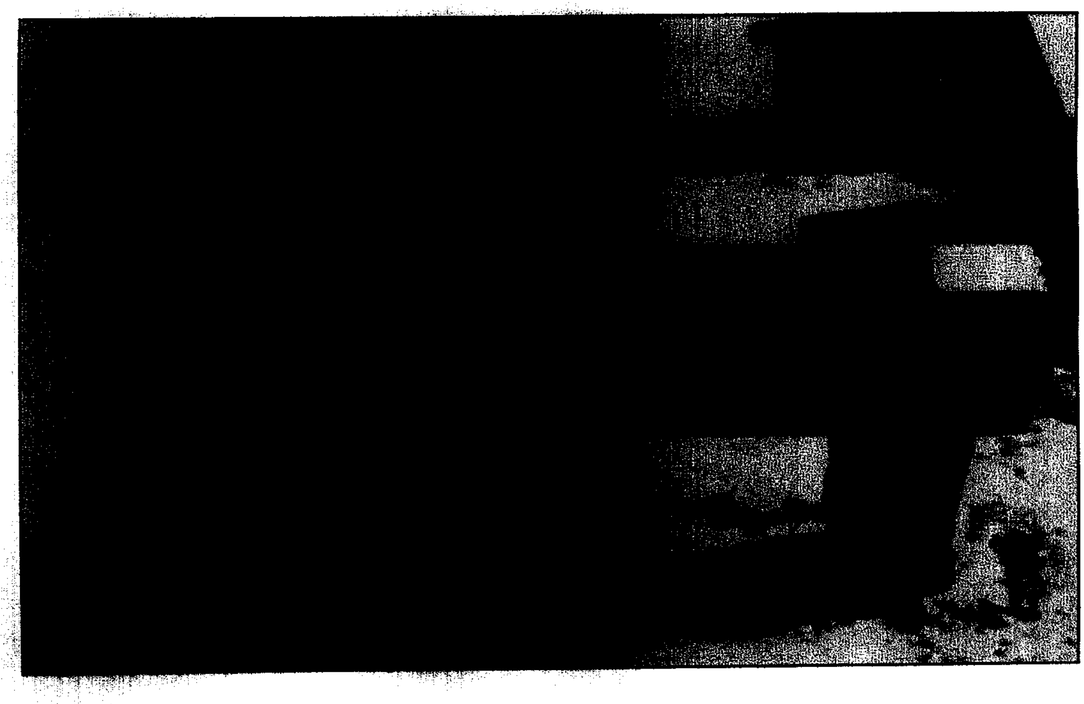

Figure 3.9- Four sides of Columns Plastered

8. The third thermocouple was placed on the furnace to measure the temperature of the column surface as shown in Figure 3.10

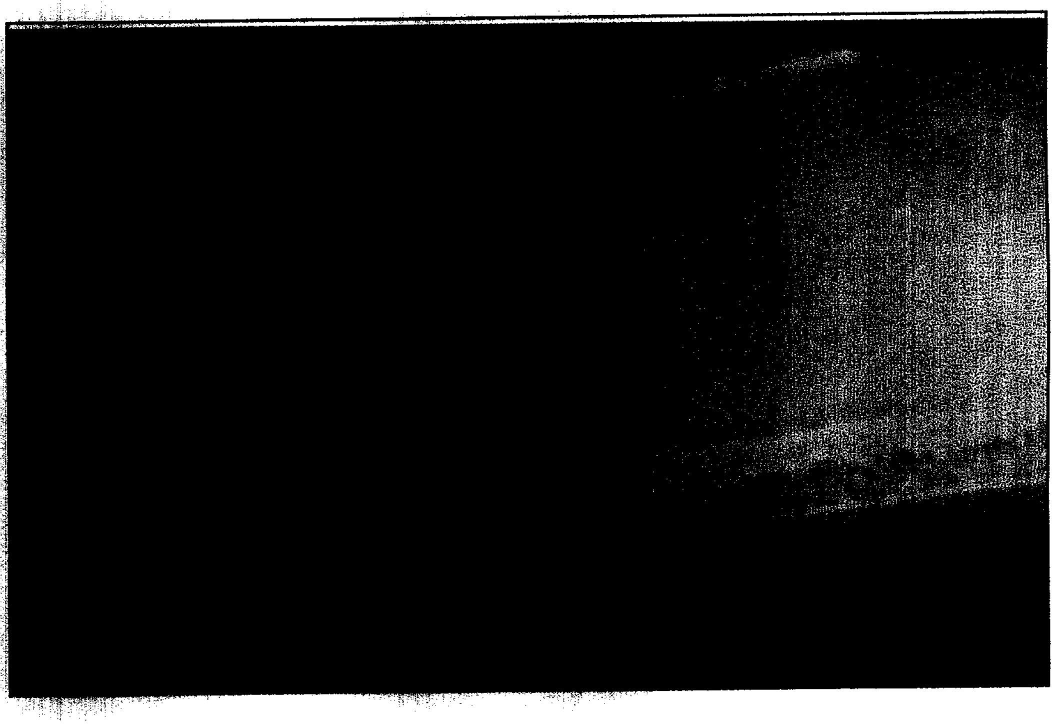

Figure 3.10- Thermocouples at the Center of the Column and at the Surface Below Plaster Material

3.4 Furnace Testing and Specimen Installation in the Furnace:

3.4.1 Furnace Setup:

The furnace used in the experimental work is composed of three main parts:

1. Loading frame
2. Firing Cage
3. Isolation Caps

Loading Frame

It consists of four main parts, the base, the top roof, the left stand, and the right stands. The four items are standard I-beam cross-section #14 welded together. The intersection between each two parts is supported with additional stiffeners and gusset plates.

The base of the loading frame consists of four-sided I-beam with an outer dimension of 1500x540 mm, and an inner dimension of 1368x408 mm. This base is rested on a horizontal reinforced concrete base to ensure that the loading frame is stable and horizontal during the test. At the short centerline of the base, three standard I-beam #10 welded with the long side of the base perpendicularly at the same top surface, to carry the reactions from the tested columns.

The left and the right stands of the loading frames are two I beam #14 of 1250mm in length each. These two are welded to the base and the top roof, and connections are supported with stiffeners. At a distance of 150 mm from the base, there are two horizontal movement prevention rods, which are 80 mm in length each and 30 mm in diameter. These rods are moving in a horizontal plane parallel to the base and are inserted in holes through the web of the stands. At the outer ends of the horizontal movement prevention rods, there are two outer disks of a 130mm in diameter, and this outer disk is supported by a handle of 70 mm in length for the rolling of the rods.

Along the right stand, there is a hole at 680 mm above the base frame, to allow for a smooth movement of the furnace tube gas supply without any obstacle.

The top roof of the loading frame has the same dimension exactly as the frame base, except for the three I-beam#10 at the centerline of the frame base. This top roof is installed to carry the hydraulic jack, which is used to apply the load on the column during testing. Four channel sections #12 of 500 mm in length each support the two long sides of the top roof at mid span.

A horizontal plate (reaction plate) lies above the top roof with a dimension of 545x290 mm, and a thickness of 22 mm. At the middle of the plate, lies a circular flange with a diameter of 130 mm and thickness of 25 mm welded to the top roof. Such flange will act as the base of the hydraulic jack. The reaction plate is rested on the top flanges of the top roof with box section at each side formed from two channels #12,with 50, 120, and 160 mm in dimensions. The box section is welded to the flange of the top roof.

The hydraulic jack is supplying maximum capacity load of 50 tons force. It's cylindrical in shape with a base diameter of 125 mm, a height of 230 mm, and a head diameter of 95 mm. The jack is connected to the flange and the reaction plate with special rivets and acts load by special manual hydraulic pump connected to the jack with hardened tube.

Firing Cage:

It's the main part of the furnace. The cage is rectangular in shape with dimensions of 270 and 540 mm and a height of 1000 mm. It's formed from six metallic test tubes made especially for ovens and furnaces to sustain a temperature up to 950°C. The metallic tubes have an outer diameter of 10 mm and an inner diameter of 6 mm. There is a corner angle of 30x50x5 along the height of the cage welded to the tubes by copper.

The firing cage is resting on two frames of 200 mm in height and 550 mm in length. The frames are formed from steel splices of 50 mm in width and 10 mm in thickness to enable the horizontal movement of the cage on the rails fixed to the base when the horizontal movement prevention rods are out. The main purpose of enabling the horizontal movement of the firing cage is to deal with the column during its insertion and removing from the jack position to be tested.

Each furnace tube has six gas nozzles (fire flame) on the long side and four on the short side to supply the furnace with fire around the four sides of the column. The tubes and the main gas distributor were tested under pressure over 15 bars as shown in Figure 3.11.

The cage is protected with two symmetrical double-layered metallic envelopes. Each envelope has a U shaped section with an outer dimensions of 660 x 230 mm, and a height of 760 mm. Thirty spacers of 30 mm in length fix the hollow distance between the outer and the inner space in each envelope. They are distributed such that 18 spacers at the back of the envelope and six on each side.

Each envelope has two end flanges formed by two equal angles 500x500x50 of 850 mm in length each. The hollow distance between the two envelopes is filled completely with rock wool to ensure complete insulation of the heat to be transmitted to the ambient temperature, which might affect the fire temperature of the furnace during the test, Figure 3.12.

The main gas distributor of the firing cage is connected by the main gas supplier tube of 1m length, which is connected to the gas source by special rubber pipe of 3m in length. Two gas controlling valves are used to ensure no fire hazards occur upon any contact between the gas source and the fire flames.

Isolation Caps:

Each tested column size has isolation caps for its two ends. The isolation cap is formed from two open boxes of 5mm thick steel sheets. The inner cap, which is located exactly on the top and the bottom of the column, has exactly the same dimension of the tested columns.

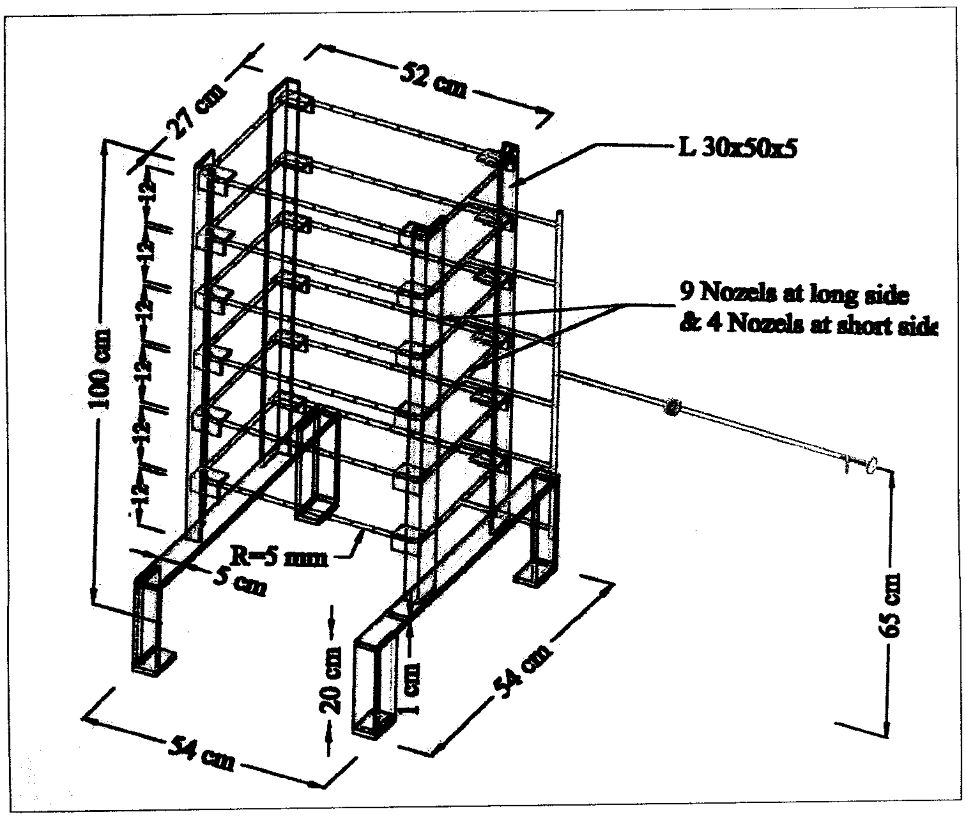

Figure 3.11- Detailed Schematic of the Firing Cage (Mossalamy, 2002)

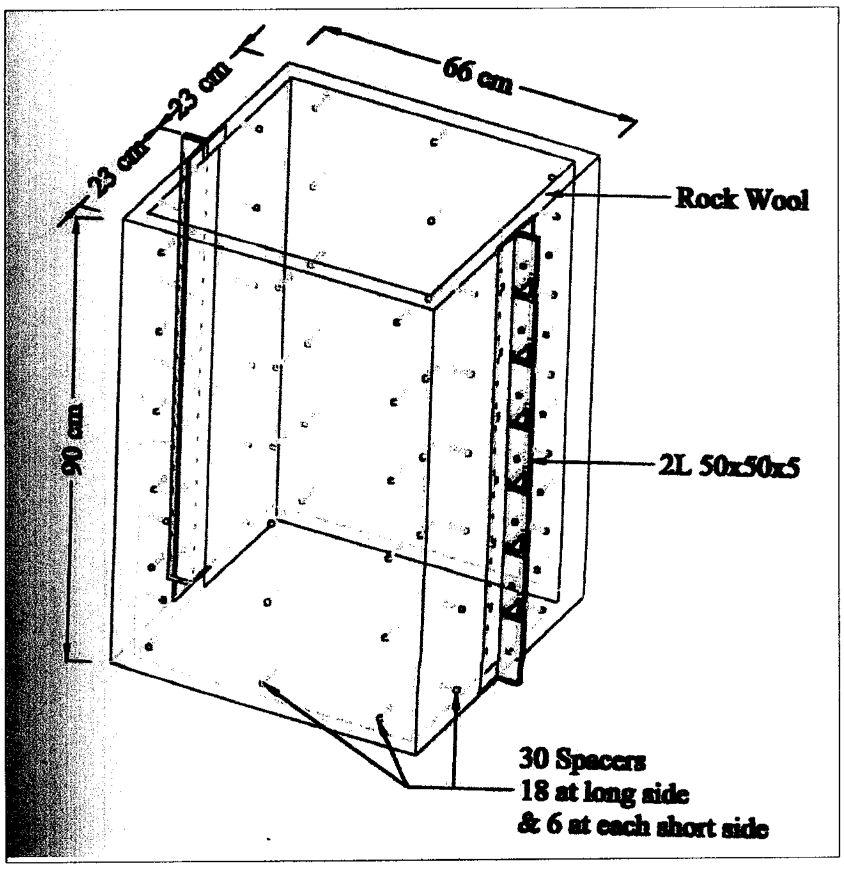

Figure 3.12- Detailed Schematic of the Envelope (Mossalamy, 2002)

3.5 Furnace Setting:

The furnace will be prepared for the test and set. The temperature generated from it must be tested to make sure it will follow with the standard fire test of ASTM E-119. This is achieved by calculating the average time-temperature readings generated by the furnace of the columns. The temperature was controlled manually by valve so as not to exceed 650°C as a maximum to avoid any damage to the metallic furnace used. Columns are inserted in the furnace using a tripod as shown in Figure 3.13 that is formed of three thick wall tubes of 50-mm inner diameter and 6000 mm long. The three tubes connected from the top with gear generation box at the connection point for the insertion of the column in and out in an easy manner, whereas the other ends are stabbed to avoid any movement prevention of the tri-pod.

The following points has to be checked prior to testing:

- The hydraulic jack and the isolation caps are vertical
- The symmetrical position of the column axis with respect to the axis. This was performed by using a vertical water balance during booth the installation and the loading of the column
- The applied load has to be controlled, it shouldn't be too fast to avoid any inclination of the axis (Musalamy,2002)

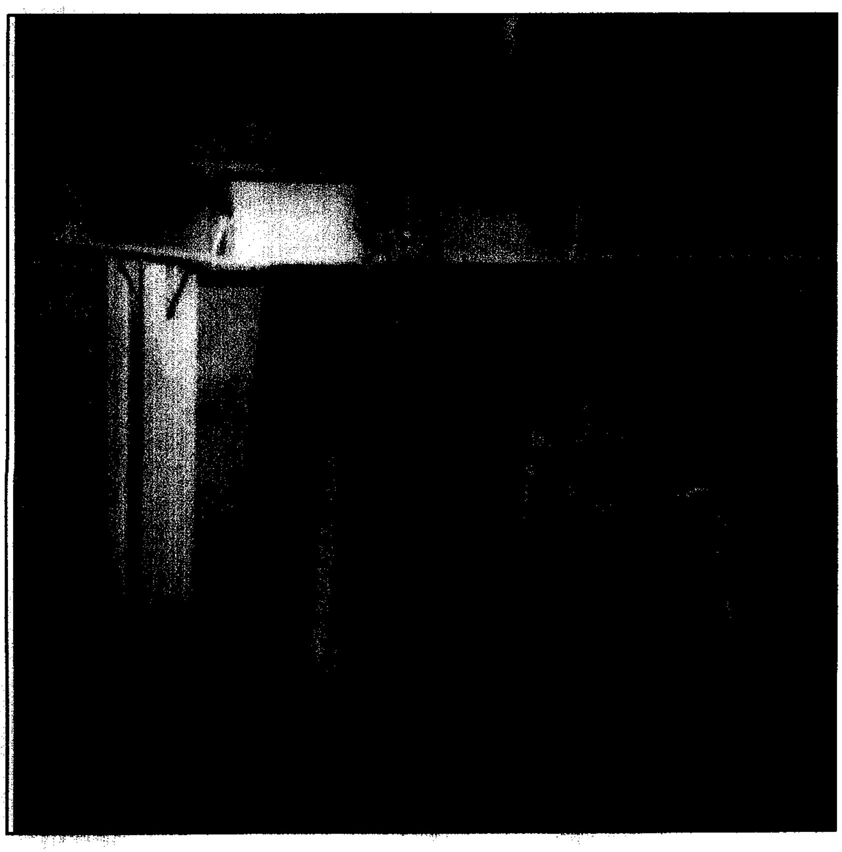

Figure 3.13- Column Inside the Furnace

3.6 Columns Testing:

1. Columns were placed in the furnace under sustain loading applied through the hydraulic jack (Fig 3.14) described in previous section and were subjected to fire from all four sides.

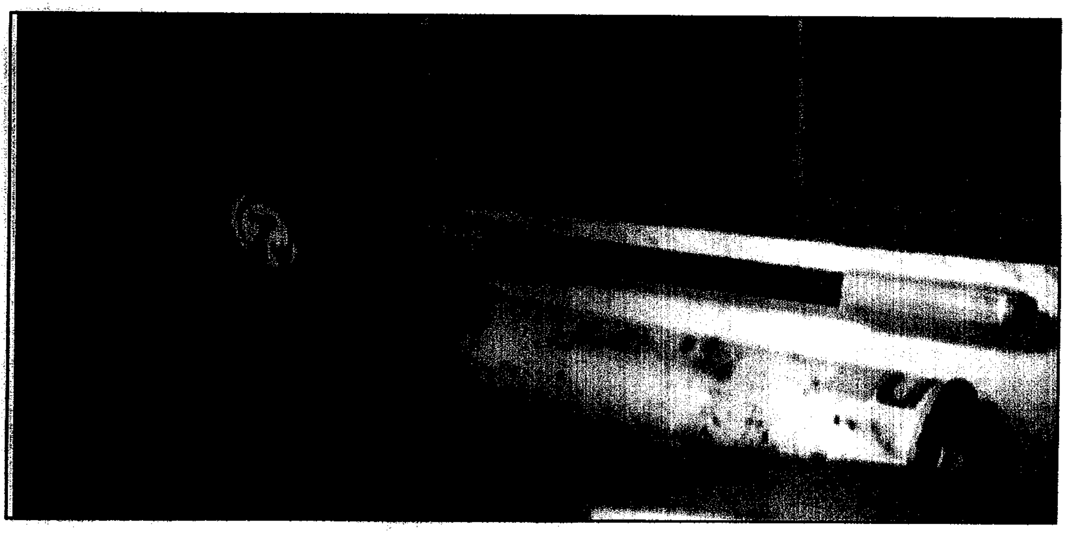

Figure 3.14- Hydraulic Jack

2. The temperature of the concrete was determined from thermocouples inserted in various locations according to ASTM E-119, as shown in Figure 3.15
3. The applied load during testing was 50% of the design load, which represents the dead load and part of the live load.

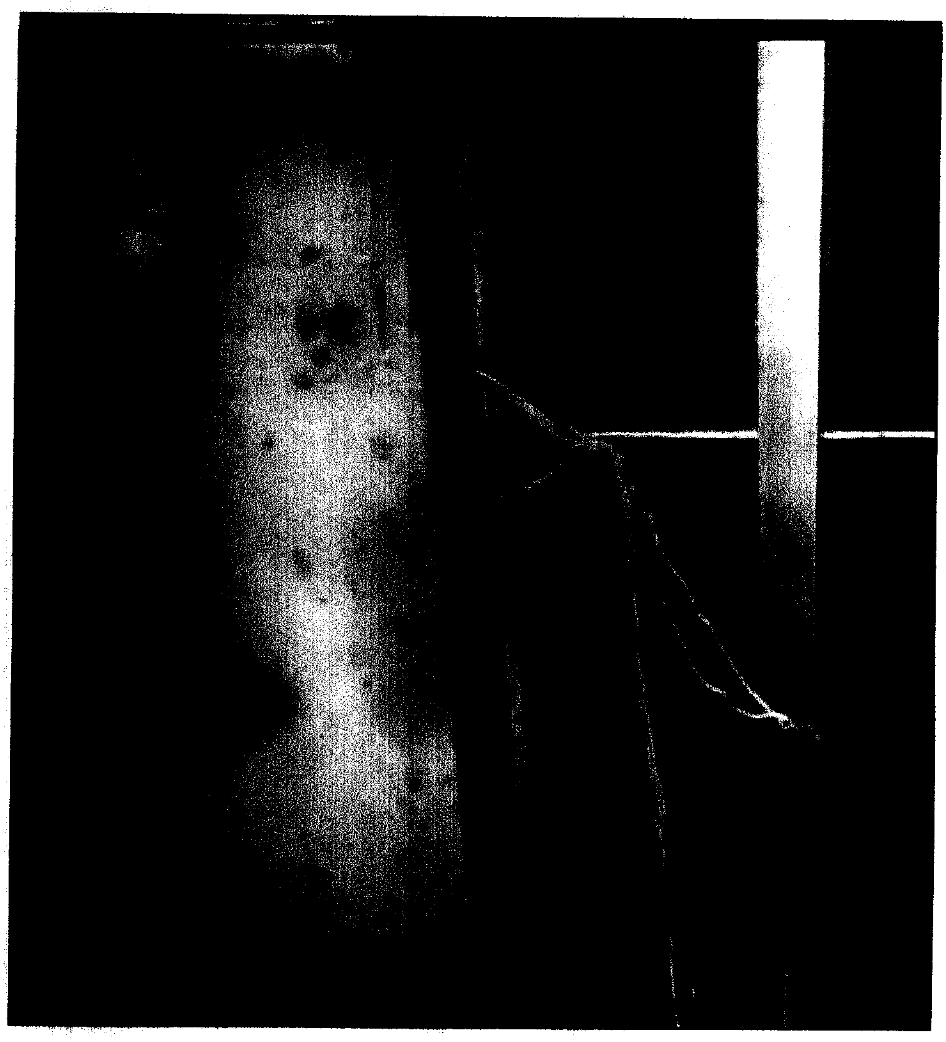

Figure 3.15- Three Thermocouples out of Column, one From Center, one at Column Surface (Beneath Plaster), and one to Measure Ambient Temperature

4. The fire test stopped when the thermocouple, that was placed just under the plaster reads (140°C+ ambient temperature), where this time is the fire resistance of the column that corresponds to the thickness of the material applied.
5. Readings were recorded through a scanning Thermometer, where the thermocouples are connected to as shown in Figure 3.16

Figure 3.16- Scanning Thermometer

6. The Columns were then left to cool inside the oven after opening the two envelops until it cool, then removed from the furnace.
7. Columns were then loaded until they fail to measure the percent loss of strength after exposure to fire as shown in Figure 3.17.

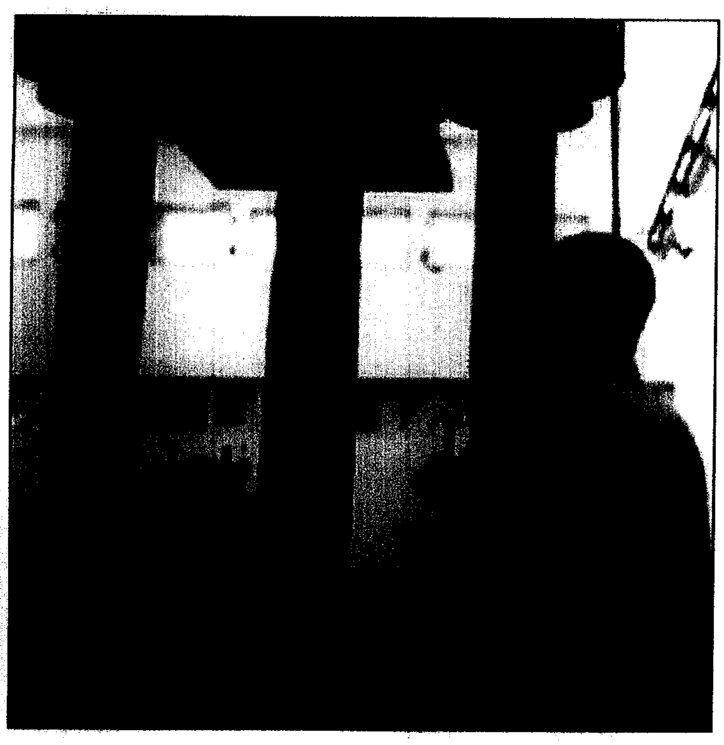

Figure 3.17- Column Loaded after fire

3.7 Equivalent Prototype Fire Resistance:

Since the material properties of the model and the prototype are the same ($\alpha_p = \alpha_p$), and both the model and the prototype fire curves retain same temperature input, then the results of .J. O' Connor and Silcock, 1992, whose studies were based on Buckingham Pi theorem, can be implemented to predict real column dimensions fire resistance as follows:

$t_m = (S)^2 * (t_p)$..(3.1)

$S_l = l_m / l_p$..(3.2)

Where:

S_l = scale Factor

l_m = characteristic length of the model = area of the model / parameter of the model exposed to fire

l_p = characteristic length of the prototype = area of the prototype / parameter of the prototype exposed to fire

Thus, to validate this model, the 100x100x1000 mm column dimension were considered as the model and the other two dimensions which are, 100x200x1000, and 100x300x1000 mm were considered as the prototype.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction:

The effect of the test parameters, which are column dimension, plaster type and plaster thickness, is presented and discussed in this chapter in terms of fire resistance time, strength loss/increase upon cooling in air after exposure to fire and surface disintegration of the plastering materials.

Effect of Temperature up to 177 °C on Concrete:

The lower boundary in examining the effect of high temperature in the concrete starts when the temperature reaches 100°C and immediately above as free water starts to be driven off. An increase in the compressive strength in the temperature range of 121 to 149°C is attributed by Zoldners, 1960 to " a heat stimulated cement hydration and densification of the cement gel due to the loss of absorbed water."

Upon fire, desorption of the evaporable water occurs as the temperature increases. After that and overlapping, the chemically bound water that is non-evaporable, is released. In addition, the decrease of the evaporable water and the chemically bound water upon dehydration of the paste changes the physical bonds existing initially and causes microcracking (Smith, Peter, 1994).

Thermal properties of the cement paste, specifically thermal volume change, appeared to have a major effect in the behavior of the concrete. There are two components of thermal volume change of paste before the decomposition occurs. First, a true thermal expansion that is constant in the anhydrous solids. Second, an apparent thermal expansion that is hygrothermal contraction dependent on the internal transportation of

4.3 Comparison Average Time-Temperature of Constructed Furnace and That of ASTM E-119:

The constructed furnace time temperature profile should follow the standard ASTM E-119 time-temperature profile. To assure that, ASTM E-119 provided a correction factor to calibrate the time-temperature profile produced from the constructed furnace against its standard time-temperature profile, where correction C is given by:

$C= 2I\,(A - A_s)\,/3\,(A_s + L)$..(4.1)

Where:

C = correction in the same units as I

I = indicated fire resistance period

A = area under the curve for indicated average furnace temperature for the first three fourths of the indicated period

A_s = area under the standard furnace curve for the same part of the indicated period

L = lag correction in the same units as A and A_s {30°C/hr (1800°C/min)}.

If the constructed furnace time temperature curve is higher than the standard then the calculated fire resistance period is increased by the amount (C) shown in equation 4.1 and vise versa.

Table 4.19-shows the average temperature of the constructed furnace and that of ASTM E-119.As suggested by Table 4.19, the difference between the two furnace time-temperature relation is not significant. A sample approximate calculation of the correction factor was performed that revealed that the Correction is relatively minor. (almost one minute) Thus as an assumption, the constructed furnace will be following the same time-temperature profile as the time-temperature profile of ASTM E-119. In this study, the correction factor will be equal to zero, and the time measured will be the fire resistance time of the model (t_m).

Table 4.1- Temperature-Time Readings of The Constructed Furnace and Those of ASTM E-119 Standards

Time (min.)	Average furnace Temperature (°C)	ASTM Temperature (°C)
0	28	20
1	195	349
2	389	445
3	509	502
4	558	544
5	590	576
6	608	603
7	631	626
8	639	645
9	643	663
10	651	678
11	658	693
12	657	705
13	652	717
14	657	728
15	658	739
16	658	748
17	660	757
18	657	766
19	659	774
20	660	781
21	656	789
22	654	796
23	654	802
24	631	809
25	652	815
26	655	820
27	649	826
28	650	832
29	654	837
30	646	842
31	646	847
32	649	851
33	648	856
34	650	860
35	653	865
36	650	869
37	651	873
38	657	877
39	659	881

40	648	885
41	651	888
42	652	892
43	655	896
44	659	899
45	648	902
46	639	906
47	638	909
48	643	912
49	642	915
50	641	918
51	642	921
52	643	924
53	643	927
54	640	930
55	643	932
56	643	935
57	639	938
58	640	940
59	645	943
60	648	945

4.4 Test Results for Concrete Columns Coated with Cement Plaster:

The change in the temperature with time for 100x100x1000-mm columns coated with 15, 25, and 35-mm thick Cement Plaster plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.1 to 4.3. As shown in Figure 4.1, the temperature of the concrete surface under the plaster reached 164.7°C after 20 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 28.5 ton compared to an uncoated control specimen load of 26 ton. Thus, there was an increase in strength of about 9.6%. As shown in Figure 4.2, the temperature of the concrete surface under the plaster reached 163.9°C after 23 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 28.5 ton compared to a uncoated control specimen load of 26 ton. Thus, there was an increase

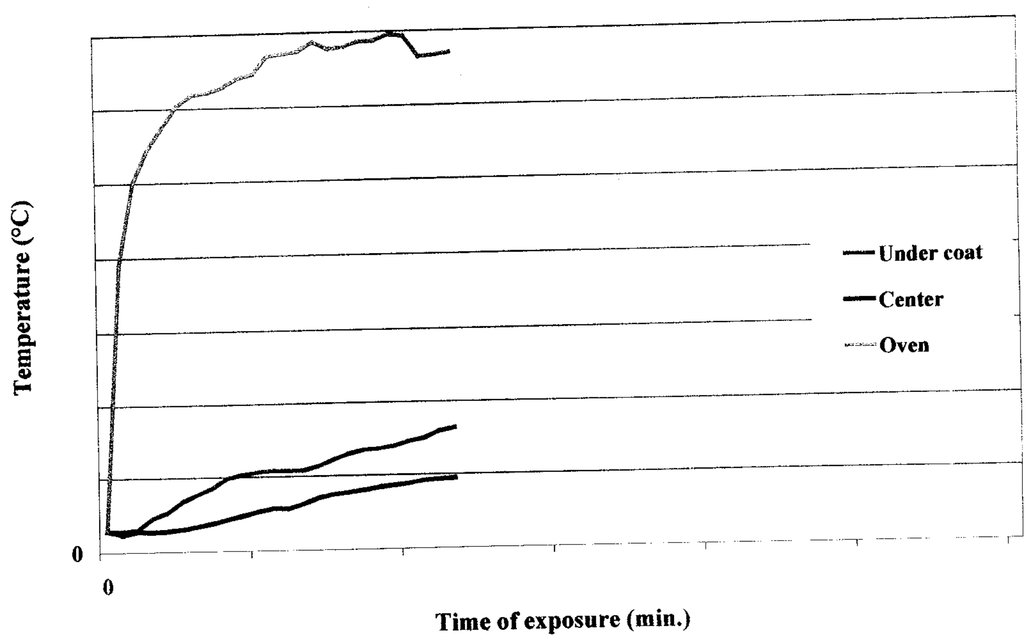

Figure 4.2- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 25 mm Cement Plaster During Fire.

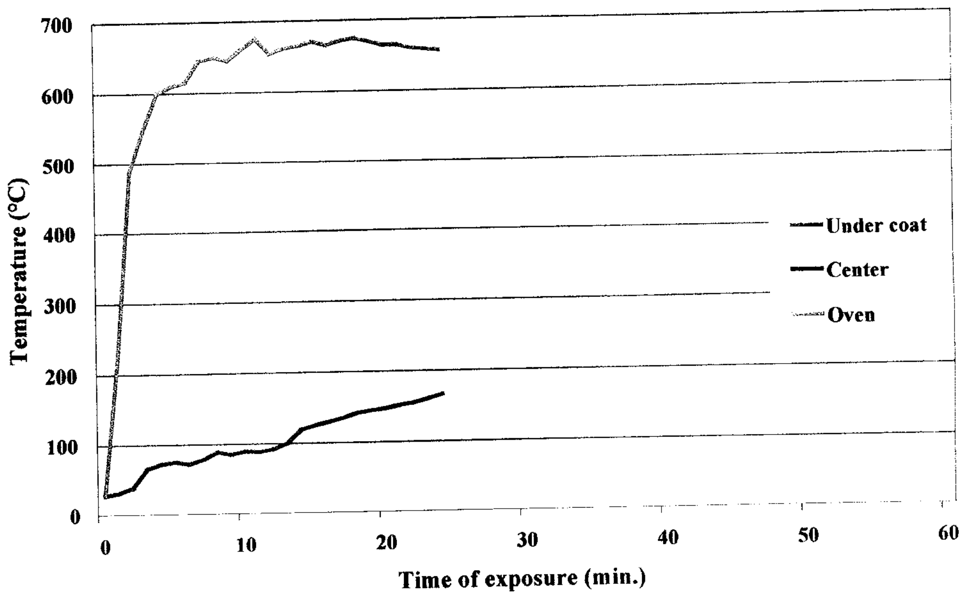

Figure 4.3- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 35 mm Cement Plaster During Fire.

The change in the temperature with time for 100x200x1000-mm columns coated with 15, 25, and 35 mm thick Cement Plaster plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.4 to 4.6. As shown in Figure 4.4, the temperature of the concrete surface under the plaster reached 171.2°C after 24 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 47.5 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 15%. As shown in Figure 4.5, the temperature of the concrete surface under the plaster reached 165.7°C after 27 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 49 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 18%. As shown in Figure 4.6, the temperature of the concrete surface under the plaster reached 167.1°C after 35 minutes. It was observed that the supplementary thermocouple inserted at the center of the column did not work due to an experimental default, as the concrete was poured over. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 64 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 55%

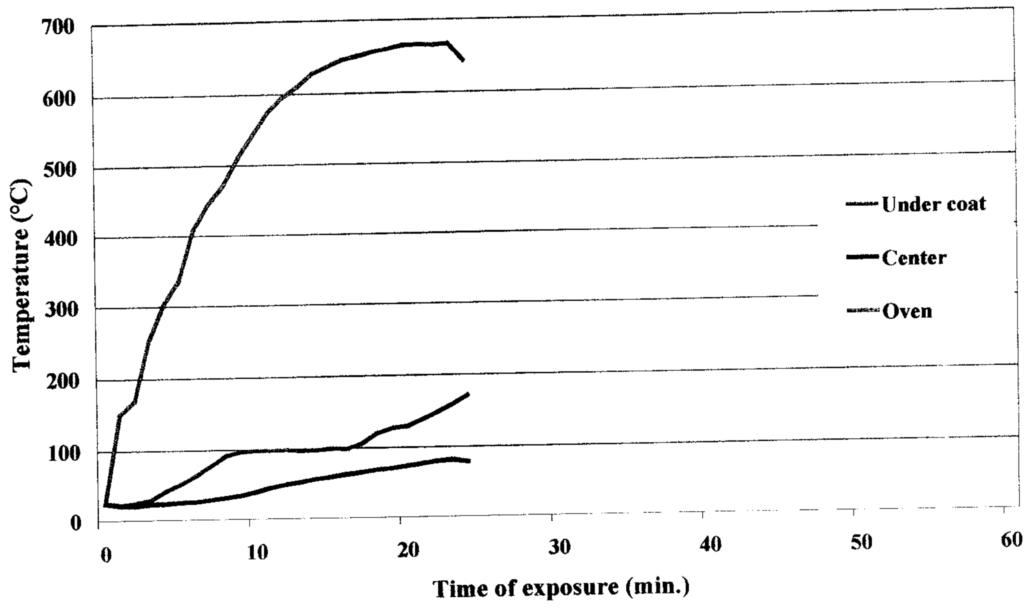

Figure 4.4- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 15 mm Cement Plaster During Fire.

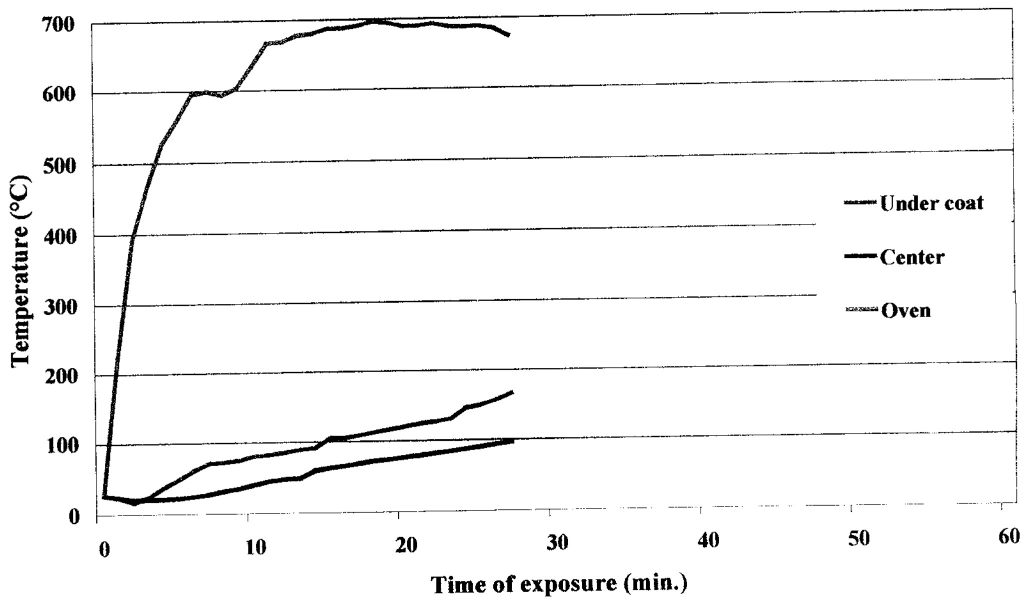

Figure 4.5- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 25 mm Cement Plaster During Fire.

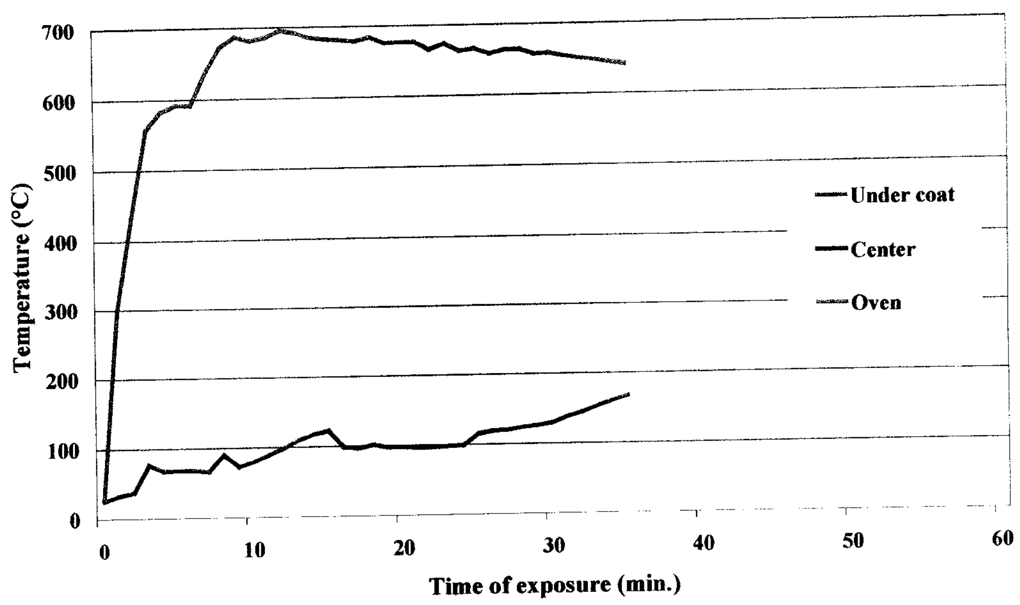

Figure 4.6- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 35 mm Cement Plaster During Fire

The change in the temperature with time for 100x300x1000-mm column coated with 15, 25, and 35 mm thick Cement Plaster plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.7 to 4.9. As shown in Figure 4.7, the temperature of the concrete surface under the plaster reached 167.5°C after 25 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 72.5 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 6 %. As shown in Figure 4.35, the temperature of the concrete surface under the plaster reached 183.1°C after 32 minutes. It was observed that the supplementary thermocouple inserted at the center of the column did not work due to an experimental default, as the concrete was poured over. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 76.5 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 11%. As shown in Figure 4.36, the temperature of the concrete surface under the plaster reached 170.6°C after 35 minutes. It was observed that major parts of the plaster completely fell off after the column was exposed to air and left to cool. The load recorded after fire was 78 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 13 %

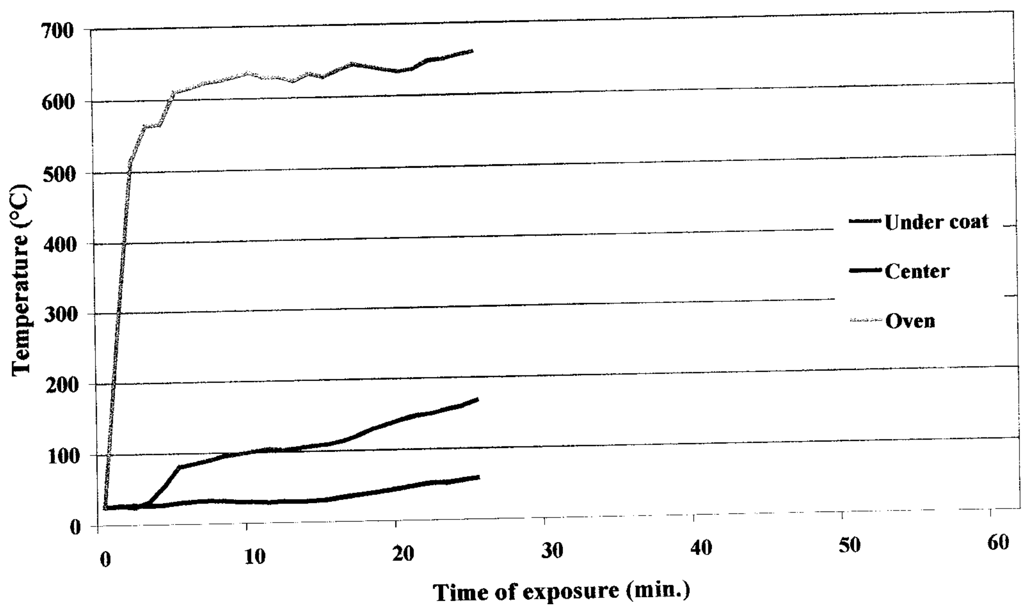

Figure 4.7- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 15 mm Cement Plaster During Fire.

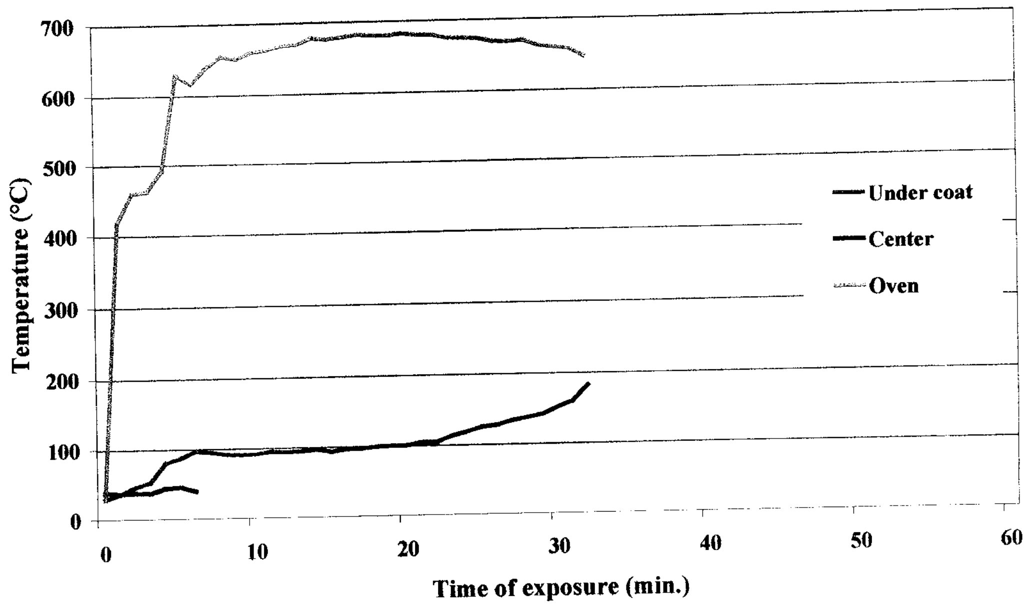

Figure 4.8- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 25 mm Cement Plaster During Fire.

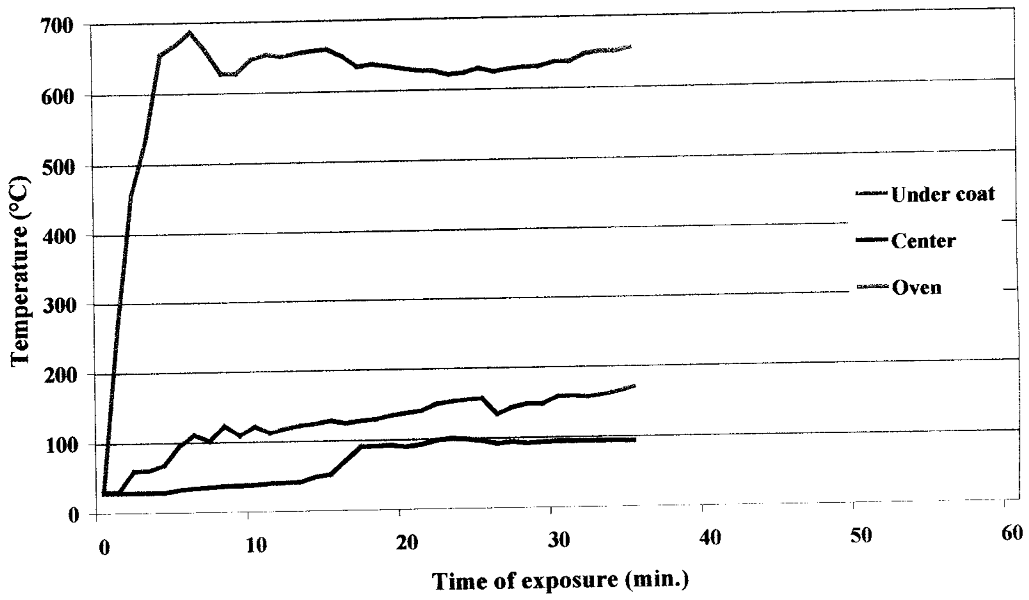

Figure 4.9- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 35 mm Cement Plaster During Fire

4.5 Summary Results and Discussion of Cement Plaster Performance:

Results obtained during and after fire exposure of cement plaster coated columns are shown in Table 4.2. The results show that, in the three dimensions of the columns 100x100x1000, 100x200x1000, 10x300x1000, fire resistance of the columns increase with the increase of the coat thickness. This might be explained as the thickness increases, the thermal resistance (R-value) of the plaster increases as well, where the amount of free and bonding water increases. Thus the amount of heat dissipated in the decomposition of the hydration reaction, and the heat stored in the plaster increases, and the amount of heat passing through the plaster to reach the column surface decreases.

Also, for different column dimensions100x100x1000, 10x200x1000, 10x300x1000, the same plaster thickness gives different fire resistance. This might be attributed to that the area exposed to fire increases by the increase in the size of the column, where the amount of water present in the mix of the plaster is higher, thus the moisture migration increases as well. Therefore, heat required evaporating the water increases, and thus more time is needed to reach the same temperature upon increasing of the column dimension.

Table 4.2- Thermo-Physical properties of Cement Plaster used in plaster

Thermal and Mechanical Properties			**Thermal Characteristics**			
Density (ρ) kg/m^3	Thermal Conductivity (K) w/mk	Specific heat (°C)	R-Value (m^{2}k/w)			Diffusivity (m^2/s)
			T=15 mm	T=25 mm	T=35 mm	
1400	1.4	840	0.180	0.187	0.195	1.19048E-06

Table 4.3- Results Obtained During and After Exposure to Fire of Cement Plaster Coated Columns

Column Size (mmxmm)	Plaster Thickn-ess (mm)	Post Fire Failure Load (ton)	Uncoated control (ton)	Time (min)	Max Temp. reached under plaster (°C)
100x100	15	28.5	26	20	164.7
100x100	25	28.5		23	163.9
100x100	35	28.5		25	166.7
100x200	15	47.5	41.5	24	171.2
100x200	25	49		27	165.7
100x200	35	64		35	167.1
100x300	15	72.5	69	25	167.5
100x300	25	76.5		32	183.1
100x300	35	78		35	170.6

It is observed from Table 4.3 that the load capacity of columns increased after fire, where the concrete surface reaches a maximum of 170°C, this might be due to, as previously explained in Zoldners, 1960, the densification of the cement gel arise because of the loss of absorbed water.

As for the surface, as mentioned the cement plaster fell off, and that might be explained due to the exposure of the surface of the cement plaster to a temperature of 650°C, and at that temperature, the dehydration is almost complete and the decomposition is irreversible. This makes the concrete friable, porous and can be taken apart with the fingers upon cooling. (Smith, Peter, 1994), as shown in Figure 4.10. In addition, as shown in Table 4.2, Cement plaster has both a high thermal conductivity and diffusivity values that allows heat to pass quickly to reach the concrete surface (under plaster) and reaches the wire mesh. Since the wire mesh expansion is different than that of the cement plaster, thus separation of the plaster might occur.

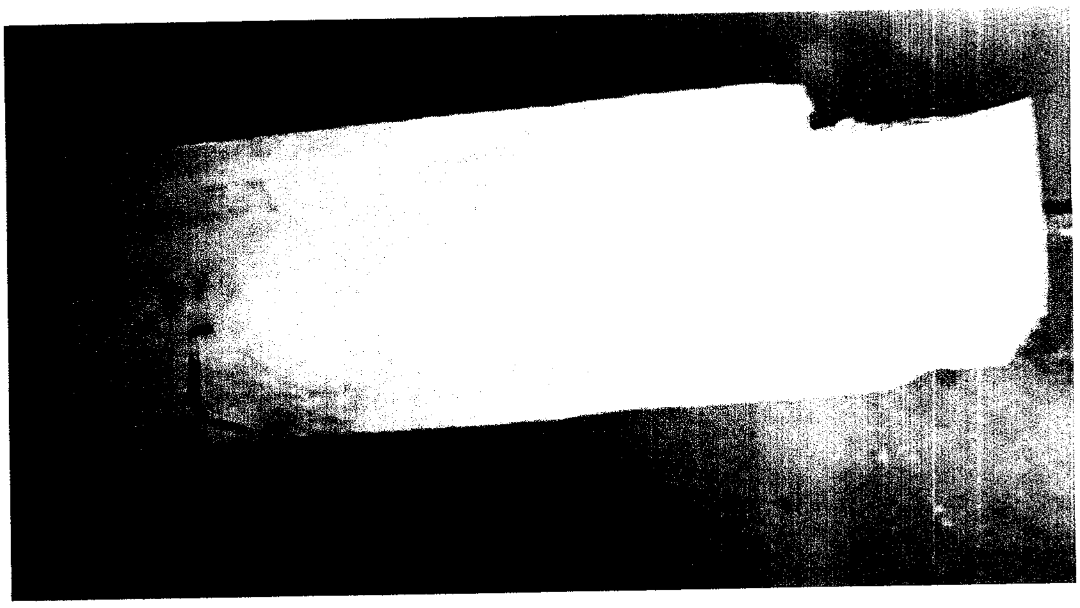

Figure 4.10- Cement Plaster is Friable After Fire Exposure

This group of columns can be considered as the control specimens that other types of plaster will be compared against in terms of fire resistance time, disintegration of the surface, and strength increase/loss.

4.6 Test Results for Concrete Columns Coated with Perlite Plaster:

The change in the temperature with time for 100x100x1000-mm column coated with 15, 25, and 35-mm thick Perlite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.11 to 4.13. As shown in Figure 4.11, the temperature of the concrete surface reached 168.5°C i.e. 140°C+ ambient temperature after 45 minutes. It was observed that the supplementary thermocouple inserted at the center of the column did not work due to an experimental default, as the concrete was poured over. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.08-2 mm. The load recorded after fire was 15.5 ton compared to an uncoated control specimen load of 26 ton. Thus, there was a loss in strength of about 40%. As shown in Figure 4.12, the temperature of the concrete surface under the plaster reached 161.4°C i.e. 140°C+ ambient temperature after 60 minutes. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.2-0.25 mm width. The load recorded after fire was 17.5 ton compared to a uncoated control specimen load of 26. Thus, there was a loss in strength of about 33%. As shown in Figure 4.13, the temperature of the concrete surface under the plaster reached 118.5°C after 60 minutes. The furnace was switched off after one hour as it's designed to be working for a period of one hour. This means that this column can stay more than one hour to reach 140°C+ambient. It was observed that the supplementary thermocouple inserted at the center of the column did not work due to an experimental default, as the concrete was poured over. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.25-mm width, and de-bonding between the plaster and the column surface is observed. The load recorded after fire was 21.5 ton compared to a uncoated control specimen load of 26. Thus, there was a loss in strength of about 17.5%.

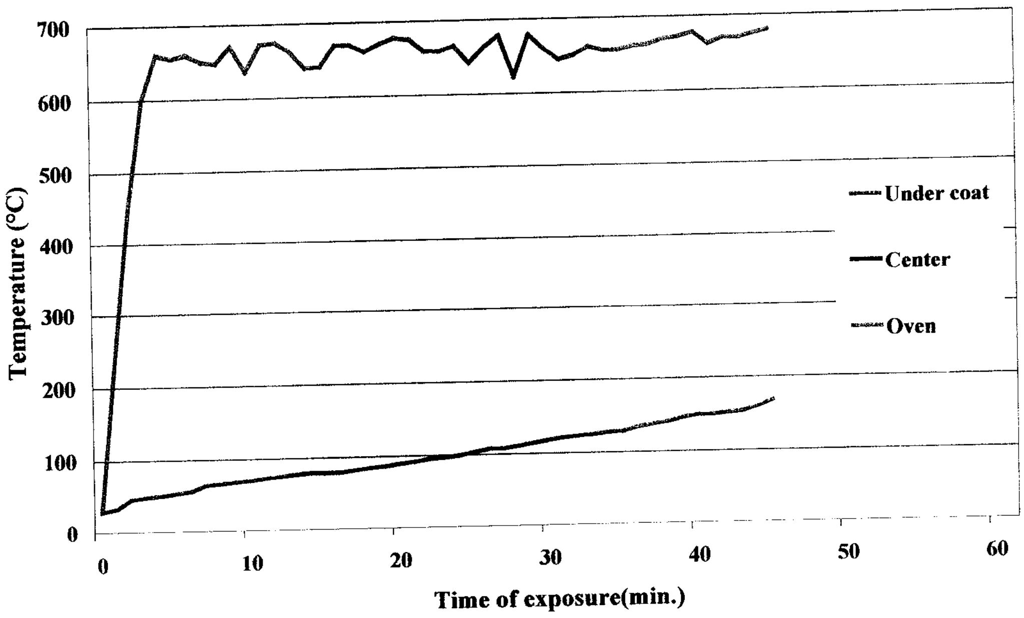

Figure 4.11-: Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 15 mm Perlite Concrete Plaster During Fire.

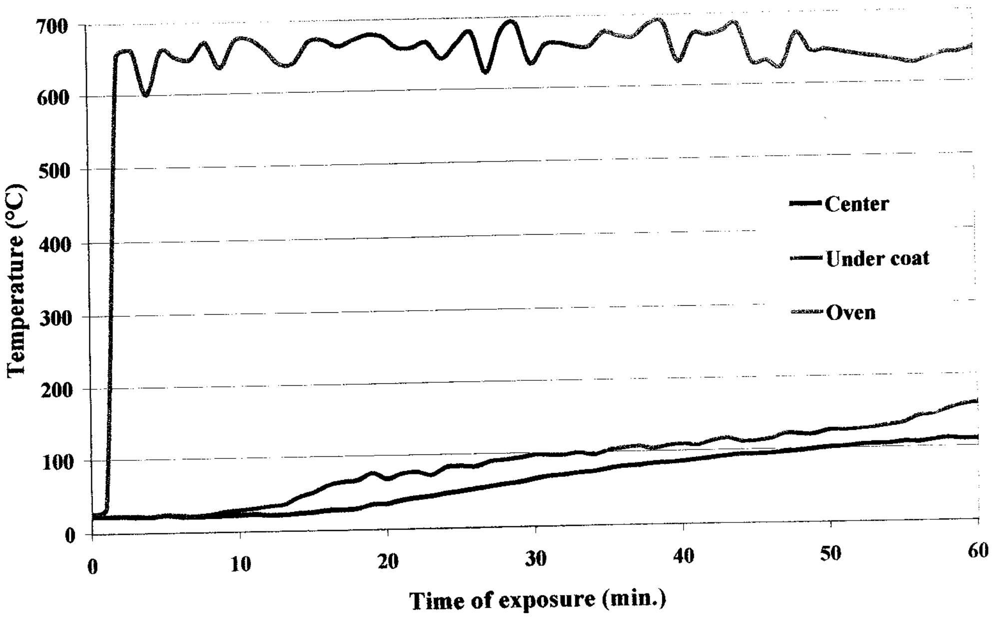

Figure 4.12- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 25 mm Perlite Concrete Plaster During Fire.

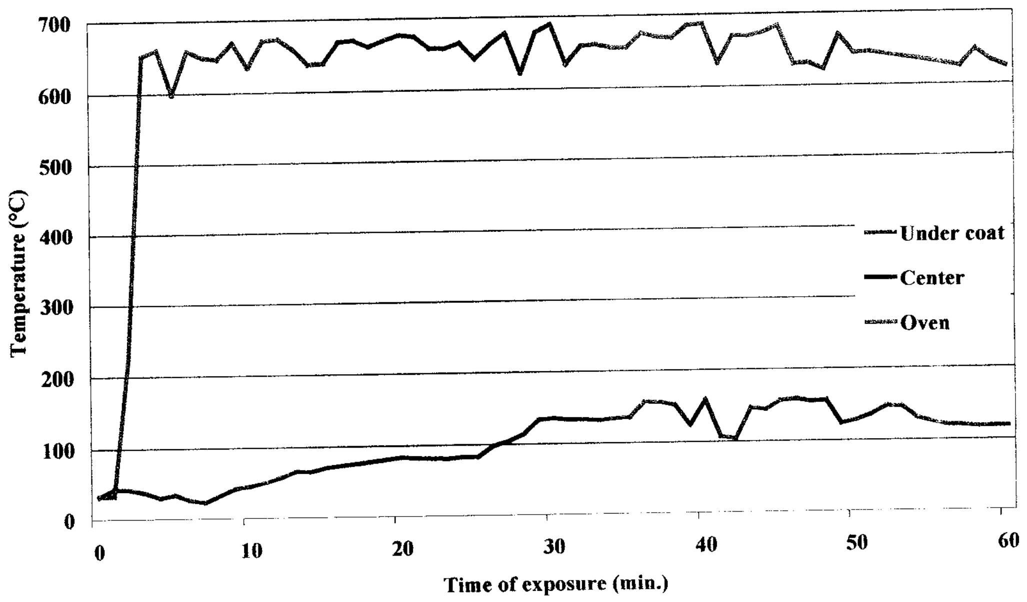

Figure 4.13- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 35 mm Perlite Concrete Plaster During Fire

The change in the temperature with time for 100x200x1000 mm columns coated with 15, 25, and 35-mm thick Perlite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.14 to 4.16.

As shown in Figure 4.14 the temperature of the concrete surface under the plaster reached 168.6°C after 51 minutes i.e. 140°C+ambient. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.1-0.2 mm width. The load recorded after fire was 43.5 mm ton compared to an uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 5%. As shown in Figure 4.15, the temperature of the concrete surface under the plaster reached 135.7°C after 60 minutes as the furnace is designed to operate for one hour at a maximum temperature of 650°C. Thus this means that the fire resistance of such column is more than one hour. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.1-0.2 mm width. The load recorded after fire was 49.5ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 20%. As shown in Figure 4.16, the temperature of the concrete surface under the plaster reached 172°C after 25 minutes. It was observed that the supplementary thermocouple inserted at the center of the column did not work due to an experimental default, as the concrete was poured over. The sudden increase in the surface temperature is observed due to the separation of the Perlite concrete plaster, which was observed after fire, and that might be due to an error in mixing or casting the plaster. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.3-mm width, and de-bonding between the plaster and the column surface is observed. The load recorded after fire was 64 ton compared to an uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 54%

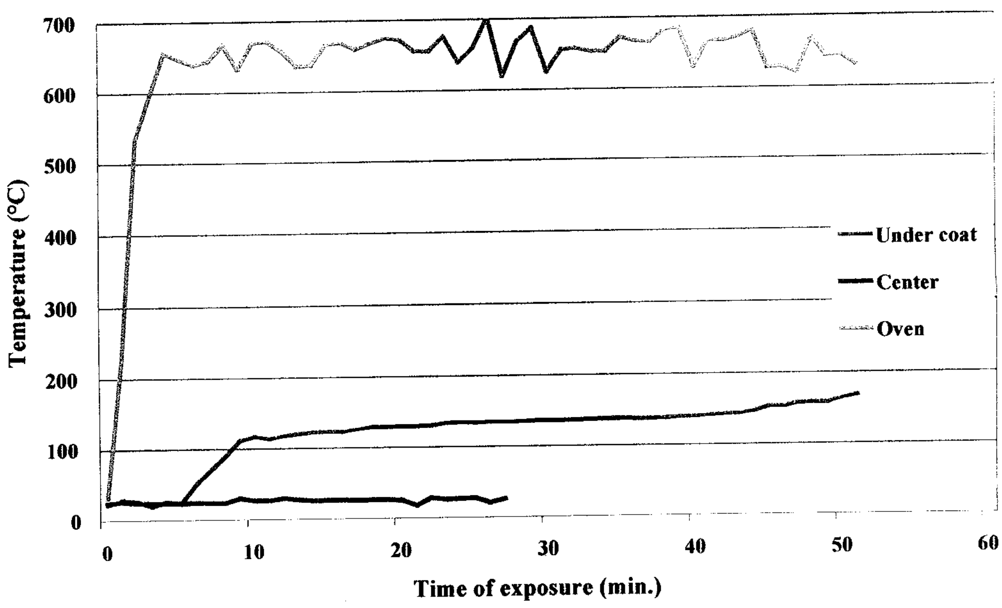

Figure 4.14- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 15 mm Perlite Concrete Plaster During Fire.

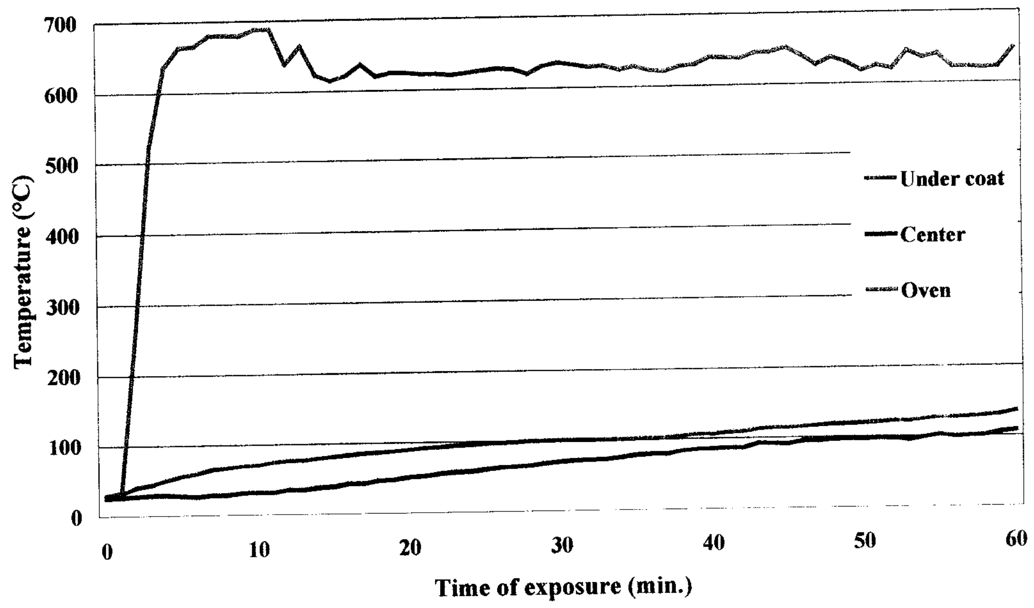

Figure 4.15- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 25 mm Perlite Concrete Plaster During Fire.

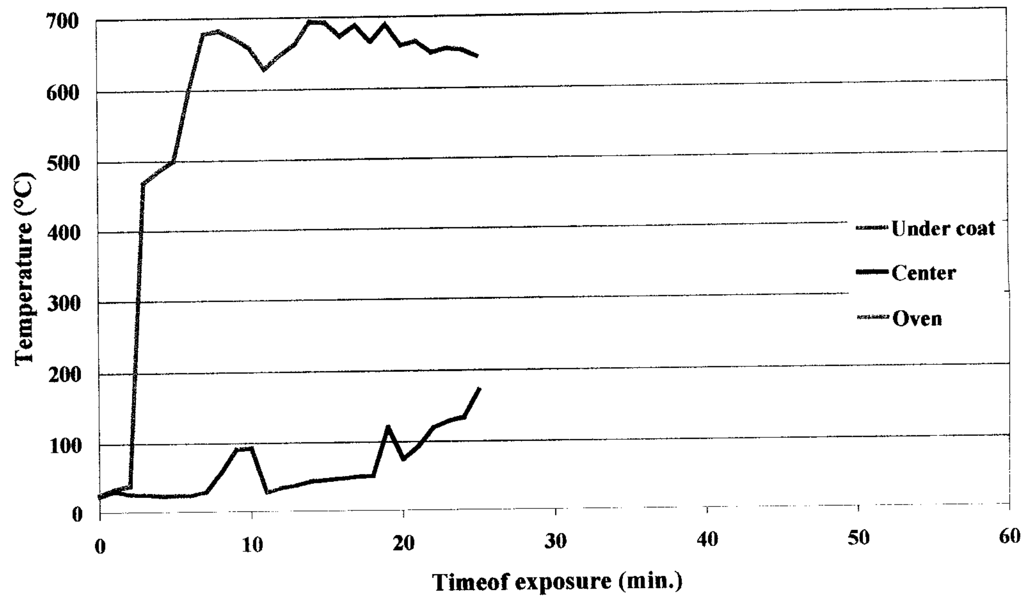

Figure 4.16- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 35 mm Perlite Concrete Plaster During Fire

The change in the temperature with time for 100x300x1000 mm columns coated with 15, 25, and 35 mm thick Perlite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C as illustrated in Figures 4.17 to 4.19. As shown in Figure 4.17, the temperature of the concrete surface under the plaster reached 160.1°C after 60 minutes. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.25-mm width. The load recorded after fire was 70 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 2%. As shown in Figure 4.18, the temperature of the concrete surface under the plaster reached 140.1°C after 60 minutes. This means that the fire resistance of such column is more than one hour. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.25-0.3 mm width. The load recorded after fire was 74.5 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 8%. As shown in Figure 4.19, the temperature of the concrete surface under the plaster reached 136.8°C after 60 minutes, which means it would stay more than one hour to reach to reach 140°C+ ambient. Also it was observed that after the column cooled, some cracks were observed with an average width of 0.25-0.35 mm width, and de-bonding between the plaster and the column surface is observed. The load recorded after fire was 70 ton compared to an uncoated control specimen load of 75.5 ton. Thus, there was an increase in strength of about 10%.

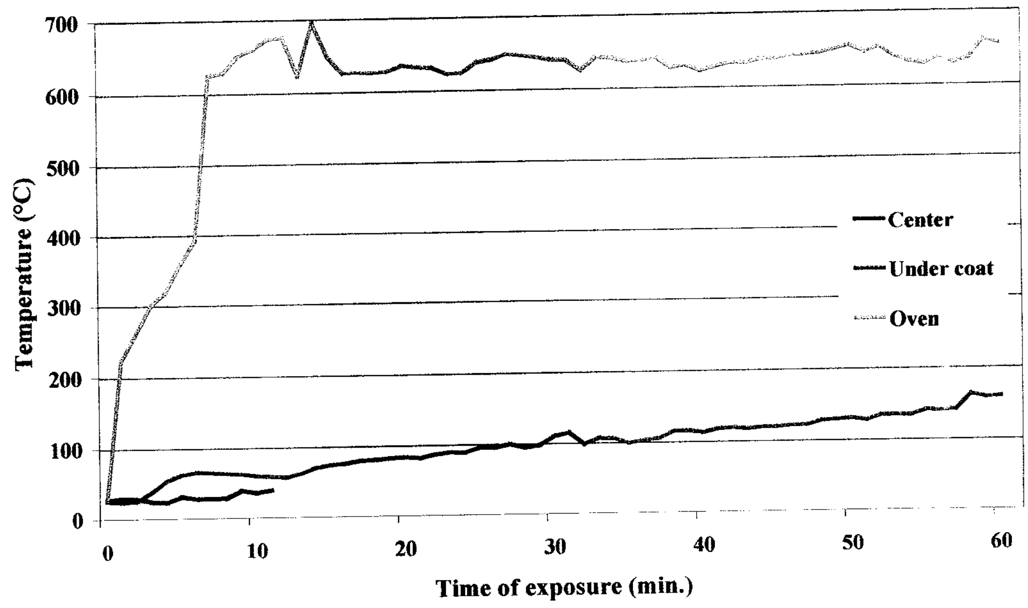

Figure 4.17- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 15 mm Perlite Concrete Plaster During Fire.

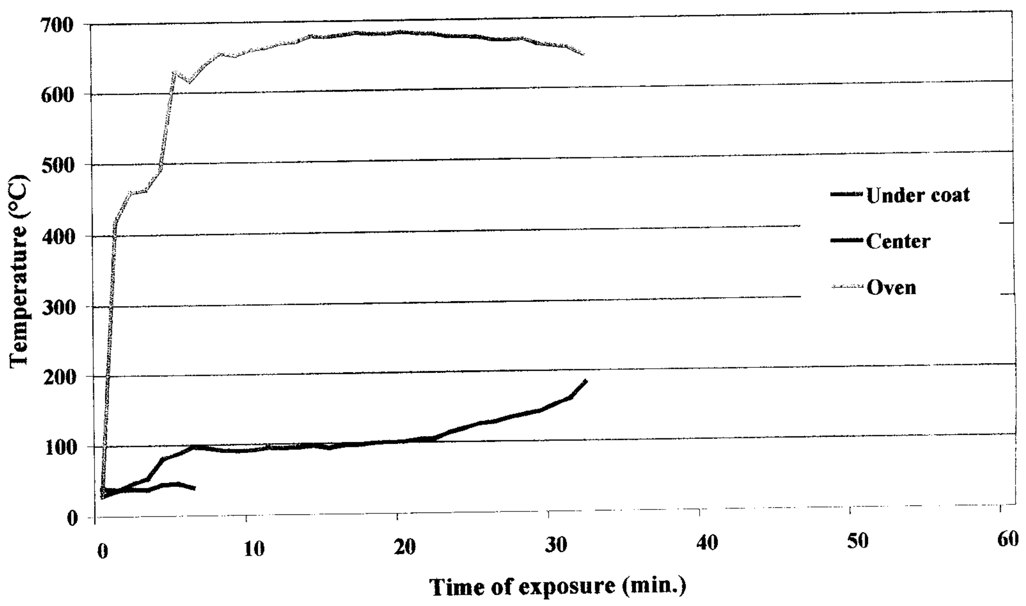

Figure 4.18- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 25 mm Perlite Concrete Plaster During Fire.

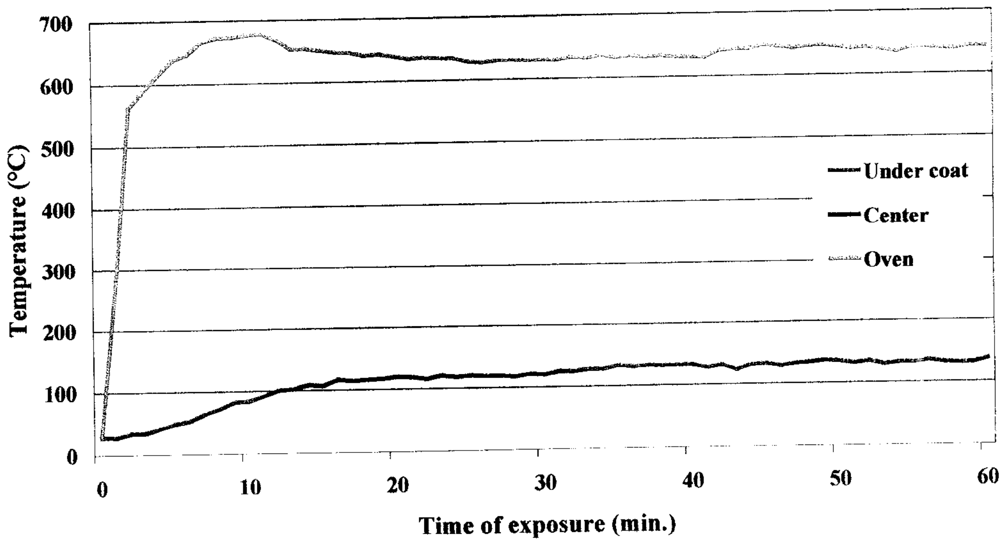

Figure 4.19- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 35 mm Perlite Concrete Plaster During Fire

4.7 Summary Results and Discussion of Perlite Plaster Performance:

When exposed to fire, Perlite plaster releases chemically combined water in the form of vapor, which maintains the plaster temperature at about 100°C until all the water has been driven off as steam. The insulating action of the Perlite aggregates delays the release of steam and retards the transmission of heat, thus highly improving the fire retardant quality. Unlike ordinary sand plaster, that develops considerable expansion at high temperature, Perlite Plaster has low linear expansion, that highly reduces the number and the size of the cracks that permits heat and flame to penetrate through the plaster barrier (Perlite Institute Inc., 1967)

The results obtained during and after fire exposure of Perlite plaster coated columns are shown in Table 4.5. The results show that, in the three dimensions of the columns100x100x1000, 10x200x1000o, 100x300x1000 mm, fire resistance of the column increases with the increase of the coat thickness.. This might be explained as the thickness increases, the thermal resistance (R-value) of the plaster increases as well, where the amount of free and bonding water increases. Thus the amount of heat dissipated in the decomposition of the hydration reaction, and the heat stored in the plaster increases, and the amount of heat passing through the plaster to reach the column surface decreases. An error in the casting prior to the fire caused heat to reach the surface and raise it to 140°C+ ambient fast. But it would be predicted that would reach at least one hour.

Also, for different column dimensions100x100x1000, 10x200x1000, 10x300x1000, the same coat thickness gives different fire resistance. For instance, the fire resistance increases, among the three-column dimension coated with 15 mm, along the increase in the column dimensions. This might be due to that the area exposed to fire increases by the increase in the size of the column, where the amount of water present in the mix of the plaster is higher thus the moisture migration increases as well. Therefore, heat required to evaporate the water increases, and thus more time is needed to reach the same temperature upon increasing of the column dimension. Whereas, the fire resistance does not increase along increase of the column dimension for the 25 and 35 mm coat thickness.

Table 4.4- Thermo-Physical Properties of Perlite Plaster

Thermal and Mechanical Properties				**Thermal Characteristics**			
Density (ρ) kg/m^3	Thermal Conductivity (K) w/mk	Specific heat (°C)	Compressive strength (kg/cm^2)	Thermal Resistance R-Value (m^{2}k/w)			Diffusivity (m^2/s)
				T=15 mm	T=25 mm	T=35 mm	
950.41	0.236	1000	80	0.233	0.275	0.318	2.48524E-07

Table 4.5- Results Obtained During and After Exposure to Fire of Perlite Plaster Coated Columns

Column Size (mmxmm)	Plaster Thickness (mm)	Post Fire Failure Load Load (ton)	Uncoated control (ton)	Time (min)	Max Temp. reached under coat (°C)
100x100	15	15.5	26	45	168.5
100x100	25	17.5		60	161.4
100x100	35	21.5		60*	118.5
100x200	15	43.5	41.5	51	168.6
100x200	25	49.5		60*	135 7
100x200	35	57.5		25 (error crack)	172
100x300	15	70	69	60	160.1
100x300	25	74.5		60*	140.1
100x300	35	75.5		60*	136.8

* *The furnace was switched off after one hour as it is designed to work only for one hour of a max Temp. Of 650°C, and they did not reach 140°C+ ambient, thus this means that their fire resistance exceeds one hour.*

From Table 4.5, it is observed that the load capacity of columns after fire decreases for the 100x100 column for all the three plaster thicknesses and that is might be due to the following: The amount of water in the 100x100 column is limited compared to other dimensions of the columns, and the same amount of heat energy of the furnace is passing to a smaller area (100x100 compared to 100x200 and 100x300), thus the center of the column reaches a high temperature that is close to that of the surface. This small difference in the temperature will make the water inside the concrete evaporates quickly and thus alters the bond initially present in the concrete, which might cause the decrease in the strength of the column

The strength in the 100x200x1000, and 100x300x1000 increased after cooling as the densification of the cement gel arises because of the loss of absorbed water. As attributed by Zoldners, 1960.

4.8 Comparison Between Perlite and Cement Plaster:

It is clear from Table from Tables 4.6, 4.7 and 4.8 that the Perlite Plaster increases the fire resistance time than the cement plaster for the same plaster thickness. This might be attributed to the high thermal diffusivity value of the cement plaster that reflects the time rate of a temperature change of a material between two of its surface. In addition, thermal conductivity of cement plaster is far higher than the Perlite plaster , thus heat will pass faster from the plaster surface to the undercoat surface quickly in cement

Also, The Perlite coated columns surface did not undergo major disintegration and was not that friable as the cement plaster as shown in Figure 4.20 . This is attributed to the insulating nature of the Perlite plaster and its fire retardant characteristics mentioned above.

Table 4.6- Results Obtained During and After Exposure to Fire of Perlite and Cement Plaster for the 100x100x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. Reached under plaster (°C)	
		Perlite	Cement		Perlite	Cement	Perlite	Cement
100x100	15	15.5	28.5	26	45	20	168.5	164.7
100x100	25	17.5	28.5		60	23	161.4	163.9
100x100	35	21.5	28.5		60*	25	118.5	166.7

Table 4.7- Results obtained during and after exposure to fire of Perlite and Cement Plaster for the 100x200x1000 columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Perlite	Cement		Perlite	Cement	Perlite	Cement
100x200	15	43.5	47.5	41.5	51	24	169	171
100x200	25	49.5	49		60*	27	136	166
100x200	35	57.5	64		25	35	172	167

Table 4.8- Results Obtained During and After Exposure to Fire of Perlite and Cement Plaster for the 100x300x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Perlite	Cement		Perlite	Cement	Perlite	Cement
100x300	15	70	72.5	69	60	25	160	168
100x300	25	74.5	76.5		60*	32	140	183
100x300	35	75.5	78		60*	35	137	171

* *The furnace was switched off after one hour as it is designed to work only for one hour of a max Temp. of 650°C, and the did not reach 140°C+ ambient, thus this means that their fire resistance exceeds one hour.*

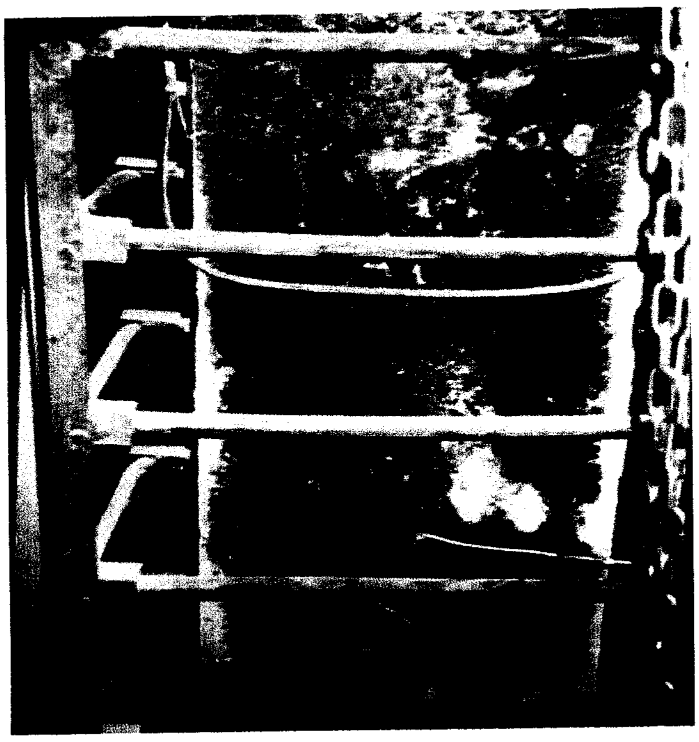

Figure 4. 20- Perlite plaster with cracks after fire exposure

Concerning the fire effect on strength, though the cement coated column- compressive strength was more (in some cases) than the Perlite coated column- compressive strength after fire, but still the reduction in the compressive strength in the Perlite does not go beyond 40% which means that the column can still carry its own load and did not fail. This might be attributed to the time of exposure to fire of the Perlite coated concrete columns compared to Cement plaster coated columns. As Perlite coated column surface took more time to reach 140C + ambient. This means that the thermal changes inside the Perlite coated concrete increases that might alters the bond initially present in the concrete and decrease its strength, especially that the columns are loaded during the test.

Thus in conclusion, The Perlite Plaster is better in fire resistance than the cement Plaster.

4.9 Test Results for Concrete Columns Coated with Vermiculite Plaster:

The change in the temperature with time for 100x100x1000 mm column coated with 15, 25, and 35 mm thick Vermiculite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.21 to 4.23. As shown in Figure 4.21, the temperature of the concrete surface under the plaster reached 163.2°C i.e. 140°C+ ambient temperature after 30 minutes. Also it was observed that after the column cooled, that the surface was completely deteriorated. The load recorded after fire was 21 ton compared to an uncoated control specimen load of 26 ton. Thus, there was a loss in strength of about 20%. As shown in Figure 4.22, the temperature of the concrete surface under the plaster reached 167.8°C i.e. 140°C+ ambient temperature after 48 minutes. Also it was observed that after the column cooled, that the surface was completely deteriorated. The load recorded after fire was 20.5 ton compared to a uncoated control specimen load of 26 ton. Thus, there was a loss in strength of about 21%. As shown in Figure 4.23, the temperature of the concrete surface under the plaster reached 120.1°C after 60 minutes, which means that it will stay more time to reach 140°C+ambient. Also it was observed that after the column cooled, that the surface was completely deteriorated, and de-bonding between the plaster and the column surface is observed. The load recorded after fire was 22 ton compared to a uncoated control specimen load of 26 ton. Thus, there was a loss in strength of about 15.5%

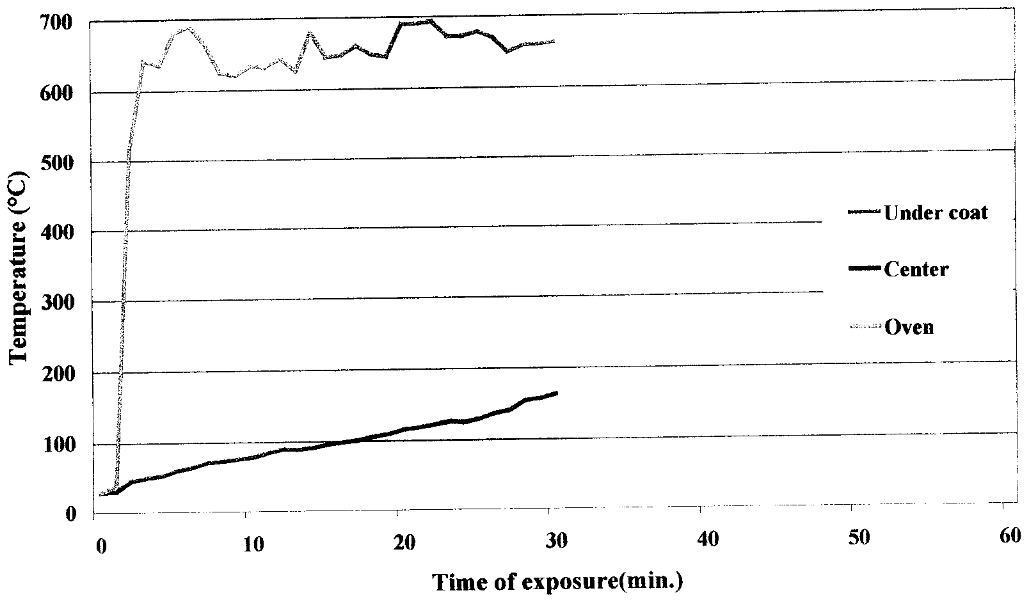

Figure 4.21- Temperature Curve of loaded 100x100x1000 mm Concrete Column Coated with 15 mm Vermiculite Concrete Plaster During Fire.

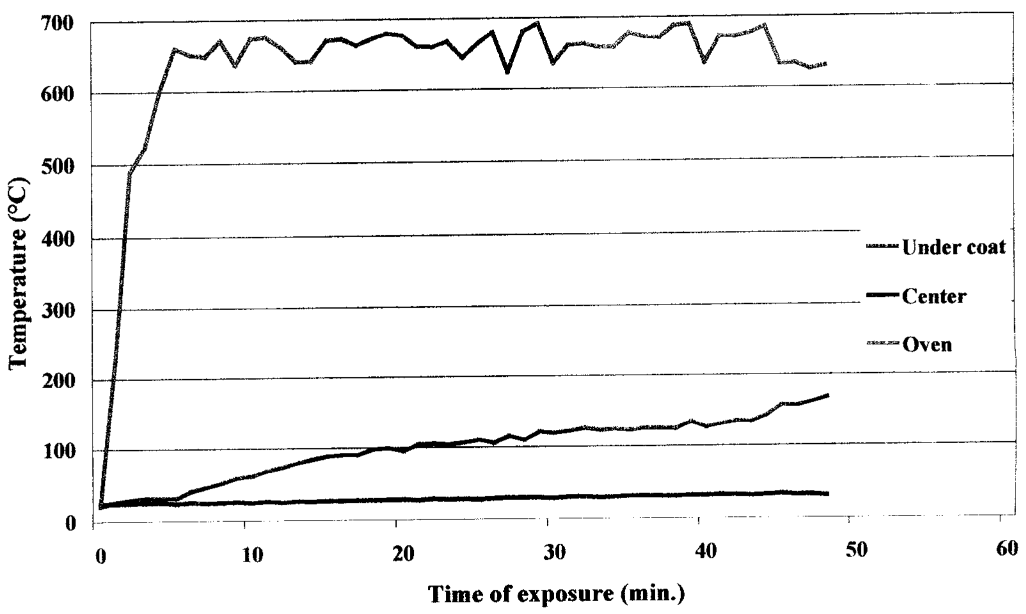

Figure 4.22- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 25 mm Vermiculite Concrete Plaster During Fire.

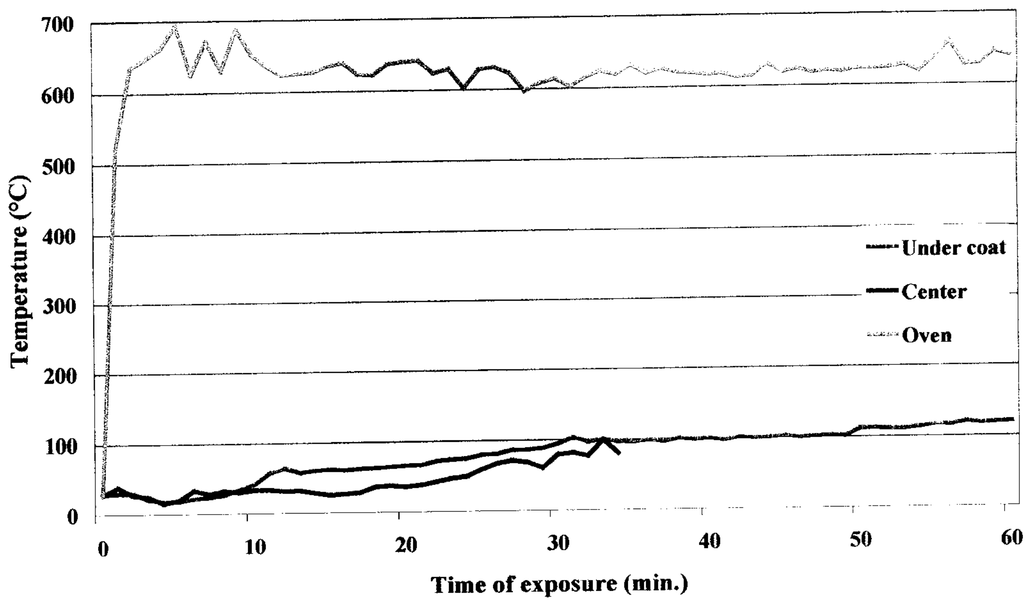

Figure 4.23- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 35 mm Vermiculite Concrete Plaster During Fire.

The change in the temperature with time for 100x200x1000mm columns coated with 15, 25, and 35 mm thick Vermiculite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.24 to 4.26. As shown in Figure 4.24, the temperature of the concrete surface under the plaster reached 171.4°C after 25 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated. The load recorded after fire was 47.5 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 15%. As shown in Figure 4.25, the temperature of the concrete surface under the plaster reached 166.7°C after 32 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated. The load recorded after fire was 49.5 ton compared to a uncoated control specimen load of 41.5ton. Thus, there was an increase in strength of about 20%. As shown in Figure 4.26, the temperature of the concrete surface reached suddenly 186.4°C after 45 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated, and de-bonding between the plaster and the column surface is observed. The load recorded after fire was 51.5 ton compared to a uncoated control specimen load of 41.5ton. Thus, there was an increase in strength of about 24%.

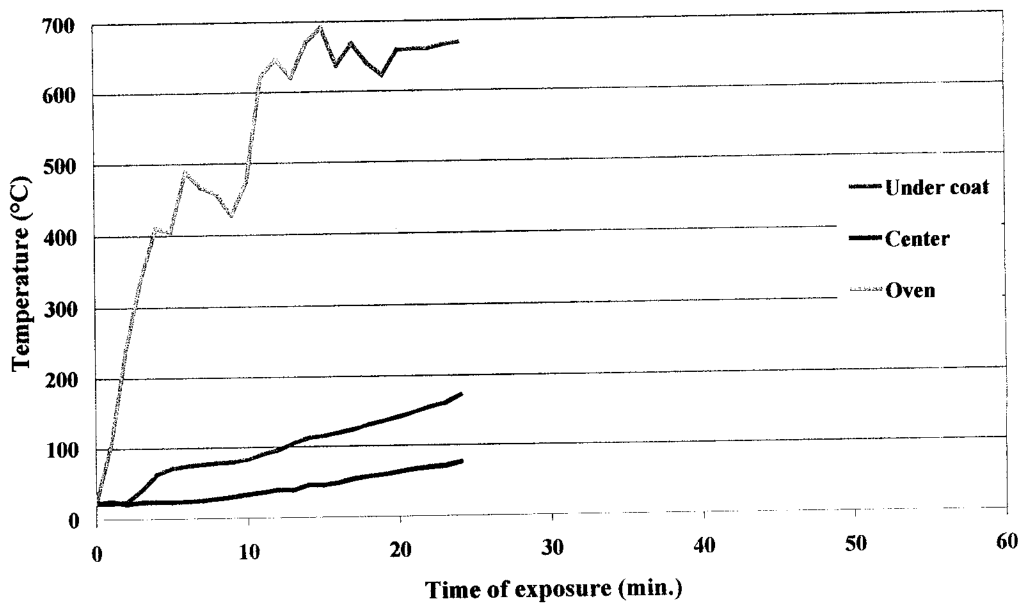

Figure 4.24- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 15 mm Vermiculite Concrete Plaster During Fire.

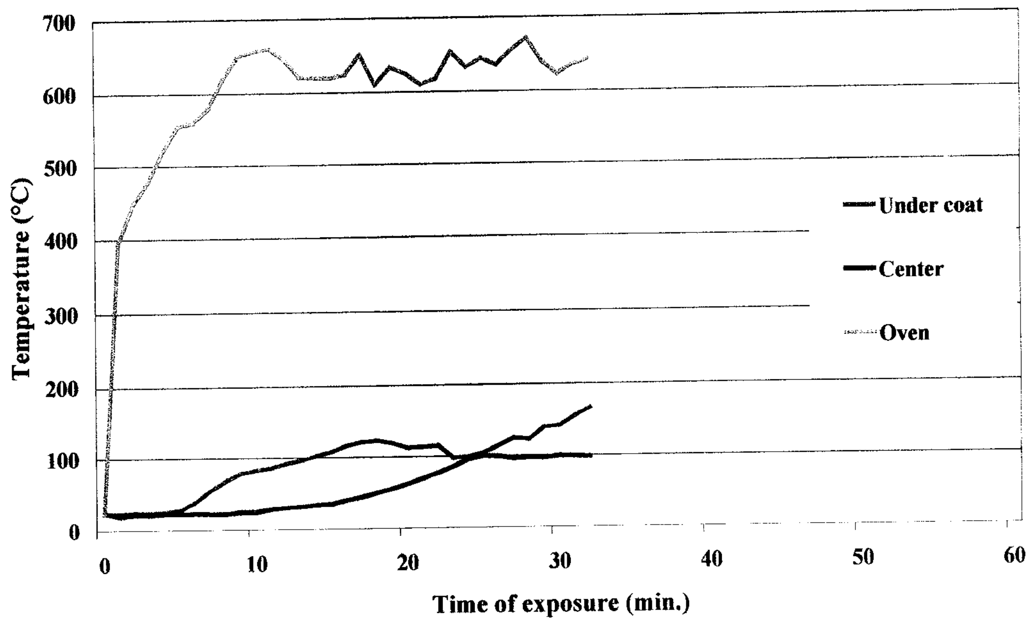

Figure 4.25- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 25 mm Vermiculite Concrete Plaster During Fire.

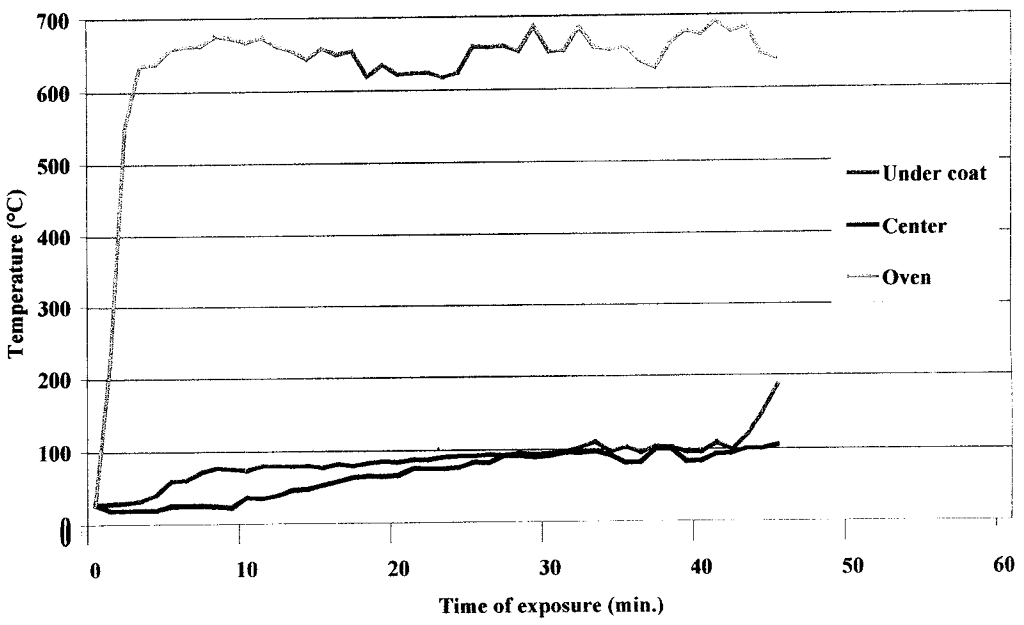

Figure 4.26- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 35 mm Vermiculite Concrete Plaster During Fire

The change in the temperature with time for 100x300x1000 mm column coated with 15, 25, and 35 mm thick Vermiculite concrete plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.27 to 4.29. As shown in Figure 4.27, the temperature of the concrete surface under the plaster reached suddenly 168.5°C after 34 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated. The load recorded after fire was 65 ton compared to a uncoated control specimen load of 69 ton. Thus, there was a loss in strength of about 6%. As shown in Figure 4.28, the temperature of the concrete surface under the plaster reached suddenly 164°C after 40 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated. The load recorded after fire was 69.5 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 1%. As shown in Figure 4.29, the temperature of the concrete surface under the plaster reached suddenly 167.5°C after 49 minutes. Also it was observed that after the column cooled, the surface was completely deteriorated. The load recorded after fire was 76 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 10%.

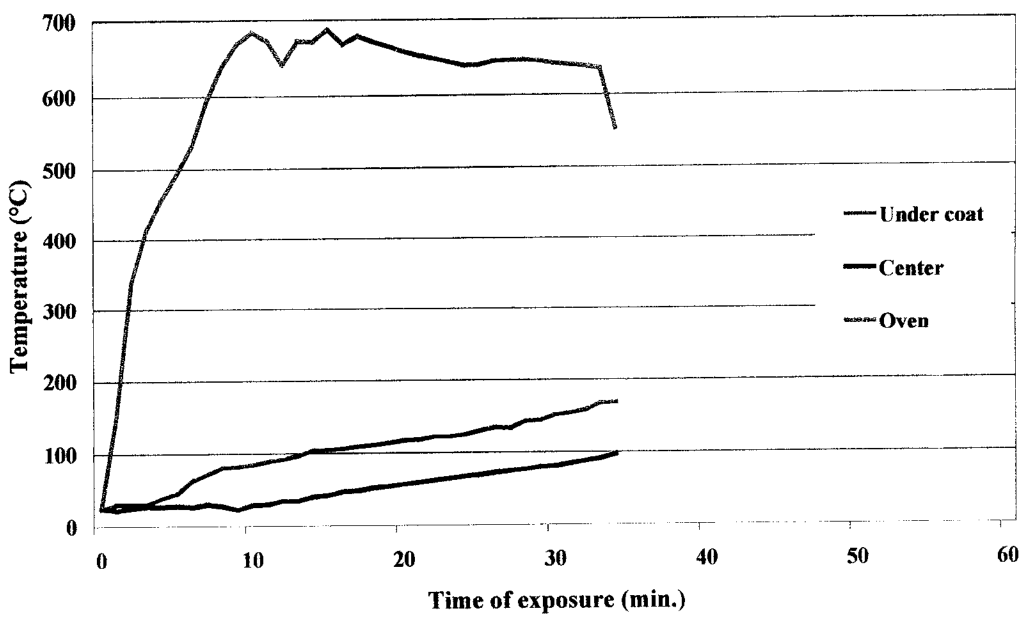

Figure 4.27- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 15 mm Vermiculite Concrete Plaster During Fire.

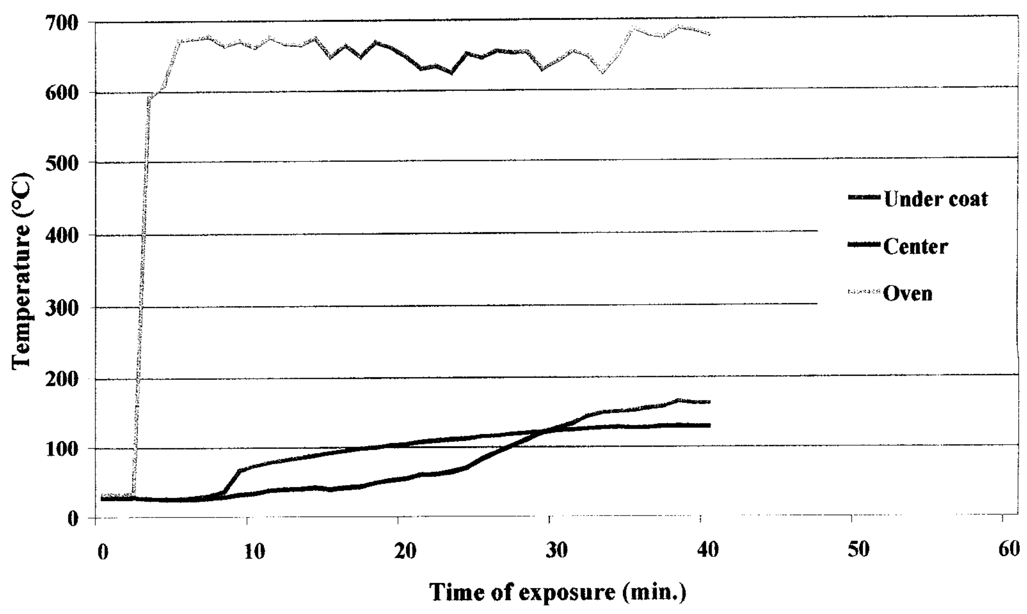

Figure 4.28- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 25 mm Vermiculite Concrete Plaster During Fire.

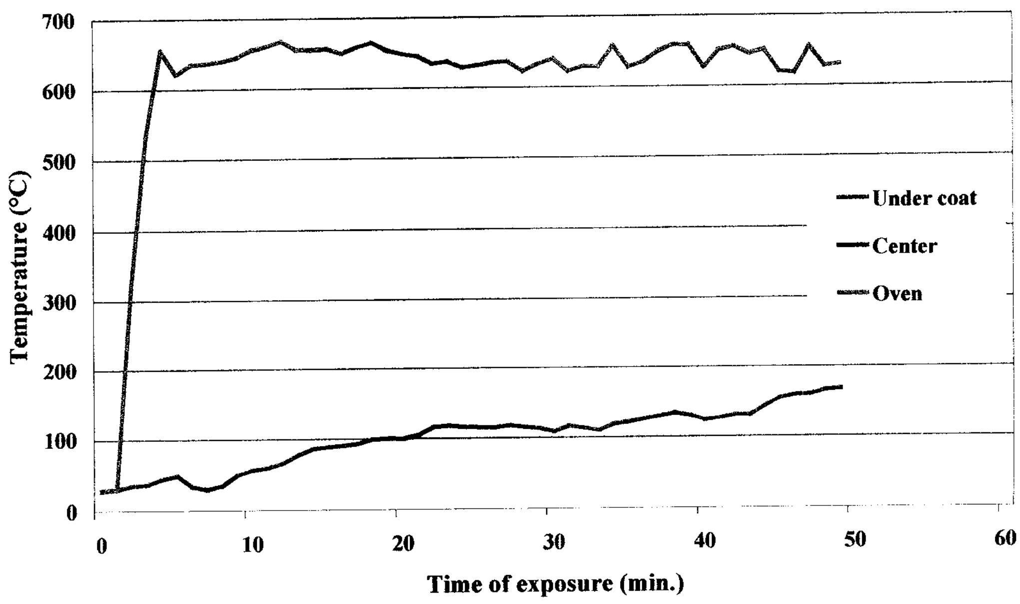

Figure 4.29- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 35 mm Vermiculite Concrete Plaster During Fire

4.10 Summary Results and Discussion of Vermiculite Plaster Performance:

When Vermiculite is heated to an elevated temperature, particles of Vermiculite exfoliate by expanding at right angles. This characteristics of the exfoliation is the result of the mechanical separation of the layers by the rapid conversion of contained water to steam (inter-laminar steam) (The Egyptian Vermiculite Industry).

The results obtained during and after fire exposure of Vermiculite plaster coated columns are shown in Table 4.10. The results show that, in the three dimensions of the columns 100x100x1000, 100x200x1000, 100x300x1000, fire resistance of the column increases with the increase of the coat thickness. This might be explained as the thickness increases, the thermal resistance (R-value) of the plaster increases as well, where the amount of free and bonding water increases. Thus the amount of heat dissipated in the decomposition of the hydration reaction, and the heat stored in the plaster increases, and the amount of heat passing through the plaster to reach the column surface decreases.

For the same plaster thickness, the fire resistance decreases with the increase of the column from 100x100 to 100x200 this is due to the following: Vermiculite has a high water content (higher than the water content of the other three types of plaster). when heat goes into the Vermiculite plaster, most of the water vapor thus formed will go to the colder interior of the concrete and reabsorbed in the voids. And as the thickness of the heated layer increases, all the water and water vapor will accumulate in the voids behind the heated layer. At a certain distance from the surface of the hot concrete, a saturated layer of some thickness (moisture clog) will be formed. The moisture clog will move to the interior of the concrete depending on the interior void structure and the heating rate. At the "interface" the water vapor is formed. The water vapor formed at the interface can't move to the inside as the interior layers are saturated with water, thus it will move to the heated layer. As the temperature increases gradually from the exterior to the interior, the temperature of the water vapor- and because of the restrained expansion, also the vapor pressure- rises at a high rate. The forces set up by the restraint expansion, that is formed between the heated layer and the saturated one, might produce a layer of almost the thickness of the heated dried out outer layer that will be separated from the surface of the concrete. (Copier, 1979).

Thus from the previous description of the internal moisture migration, the moisture content can influence such migration. As the moisture content increases, so the probability of the formation of a saturated layer increases, and thus increases spalling which allows heat more to strike behind the Vermiculite plaster and increase the surface temperature of the concrete column. (Copier, 1979).

However, for the same plaster thickness, the fire resistance increases slightly with the increase of the column from 100x200 to 100x300 this is due to the following:

The following above reasons are valid concerning the moisture migration, but in such case, the amount of Vermiculite exposed increases, thus such an increases in area exposed results in slightly increasing the fire resistance of the columns.

Table 4.9- Thermo-Physical Properties of Vermiculite Plaster

Thermal and Mechanical Properties				**Thermal Characteristics**			
Density (ρ) kg/m^3	Thermal Conductivity (K) w/mk	Specific heat (°C)	Compressive strength (kg/cm^2)	Thermal Resistance R-Value (m^{2}k/w)			Diffusivity (m^2/s)
				T=15 mm	T=25 mm	T=35 mm	
903.6	0.222	1100	46.6	0.237	0.282	0.327	2.2413E-07

Table 4.10- Results Obtained During and After Exposure to Fire of Vermiculite Coated Columns

Column Size (mmxmm)	**Plaster Thickness (mm)**	**Post Fire Failure Load (ton)**	**Uncoated control (ton)**	**Time (min)**	**Max Temp. reached under plaster (°C)**
100x100	15	21		30	163.2
100x100	25	20.5	26	48	167.8
100x100	35	22		60*	139.5
100x200	15	47.5		25	171.4
100x200	25	49.5	41.5	32	166.7
100x200	35	51.5		45	186.4
100x300	15	65		34	168.5
100x300	25	69.5	69	41	164
100x300	35	76		50	167.5

**The furnace was switched off after one hour as it is designed to work only for one hour of a max Temp. of 650°C, and the did not reach 140°C+ ambient, thus this means that their fire resistance exceeds one hour.*

From Table 4.10, it's observed that the load capacity of columns after fire decreased for the 100x100 column for all the three plaster thicknesses and that might be due to the following: The amount of water in the 100x100 column is limited compared to the other dimensions of the columns, and the same amount of heat energy is entering to a smaller dimension. Thus, this might alters the bond initially present in the concrete, which decreases the strength of the column

The strength in the 10x200x1000, and 100x300x1000 increased after cooling as the densification of the cement gel arises because of the loss of absorbed water as attributed to by Zoldners, 1960.

4.11 Comparison Between Vermiculite and Cement Plaster:

It is clear from Table from Tables 4.11, 4.12 and 4.13 that the Vermiculite Plaster increases the fire resistance time than the cement plaster for the same plaster thickness. This might be attributed to the high thermal diffusivity value of the cement plaster that reflects the time rate of a temperature change of a material between two of its surface. In addition, thermal conductivity of cement plaster is far higher than the Vermiculite plaster , thus heat will pass faster from the cement plaster surface to the undercoat surface quickly.

As for the disintegration of the cement plaster, the surface of the Vermiculite plaster undergoes deterioration of the surface, but still the plaster is somehow intact with the surface of the concrete, whereas, the cement plaster is friable and can be taken apart by hand. This is shown in the Figure 4.30.

Table 4.11- Results Obtained During and after Exposure to Fire of Vermiculite and Cement Plaster for the 100x100x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Verm - iculite	Cement		Verm - iculite	Cement	Verm - iculite	Cement
100x100	15	21	28.5	26	30	20	163.2	164.7
100x100	25	20.5	28.5		48	23	167.8	163.9
100x100	35	22	28.5		60	25	139.5	166.7

Table 4.12- Results Obtained During and After Exposure to Fire of Vermiculite and Cement Plaster for the 100x200x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Verm - iculite	Cement		Verm - iculite	Cement	Verm - iculite	Cement
100x200	15	47.5	47.5	41.5	24	25	24	171.2
100x200	25	49.5	49		32	27	32	165.7
100x200	35	51.5	64		45	35	45	167.1

Table 4.13- Results Obtained During and After Exposure to fire of Vermiculite and Cement Plaster for the 100x300x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Verm - iculite	Cement		Verm - iculite	Cement	Verm - iculite	Cement
100x300	15	65	72.5	69	34	25	169	168
100x300	25	69.5	76.5		41	32	164	183
100x300	35	76	78		50	35	168	171

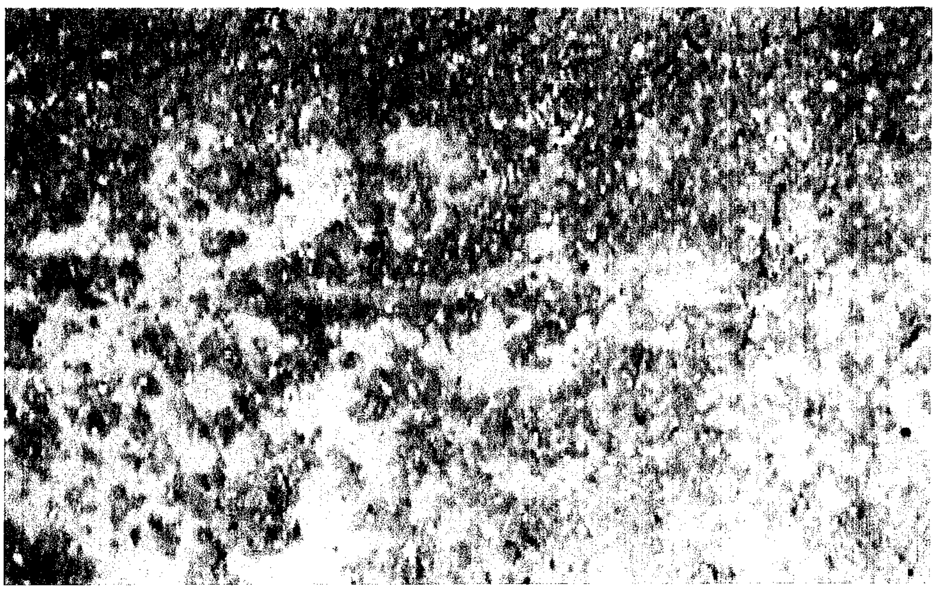

Figure 4.30- Vermiculite surface after exposure to fire

Concerning strength, though the Cement coated columns compressive strength was more (in some cases) than the Vermiculite compressive strength after fire, but still the reduction in the compressive strength in the Vermiculite does not go beyond 20% which means that the column can still carry its own load and did not fail.

Thus in conclusion, The Vermiculite Plaster provides better fire resistance than the cement Plaster.

4.12 Test Results for Concrete Columns Coated with Rock wool Plaster:

The change in the temperature with time for 100x100x1000 mm column coated with 15, 25, and 35 mm thick Rock wool plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.31 to 4.33. As shown in Figure 4.31 the temperature of the concrete surface under the plaster reached 164.3°C after 29 minutes. Also it was observed that after the column cooled, hair cracks were observed. The load recorded after fire was 21.5 ton compared to an uncoated control specimen load of 26 ton. Thus, there was a loss in strength of about 17.5%. As shown in Figure 4.32, the temperature of the concrete surface under the plaster reached suddenly 169.7° C after 40 minutes. Also it was observed that after the column cooled, hair cracks were observed and no separation of the plaster. The load recorded after fire was 27 ton compared to a uncoated control specimen load of 26 ton. Thus, there was an increase in strength of about 4%. As shown in Figure 4.33, the temperature of the concrete surface under the plaster reached 120.1°C after 60 minutes, this means that this column can stay for more than one hour to fail. Also it was observed that after the column cooled, hair cracks were observed and slight de-bonding between the plaster and the concrete surface took place. The load recorded after fire was 28 ton compared to a uncoated control specimen load of 26 ton. Thus, there was an increase in strength of about 8%

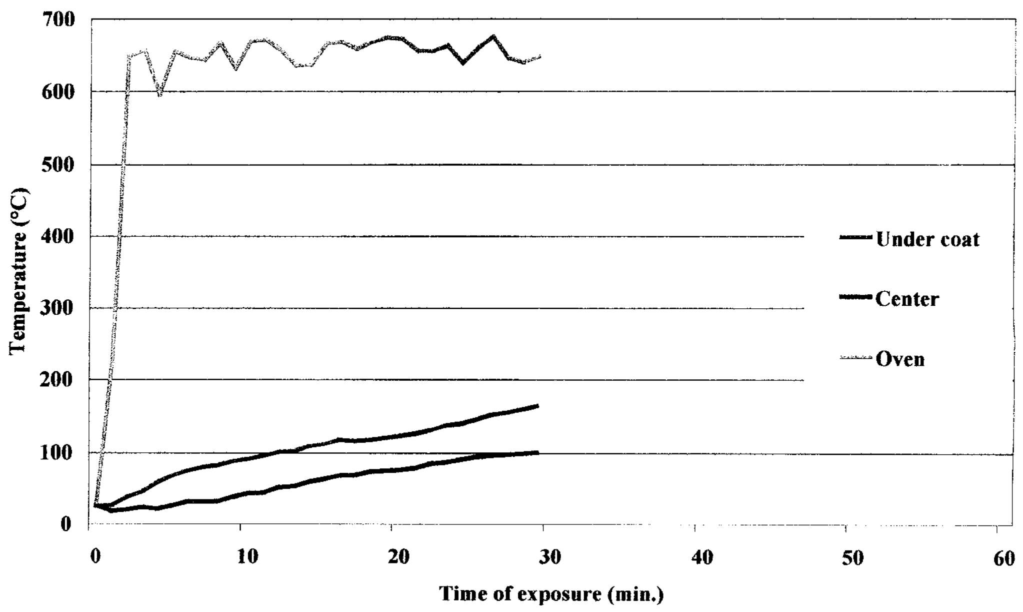

Figure 4.31- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 15 mm Rock wool Plaster during Fire.

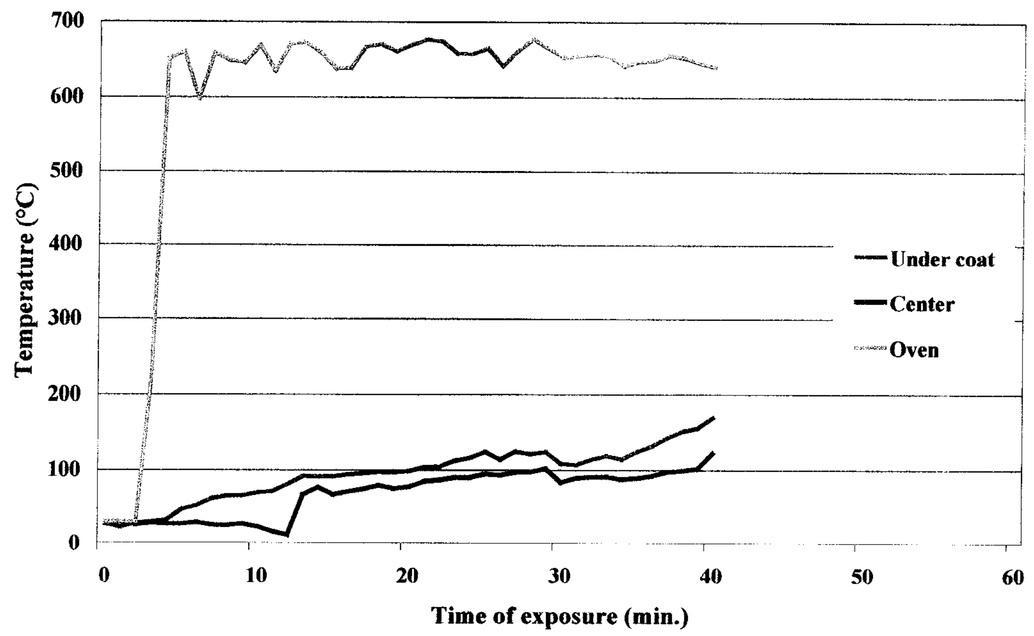

Figure 4.32- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 25 mm Rock wool Plaster during Fire.

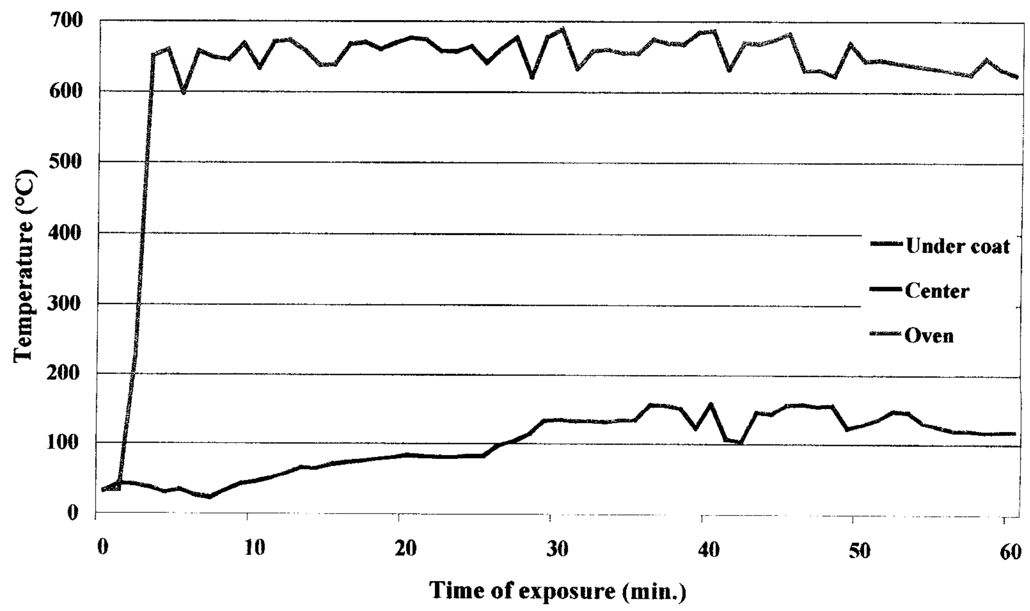

Figure 4.33- Temperature Curve of Loaded 100x100x1000 mm Concrete Column Coated with 35 mm Rock wool Plaster during Fire

The change in the temperature with time for 100x200x1000-mm columns coated with 15, 25, and 35 mm thick Rock wool plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.34 to 4.36. As shown in Figure 4.34 the temperature of the concrete surface under the plaster reached 165.7°C after 37 minutes. Also it was observed that after the column cooled, hair cracks were observed. The load recorded after fire was 47.5 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 15%. As shown in Figure 4.35, the temperature of the concrete surface under the plaster reached suddenly 167.5 °C after 46 minutes. Also it was observed that after the column cooled, hair cracks were observed and no separation of the plaster. The load recorded after fire was 49.5 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 19.5%. As shown in Figure 4.36, the temperature of the concrete surface under the plaster reached 117.8°C after 60 minutes, this means that this column can stay for more than one hour to fail. Also it was observed that after the column cooled, hair cracks were observed and no separation of the plaster. The load recorded after fire was 52 ton compared to a uncoated control specimen load of 41.5 ton. Thus, there was an increase in strength of about 25.5%

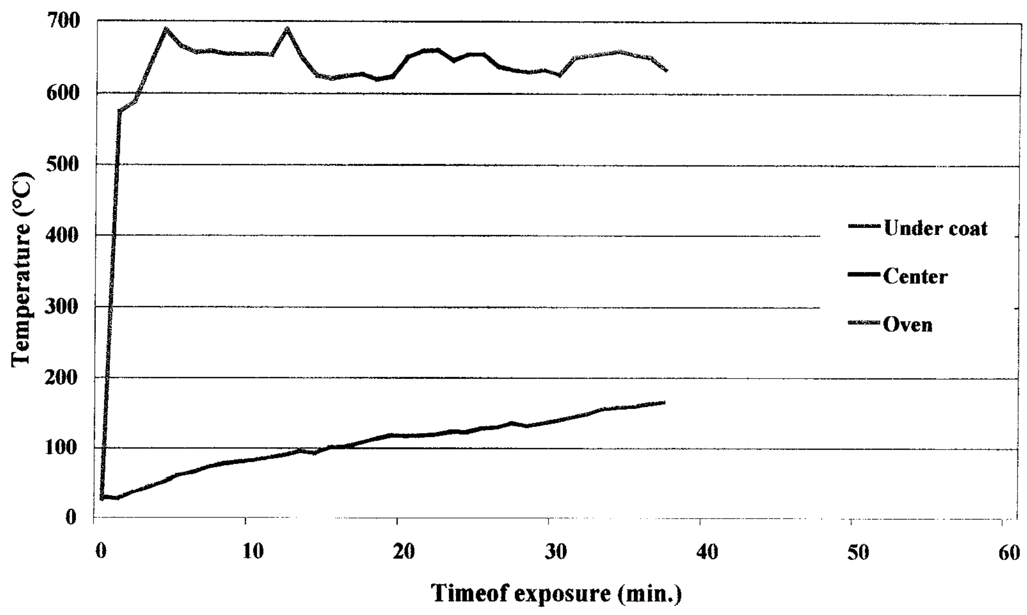

Figure 4.34- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 15 mm Rock wool Plaster During Fire.

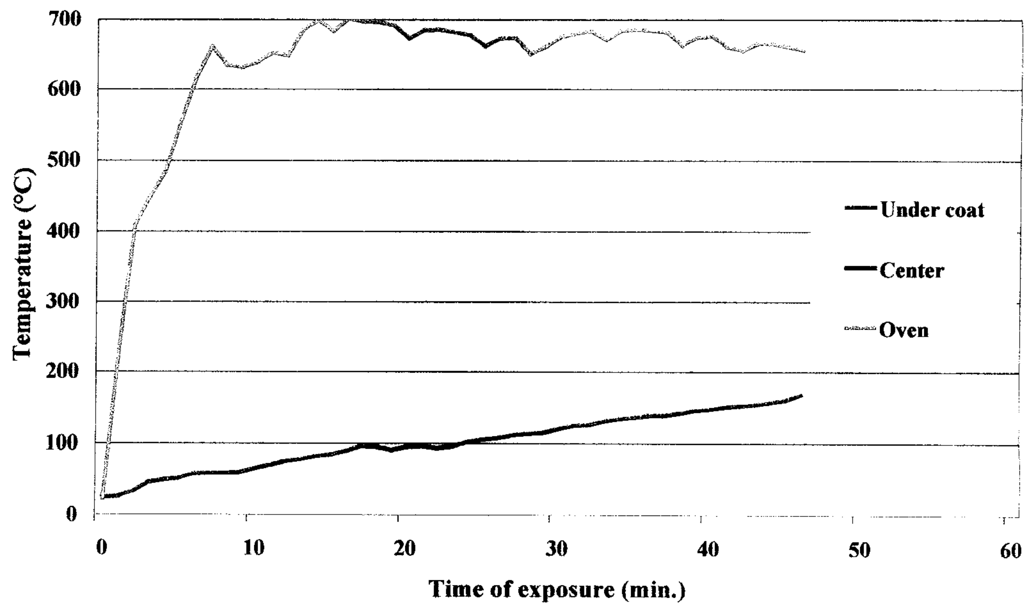

Figure 4.35- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 25 mm Rock wool Plaster During Fire.

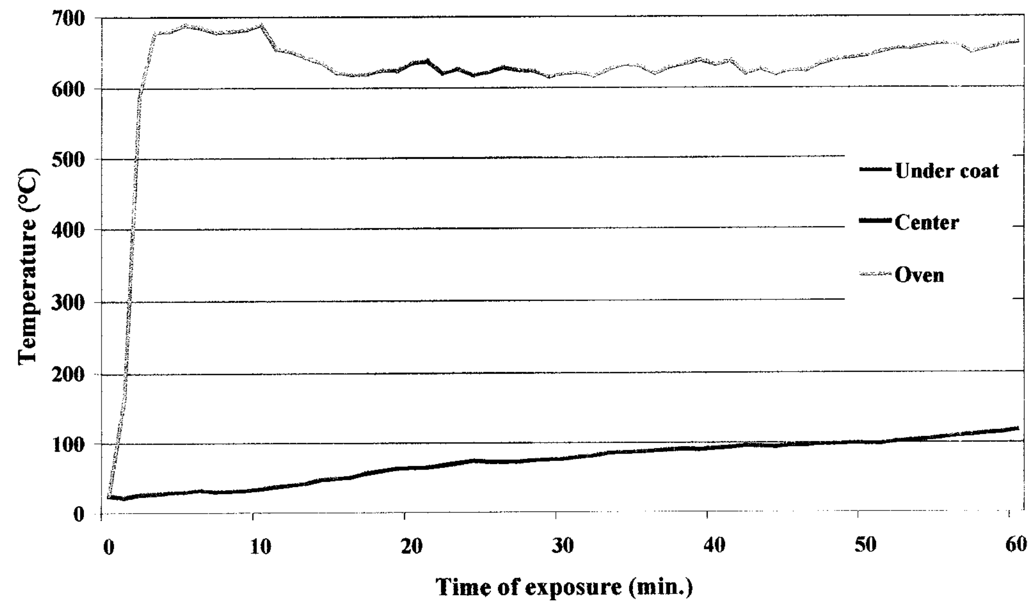

Figure 4.36- Temperature Curve of Loaded 100x200x1000 mm Concrete Column Coated with 35 mm Rock wool Plaster During Fire.

The change in the temperature with time for 100x300x1000 mm columns coated with 15, 25, and 35 mm thick Rock wool plaster respectively, and exposed to fire from all the four sides in a furnace at 650°C is illustrated as shown in Figures 4.37 to 4.39. As shown in Figure 4.37 the temperature of the concrete surface reached 164.5°C after 51 minutes. Also it was observed that after the column cooled, hair cracks were observed. The load recorded after fire was 69 ton compared to an uncoated control specimen load of 69 ton. Thus the strength is not affected by fire. As shown in Figure 4.38, the temperature of the concrete surface under the plaster reached suddenly 169.4 °C after 55 minutes. Also it was observed that after the column cooled, hair cracks were observed and no separation of the plaster. The load recorded after fire was 72.5 ton compared to an uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 6%. As shown in Figure 4.39, the temperature of the concrete surface under the plaster reached suddenly 170°C after 40 minutes, this was due to an error crack observed at the thermocouple location inserted at the center of the column due to an error in casting. Also it was observed that after the column cooled, hair cracks were observed and slight de-bonding between the plaster and the concrete surface took place. The load recorded after fire was 81 ton compared to a uncoated control specimen load of 69 ton. Thus, there was an increase in strength of about 17.5%

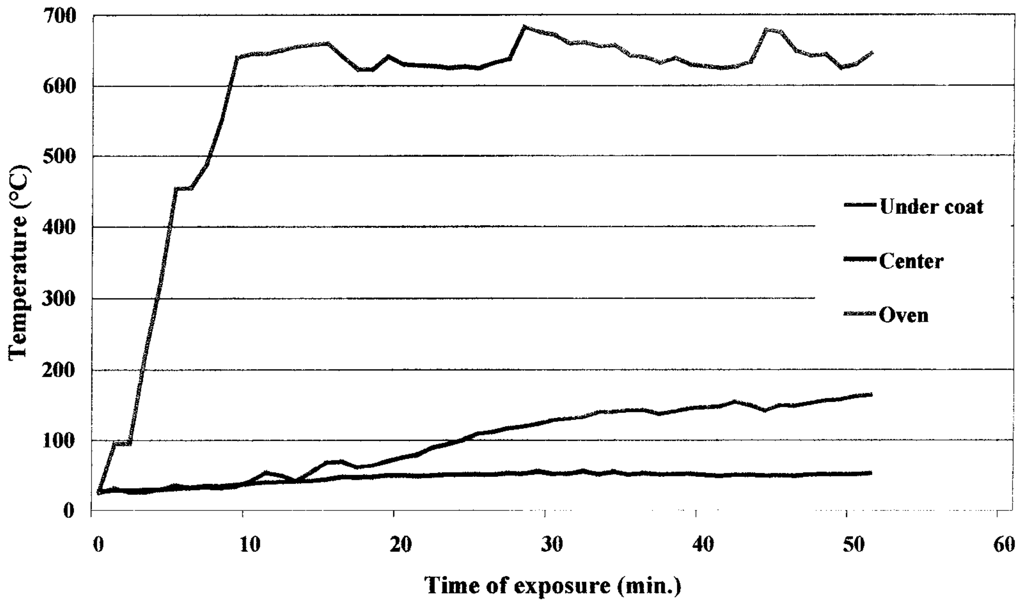

Figure 4.37- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 15 mm Rock wool Plaster During Fire.

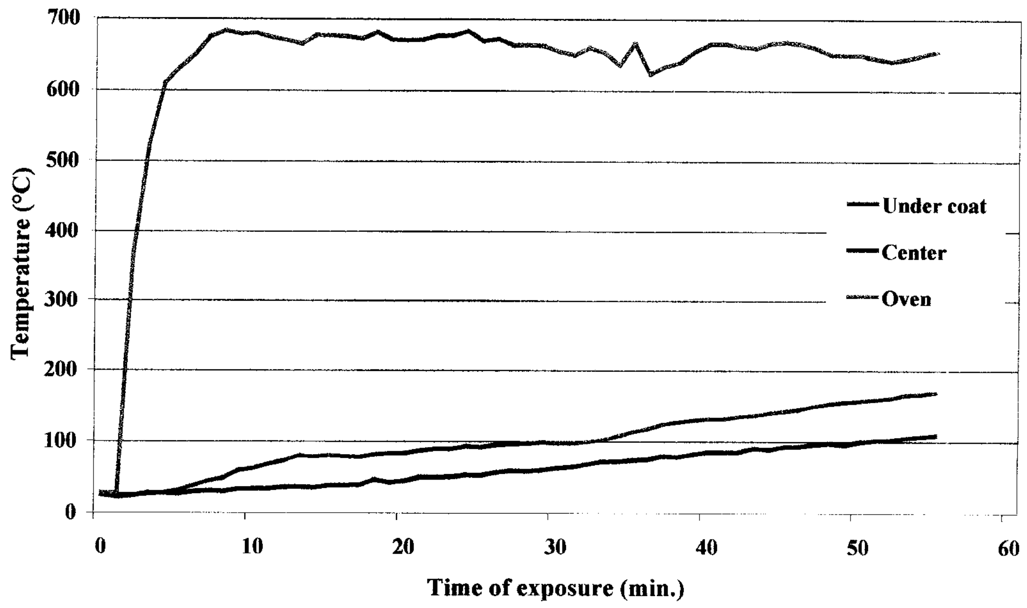

Figure 4.38- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 25 mm Rock wool Plaster During Fire.

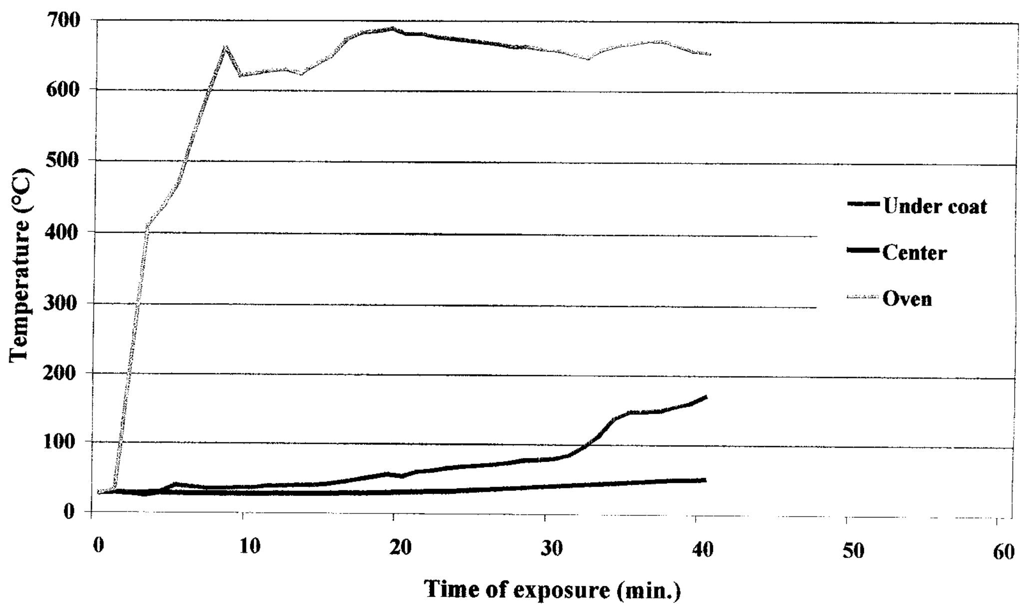

Figure 4.39- Temperature Curve of Loaded 100x300x1000 mm Concrete Column Coated with 35 mm Rock wool Plaster During Fire.

4.13 Summary Results and Discussion on Rock wool Plaster:

Rock wool is made of stone and therefore cannot burn. It resists temperatures higher than 1,000°C. As it is heated, the resin binder evaporates; this only occurs in the hot outer layer. Even without this binder the rock fibers remain intact, protecting the rest of the material. This is a very important quality under fire conditions. Rock wool therefore acts as a shield against fire when it is incorporated in the structural members of the building. When the temperature rises above 250°C, the binder will evaporate in the zone, which is exposed and their in-built cohesiveness and layering will keep the fibers together, ensuring that the material will retain its rigidity and protect the material beneath it from being affected by the fire. (VJF Marketing and Constancy LTD). Also, upon the evaporation of the binder, the voids will be filled by air and that will increase the pressure inside the plaster that might result in hair cracks to appear on the surface.

Table 4.14- Thermo-Physical Properties of Rock wool Plaster

Thermal and Mechanical Properties							**Thermal Characteristics**
Density (ρ) kg/m^3	Thermal Conductivity (K) w/mk	Specific heat (°C)	Compressive strength (kg/cm^2)	Thermal Resistance R-Value (m^2k/w)			Diffusivity (m^2/s)
				T=15 mm	T=25 mm	T=35 mm	
751.9	0.184	940	40	0.251	0.306	0.360	2.60752E-07

Table 4.15- Results Obtained During and After Fire Exposure for Rock wool Coated Concrete Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)	Uncoated control (ton)	Time (min)	Max Temp. reached under plaster (°C)
100x100	15	21.5	26	29	164.3
100x100	25	27		40	169.7
100x100	35	28		60*	120.1
100x200	15	47.5	41.5	37	165.7
100x200	25	49.5		46	167.5
100x200	35	52		60*	117.8
100x300	15	69	69	51	164.5
100x300	25	72.5		55	169.4
100x300	35	81		40(error crack at the thermocouple location)	170

** The furnace was switched off after one hour as it is designed to work only for one hour of a max Temp. of 650°C, and the did not reach 140°C+ ambient, thus this means that their fire resistance exceeds one hour.*

The results obtained during and after fire exposure of Rock wool plaster coated columns are shown in Table 4.15. The results show that, in the three dimensions of the columns100x100x1000, 100x200x1000, 100x300x1000, fire resistance of the column increases with the increase of the plaster thickness. This might be explained as the thickness increases, the thermal resistance (R-value) of the plaster increases as well, where the amount of free and bonding water increases. Thus the amount of heat dissipated in the decomposition of the hydration reaction, and the heat stored in the plaster increases, and the amount of heat passing through the plaster to reach the column surface decreases.

Also, for different column dimensions100x100x1000, 10x200x1000, 10x300x1000, the same plaster thickness gives different fire resistance. This might be attributed to that the area exposed to fire increases by the increase in the size of the column, where the amount of water present in the mix of the plaster is higher, thus the moisture migration increases as well. Therefore, heat required evaporating the water increases, and thus more time is needed to reach the same temperature upon increasing of the column dimension.

From Table 4.14, it's observed that the load capacity of columns after fire decreased for the 100x100 column for all the three plaster thicknesses and that is might be due to the following: The amount of water in the 100x100 column is limited compared to the other dimensions of the columns, and the same amount of heat energy is entering to a smaller dimension, thus the net results of the expansion and shrinkage occurs in a limited area, and that alters the bond initially present in the concrete, which decreases the strength of the column

The strength in the 10x200x1000, and 100x300x1000 increased after cooling as the densification of the cement gel arises because of the loss of absorbed water as attributed to by Zoldners, 1960.

4.14 Comparison Between Rock wool and Cement Plaster:

It is clear from Table from Tables 4.16, 4.17 and 4.18 that the Rock wool Plaster increases the fire resistance time than the cement plaster for the same plaster thickness.

As for the disintegration of surface, the surface of the Rock wool plaster experienced only hair cracks on the surface and undergoes slight de-bonding from the column surface shown in Figure 4. 40, whereas, the cement plaster is friable and can be taken apart by hand.

Table 4.16- Results Obtained During and After Exposure to Fire of Rock wool and Cement Plaster for the 100x100x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (°C)	
		Rock wool	Cement		Rock wool	Cement	Rock wool	Cement
100x100	15	21.5	28.5	26	29	20	164.3	164.7
100x100	25	27	28.5		40	23	169.7	163.9
100x100	35	28	28.5		60	25	120.1	166.7

Table 4.17- Results Obtained During and After Exposure to Fire of Rock wool and Cement Plaster for the 100x200x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time (min)		Max Temp. reached under plaster (C)	
		Rock wool	Cement		Rock wool	Cement	Rock wool	Cement
100x200	15	47.5	47.5	41.5	37	24	166	171.2
100x200	25	49.5	49		46	27	168	165.7
100x200	35	52	64		60	35	118	167.1

Table 4.18- Results Obtained During and After Exposure to Fire of Rock wool and Cement Plaster for the 100x300x1000 Columns

Column Size (mmxmm)	Plaster Thick-ness (mm)	Post Fire Failure Load (ton)		Uncoated control (ton)	Time(min)		Max Temp. reached under plaster (C)	
		Rock wool	Cement		Rock wool	Cement	Rock wool	Cement
100x300	15	69	72.5	69	51	25	165	168
100x300	25	72.5	76.5		5	32	169	183
100x300	35	81	78		40	35	170	171

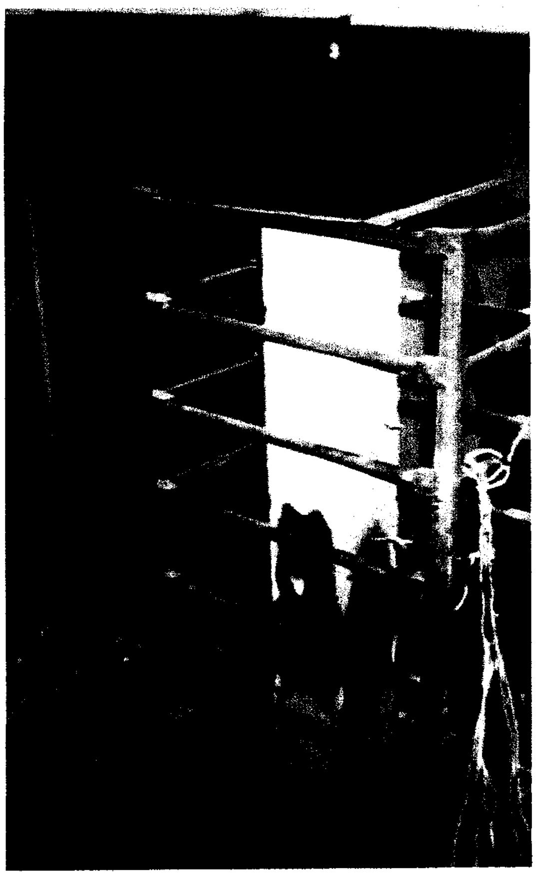

Figure 4.40- Rock wool Plaster After Fire

Concerning strength, though the cement coated columns-compressive strength was more (in some cases) than the Rock wool coated columns -compressive strength after fire, but still the reduction in the compressive strength in the Rock wool does not go beyond 17% which means that the column can still carry its own load and did not fail. Thus in conclusion, The Rock wool Plaster is better than the cement Plaster.

4.15 Comparison Between Perlite, Vermiculite, Rock wool and Conventional Cement Plaster:

4.15.1 For Column Dimension 100x100x1000

The effect of the plaster type for thickness 15,25, 35 mm respectively on 100x100x1000 columns is shown as illustrated in Figures 4.41 to 4.43 The alterations of the temperature till it reach 140°C + ambient temperature in each column might be due to the moisture migration inside the column while heating.

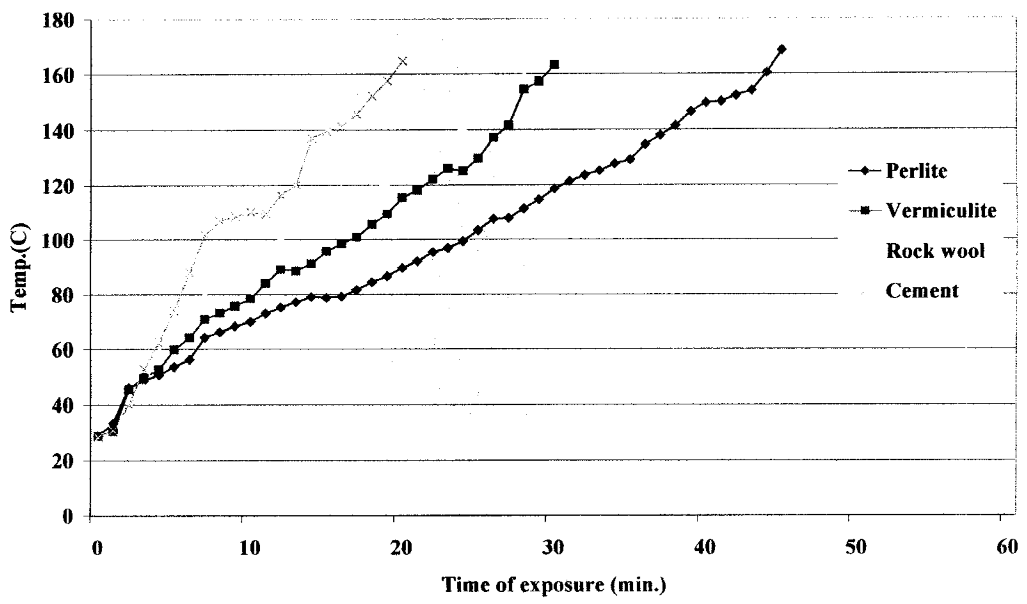

Figure 4.41- Effect of Plaster Type with thickness of 15 mm on 100x100x1000 Column

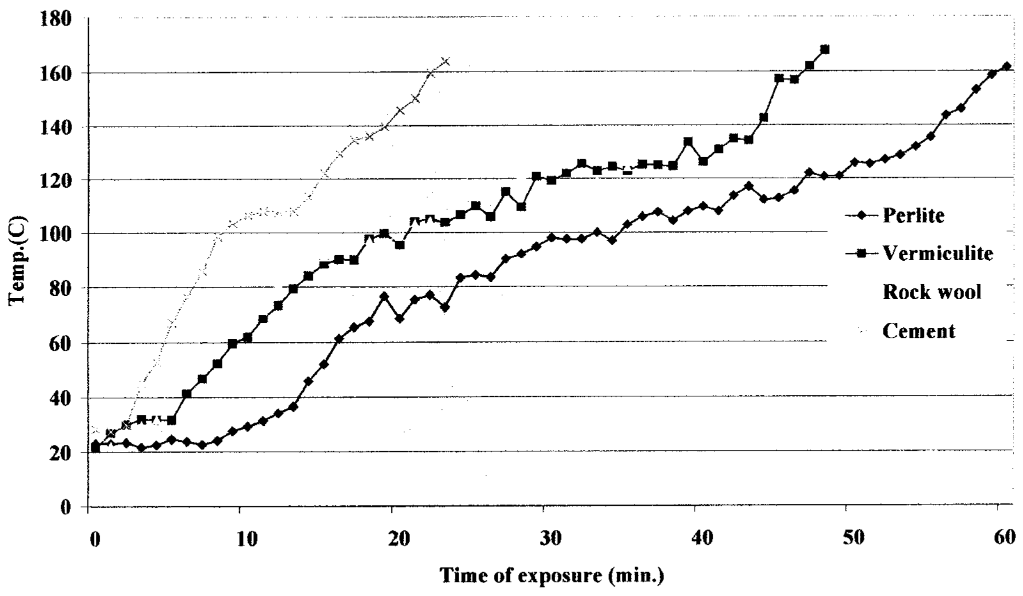

Figure 4.42- Effect of Plaster Type with thickness of 25 mm on 100x100x1000 Column

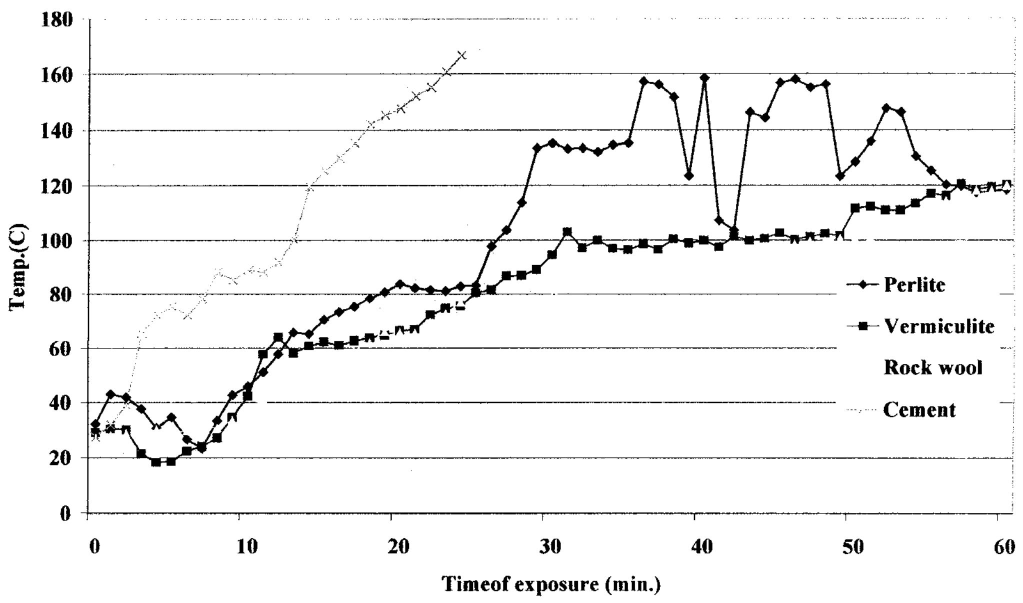

Figure 4.43- Effect of Plaster Type with thickness of 35 mm on 100x100x1000 Column

The effect of high temperature on the strength of 100x100x1000 columns with a 15, 25 and 35 mm plaster thick of Perlite, Vermiculite, Rock wool, and Cement plaster is shown as illustrated in Figures 4.44 to 4.46.

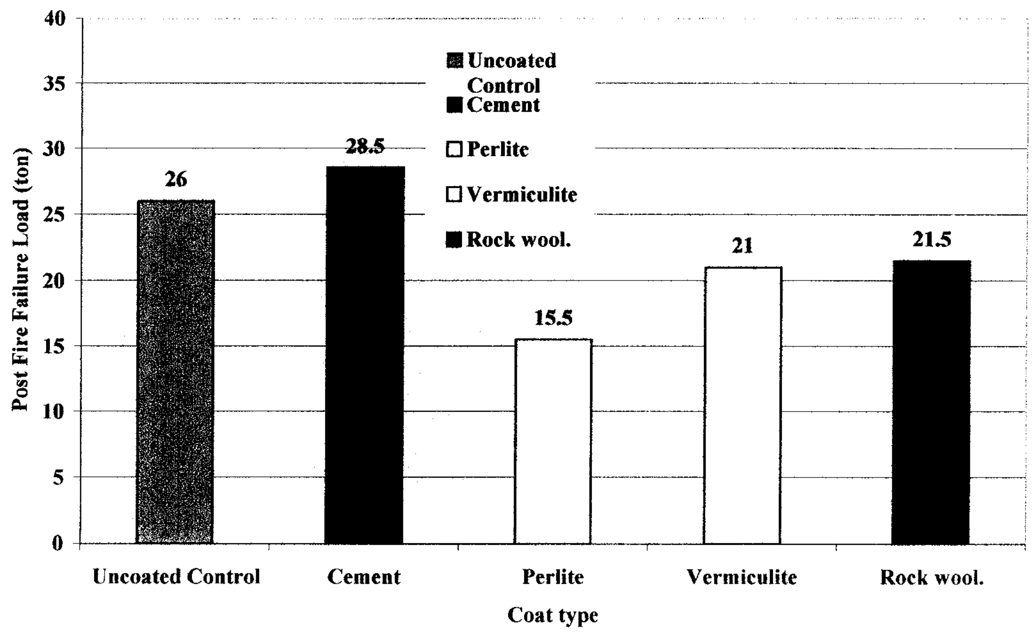

Figure 4.44- Effect of High Temperature on Strength for 100x100x1000 Columns Coated with 15 mm Thick Plaster.

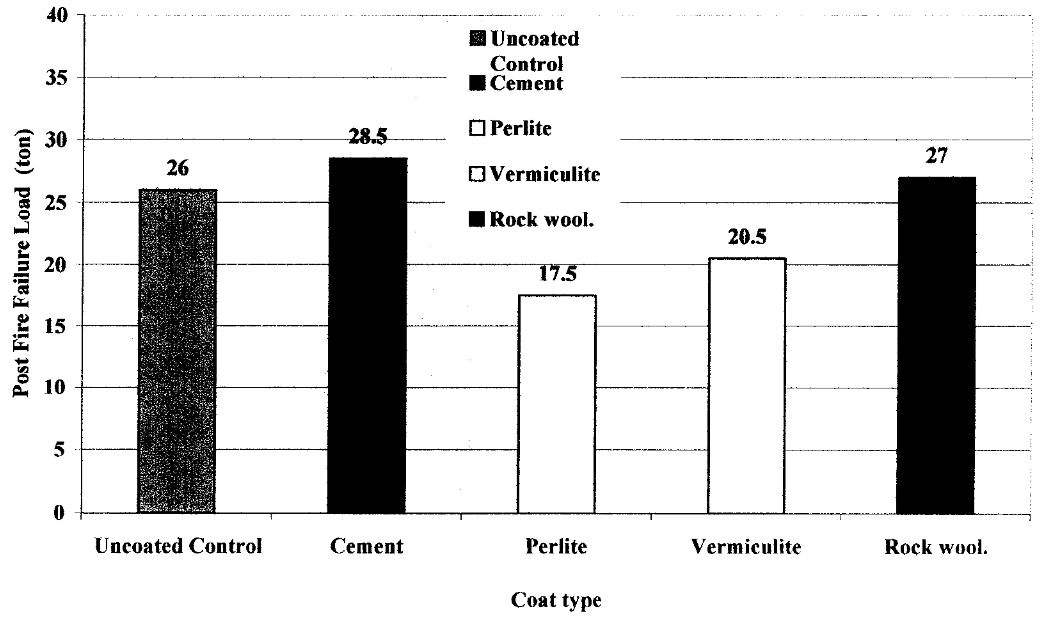

Figure 4.45- Effect of High Temperature on Strength for 100x100x1000 Columns Coated with 25 mm Thick Plaster

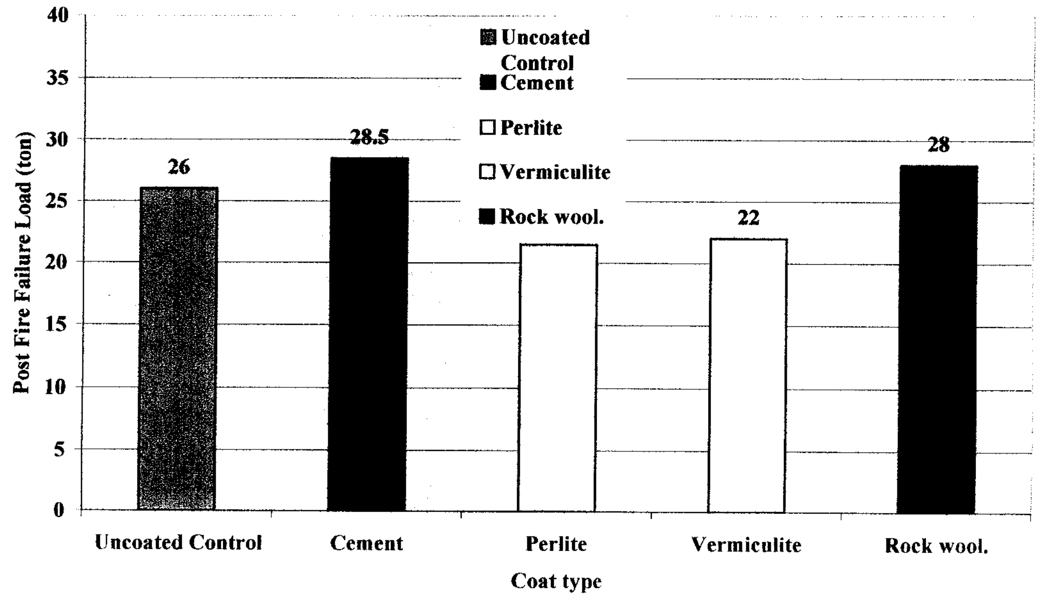

Figure 4.46- Effect of High Temperature on Strength for 100x100x1000 Columns Coated with 35 mm Thick Plaster

Table 4.19- Comparison of the Performance of 100x100X1000 mm Column Coated with Perlite, Vermiculite, Rock wool and Cement Plaster

Column Dimension (mm)	**100x100x1000**					
Load/ Time Effect	**Time Effect (min)**			**Load Effect (% increase)**		
Plaster Thickness (mm)	**15**	**25**	**35**	**15**	**25**	**35**
Perlite Plaster	45	60	60 (118.5)			**-17**
Vermiculite Plaster	30	48	*60 (120.5)	**-19**	**-21**	**-15**
Rock Wool Plaster	**29**	**40**	**60 (120.1)**	**-17**	4	8
Cement Plaster				9.6	9.6	9.6

(Temperature reached after 60 minutes and does not reach 140C + ambient)

	2 (GOOD)		4 (BEST)

4.14.2 For Column Dimension 100x200x1000

The effect of the plaster type for thicknesses 15,25, 35 mm respectively on 100x200x1000 columns is shown as illustrated in Figures 4.47 to 4.49.

Scanning Thermometer one-minute increment temperature readings for these groups are presented in Appendix A, B, C, and D.

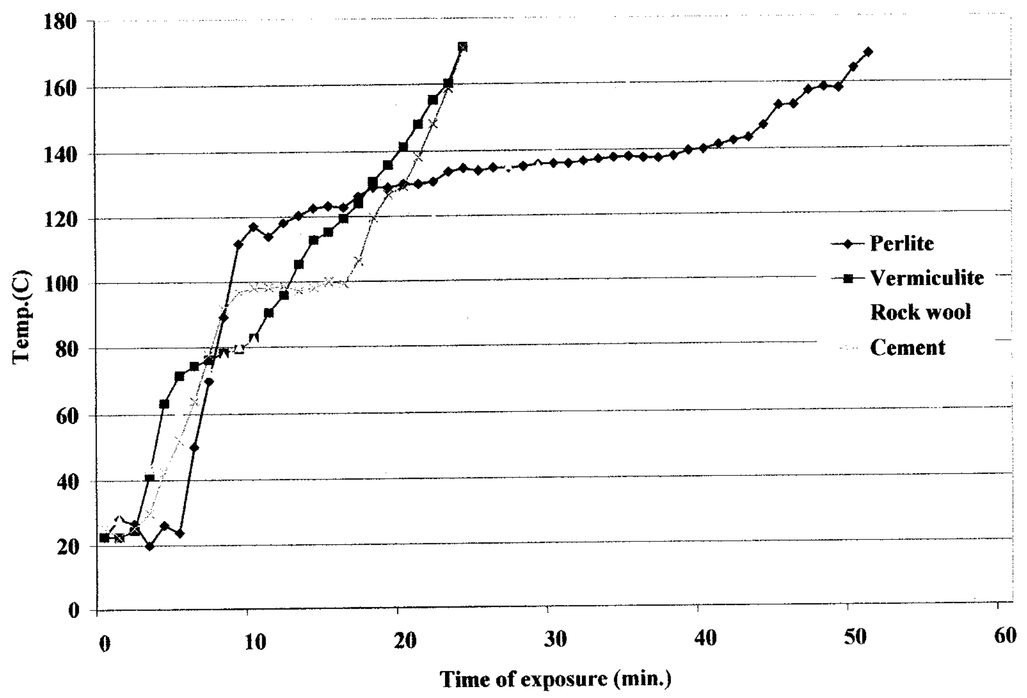

Figure 4.47- Effect of Plaster Type with thickness of 15 mm on 100x200x1000 Column

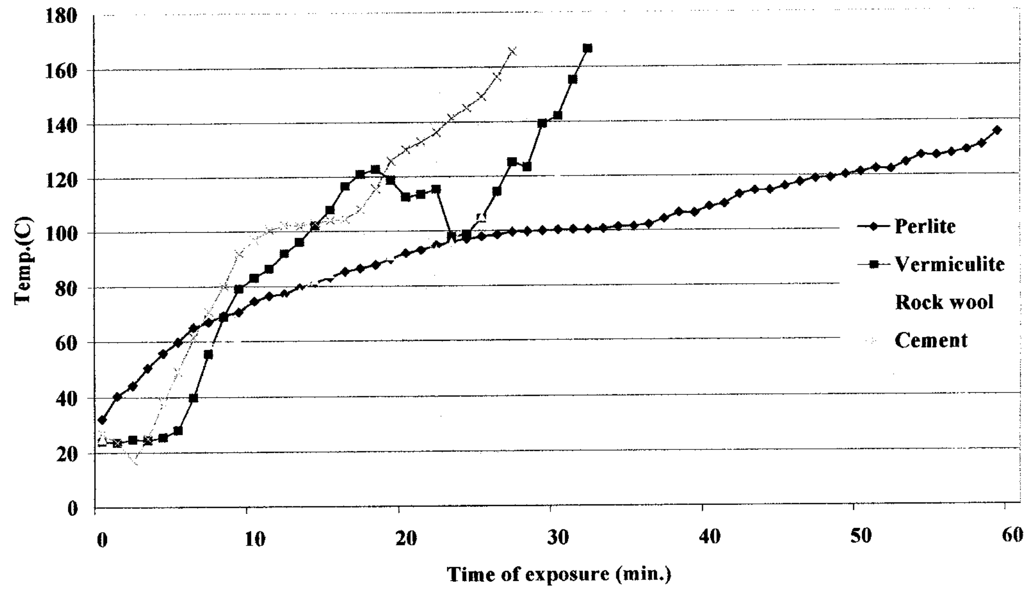

Figure 4.48- Effect of Plaster Type with thickness of 25 mm on 100x200x1000 Column

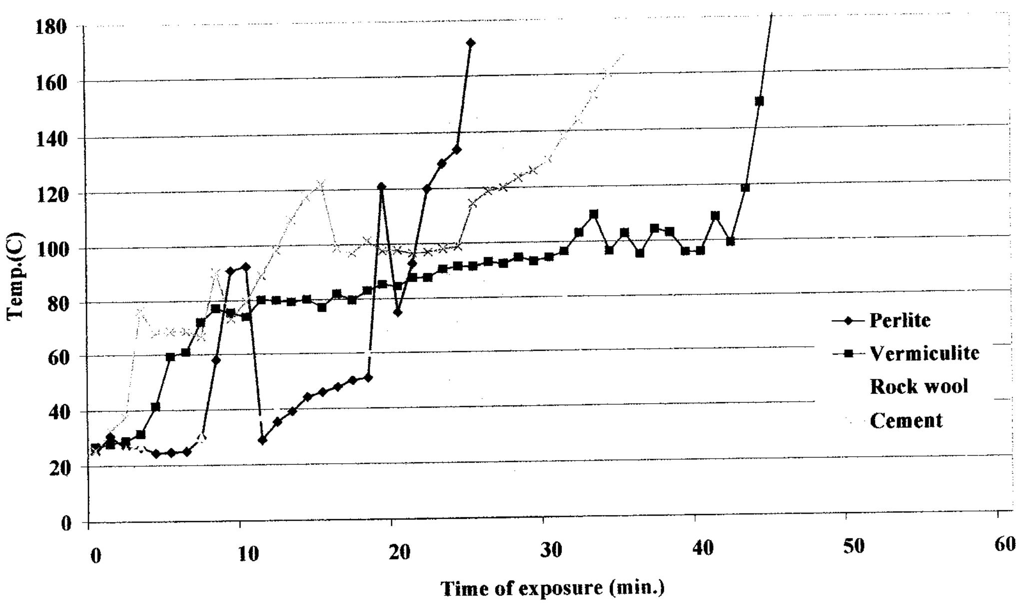

Figure 4.49- Effect of Plaster Type with thickness of 35 mm on 100x200x1000 Column

The effect of high temperature on the strength of 100x200 x1000 columns with a 15, 25 and 35 mm plaster thick of Perlite, Vermiculite, Rock wool, and Cement plaster is shown as illustrated in Figures 4.50 to 4.52

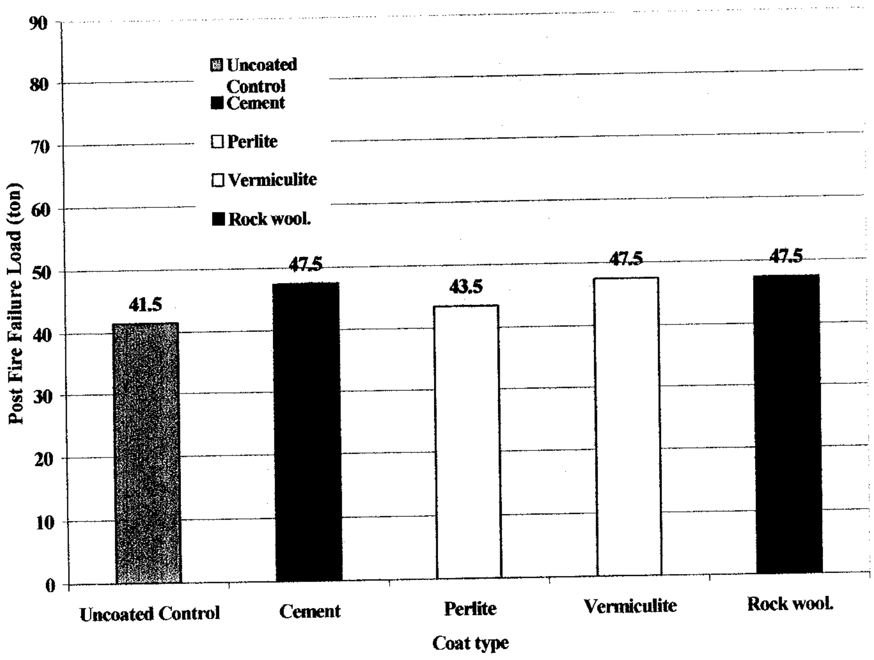

Figure 4.50- Effect of High Temperature on Strength for 100x200x1000 Columns Coated with 15 mm Thick Plaster.

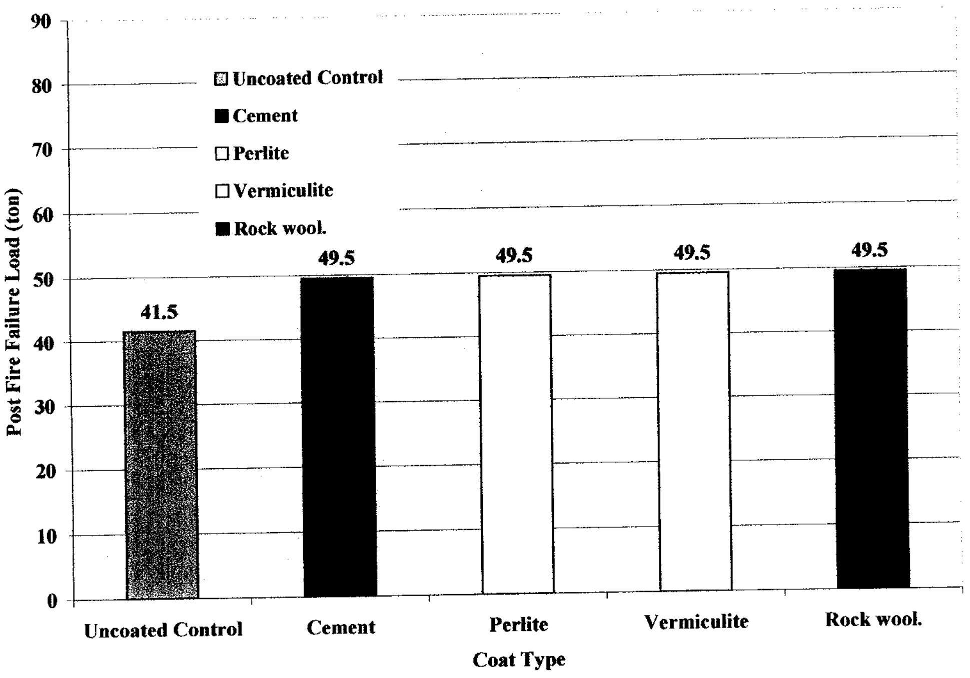

Figure 4.51- Effect of High Temperature on Strength for 100x200x1000 Columns Coated with 25 mm Thick Plaster.

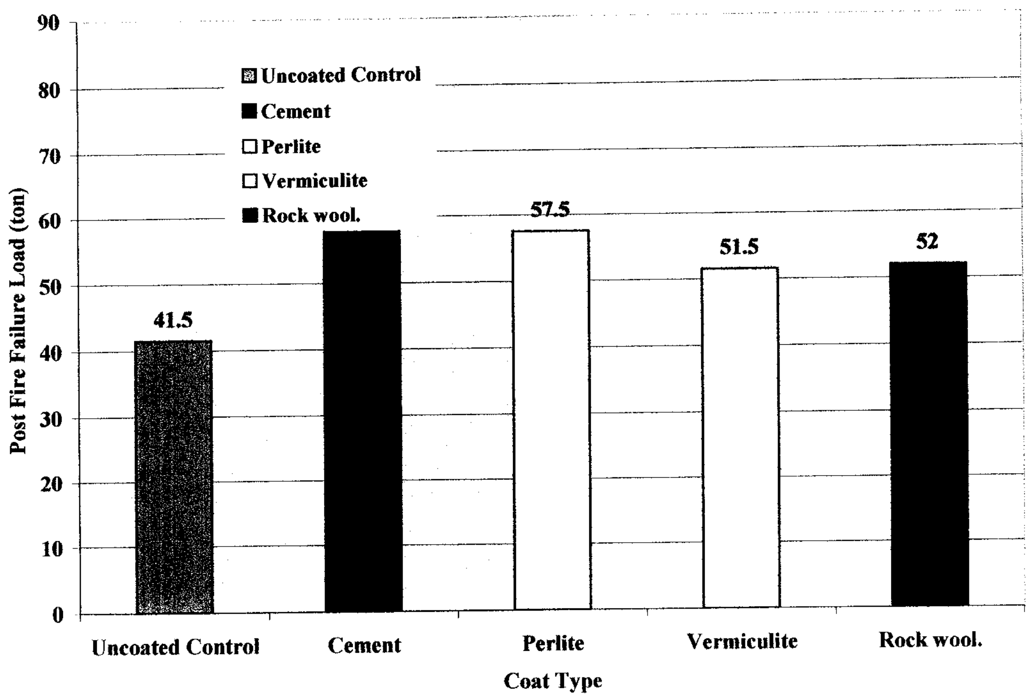

Figure 4.52- Effect of High Temperature on Strength for 100x200x1000 Columns Coated with 35 mm Thick Plaster

For the 100x200x1000 columns, concerning the fire resistance time, it is clear from the Table 4.20 that Perlite gives the highest fire resistance time for the 15 and 25 mm thicknesses, and it would be expected to be high for the 35 mm thickness except that the column failed after 25 minutes, due to a crack that was present before the test or due to an error in mixing the, or placing the plaster. It is then followed by Rock wool, then Vermiculite, and finally comes the Cement Plaster. The Vermiculite moved to the second rank here and that might be explained that the amount of plaster increases by the increase in the dimension of the column, thus the amount of water present increases as well, which caused spalling in the Vermiculite surface, thus the Vermiculite coated columns reaches 140°C + ambient faster.

As for the effect on post failure fire load, all the columns coated with the three plasters experienced an increase in strength due to the densification of the cement gel as attributed to by Zoldners, and also that the amount of heat energy of the furnace is entering into a larger surface area (compared to 100x100x1000), thus it takes more time to reach the surface and raises it to 140°C + ambient. In table 4.20, columns that exhibited a loss in post failure fire load, as compared to the uncoated control specimen not exposed to fire, higher than 20% are the" worst", lower than 20% are "good", and those exhibited an increase higher than 20% are "best", and lower than 20% are "better".

As for surface disintegration, Perlite as mentioned experienced cracks of 0.1-0.3 mm thickness, whereas, Vermiculite experienced major surface deterioration, Rock wool experienced just hair cracks on it surface , and finally Cement plaster plaster fell off upon fire exposure of 650°C temperature. Perlite, Vermiculite, Rock wool and Cement plasters experienced de- bonding at the higher thicknesses (35 mm).

Table 4.20- Comparison of the Performance of 100x200X1000 mm Column Coated with Perlite, Vermiculite, Rock wool and Cement Plaster.

Column Dimensions (mm)	**100x200x1000**					
Load/ Time Effect	**Time Effect (min.)**			**Load Effect (% increase)**		
Plaster Thickness (mm)	**15**	**25**	**35**	**15**	**25**	**35**
Perlite Plaster	51	*60 (136)	25 (error crack)	5	19	39
Vermiculite Plaster	**25**	**32**	**45**	14	19	24
Rock Wool Plaster	37	46	*60 (118)	14	19	25
Cement Plaster				14.5	18.1	54.2

***(Temperature reached after 60 minutes and does not reach 140°C + ambient)**

	2 (GOOD)	3 (BETTER)	

4.15.3 For Column Dimension 100x300x1000

The effect of the plaster type for thicknesses 15, 25, 35 mm respectively on 100x200x1000 columns is shown as illustrated in Figures 4.53 to 4.55.

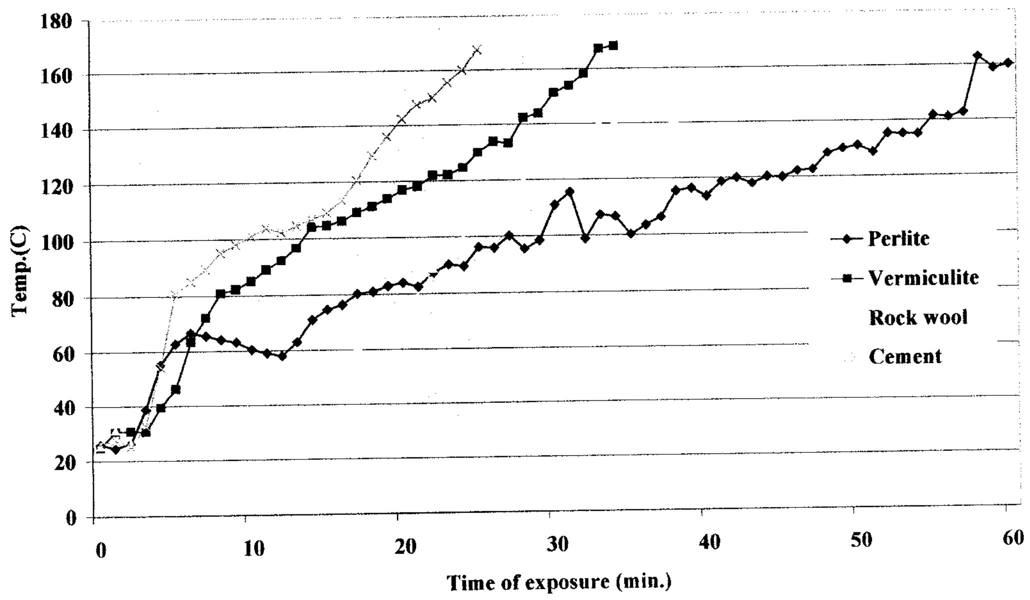

Figure 4.53- Effect of Plaster Type with thickness of 15 mm on 100x300x1000 Column

As for surface disintegration, Perlite as mentioned experienced cracks of 0.25-0.35 mm thickness, whereas, Vermiculite experienced major surface deterioration, Rock wool experienced just hair cracks on it surface, whereas Cement plaster completely fell off upon fire exposure of 650°C temperature. Perlite, Vermiculite, Rock wool, and Cement plasters experienced de- bonding at the higher thicknesses (35 mm)

Table 4.21- Comparison of the Performance of 100x300X1000 mm Column Coated with Perlite, Vermiculite, Rock wool and Cement Plaster

Column Dimensions (mm)	**100x300x1000**					
Load/ Time Effect	**Time Effect (min.)**			**Load Effect (%increase)**		
Plaster Thickness (mm)	**15**	**25**	**35**	**15**	**25**	**35**
Perlite Plaster	60	*60 (140)	*60 (137)	1	8	9
Vermiculite Plaster	**34**	**40**	**50**	**-6**	1	10
Rock Wool Plaster	51	55	40 (error crack)	0	5	17
Cement Plaster				5.1	10.9	13

***(Temperature reached after 60 minutes and does not reach 140°C + ambient)**

	2 (GOOD)	3 (BETTER)

4.16 Fire Resistance Time of Prototype Columns:

Based on, .J. O' Connor and Silcock, 1992, whose studies were based on Buckingham Pi theorem, the following equations can be used to represent fire resistance of real column dimensions and it is as follows:

$t_m = \{1/(S)^2\} * (t_p)$ ....(4.2)

$S_l = L_p / L_m$ ....(4.3)

Where:

S_l = length scale Factor

l_m = characteristic length of the model = area of the model / parameter of the model exposed to fire

l_p = characteristic length of the prototype = area of the prototype / parameter of the prototype exposed to fire

Thus, to validate this model, the fire resistance time for 100x100x1000 mm column dimension were considered as the fire resistance of mode column (t_m) and the other two dimensions fire resistance, which are, 100x200x1000 , and 100x300x1000 mm were considered as the prototype. Ire resistance (t_{p1}), and (t_{p2})respectively. Based on the above equations, the expected length scale factor is in the Table 4.22.

Table 4.22- Calculated length scale factors for the two sizes of columns

L_m (100x100x1000)	L_{p1} (100x200x1000)	L_{p2} (100x300x1000)	S_{l1}	S_{l2}
25	33.33	37.5	1.33	1.5

Thus if such model is applicable to the resukts, the following relation should be valid between the model 100x100x1000 mm column,

$t_{p1} = 1.77\ t_m$

$t_{p2} = 2.25\ t_m$

Comparing with the actual results from the experiments, the following was shown in Table 4.23.

Table 4.23- Actual length scale factors for the two sizes of columns

Plaster Type	t_{p1}/t_m			t_{p2}/t_m		
Plaster Thickness	15	25	35	15	25	35
Cement	1.20	1.17	1.40	1.25	1.39	1.40
Perlite	1.13			1.33		
Vermiculite	0.80	0.67		1.13	0.83	
Rock wool	1.28	1.15		1.76	1.38	

It is shown tat the actual reults are some how close in some cases to the model columns. However, it is highly recommended that further studies to be conducted to validate and examine the predicted fire resistance time relationship between the fire resistance time of the model and that in real practice.

4.17 Effect of Column Dimension on Fire Resistance:

1.Increasing the columns dimension, increases the fire resistance of the concrete columns. This might be attributed to the increase in the amount of water present in the mix, and upon fire, water starts to go to the interior cold layers of the column thus, that increases the temperature of the center and delays the decomposition of the mix constituents.

2. Also, the area exposed to the fire increases, thus the amount of heat energy absorbed will be divided among a larger cross section that might decrease the rate of heat entering to the column interior layers, and reaching 140°C + ambient at a longer time.

4.18 Effect of Plaster Material on Fire Resistance:

1. Perlite Proves to be the most effective plaster in increasing the fire resistance time due to its thermal properties, of low thermal conductivity and diffusivity values that delays the heat transfer to the interior surface. The loss in strength encountered in the smaller size of the column (100x100x1000), that was attributed to the longer exposure time to fire, is accepted as it does not exceed the critical limit which is a loss of more than 40%.
2. Vermiculite provides moderate fire resistance time, however the high water content in the mix causes major spalling and deterioration in the plaster surface. The strength reduction was not a major aspect in Vermiculite plaster.
3. Rock wool provides a moderate fire resistance time and experienced only hair cracks on the surface that might be attributed to the evaporation of the binder at temperatures above 250°C, and the voids inside will be filled by air that might increase the pressure inside the plaster causing such hair cracks. The strength reduction was not a major aspect in Rock wool plaster.
4. Cement Plaster has both a very high thermal conductivity and diffusivity values that reduce its fire resistance characteristics.

4.19 Effect of Plaster Thickness on Fire Resistance:

1. A plaster thickness of 15 mm provides a smaller fire resistance and can be easily fell off at high temperature especially that the columns were wrapped by a steel wire mesh that has a thermal expansion different than that of cement paste.
2. A plaster thickness of 25 mm provides a considerable fire resistance time, and does not undergo any separation from the column surface.

3. A plaster thickness of 35 mm provides a higher fire resistance time, however de-bonding between the plaster and the concrete surface was experienced. Such lack of bonding might lead to major hazards if the fire continuos at longer time intervals

CHAPTER V

MAJOR FINDINGS AND RECOMMENDATIONS

5.1 Findings:

Based on the scope, materials, procedures and other parameters associated with this work and considering general trends of results, the following findings can be stated:

1. All tested plasterings layers have contributed to fire protection of the columns at various degrees as reflected by extended protection time and good post-fire strength.
2. When applying formula to correlate experimental results with full sized columns in practice, the predicted extension in protection time offered by plastering materials exceed 360 minutes.
3. Exposure to fire for a limited duration of time can contribute to some increase in compressive strength possibly due to further hardening and strengthening of the cement matrix and the "autoclave effect".
4. Conventional cement plaster provided the least fire protection time yet the retained post-strength of the column specimens was fairly good.
5. Of the four tested plastering materials, Perlite offered the best resistance to fire as reflected by extended protection time and fair post-fire strength.
6. The fire resistance, one the whole, was enhanced upon increasing the plastering material from 15 to 25 mm. However, de-bonding and collapse of plastering layer occurred when the plastering was increased to 35 mm.
7. The results of this study suggests that the selection of the plastering thickness is a function of both the plastering material used and some what of the column dimensions.
8. Relatively little protection occurred when applying the 15 mm plasterings on

the 100x 100 mm columns. The protection was enhanced upon applying the same plastering thickness on the larger column specimens. This suggests that a relationship exists between the plastering thickness and the column dimensions.

9. Significant cracking upon exposure to fire was experienced for columns plastered with Vermiculite as well as conventional cement plaster. This can have negative post-fire durability implications when assuming structural safety after fire.

10. Vermiculite and Rock wool exhibited results that are superior to conventional cement paste yet inferior to Perlite. The results of both close to one another and thus allowing more room for economic feasibility to become a determining factor.

11. The findings of this work indicates that the structural integrity of columns post fire should not prevent a thorough repair of resulting cracks to serve towards better structural performance.

5.2 Work Limitations:

This study has several limitations which need to be avoided in future experimental works The key limitations can be summarized as :

1. The temperature scheme used was not high enough to show differences in performances of various plasterings for duration longer than one hour. Data beyond that time limit will certainly be helpful.

2. The columns tested possessed, in general, good results, yet this study did not succeed in pinpointing defects and damage of specimens close to failure stage.

3. Due to technical difficulties, temperature was not consistently recorded in the core of specimens. Thus, useful data of the thermal behavior of the interior of components was not readily available. Such data could have been useful in relating surface, underplaster and internal temperature of concrete components.

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APPENDIX A

TEMPERATURE DISTRIBUTION ALONG TH CROSS SECTION OF 100x200x1000 mm COLUMNS PLASTERED WITH CEMENT FOR EQUAL INCREMENT OF ONE MINUTE

Table A.1- Time-Temperature Reading of 15 mm Cement Plaster Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	25.6	25.2	27.7
1	22.5	21.8	150.1
2	25.4	21.4	169.4
3	29.9	23.8	253.6
4	42.6	24.3	304.1
5	52.1	25.7	336.2
6	64.0	26.1	408.5
7	77.8	29.2	445.0
8	91.7	32.0	471.6
9	96.8	35.2	510.6
10	98.3	39.6	543.1
11	98.3	45.6	574.7
12	98.9	49.8	595.6
13	97.3	53.3	610.0
14	98.1	57.0	628.2
15	100.0	59.6	637.3
16	99.4	62.8	646.5
17	106.3	65.5	651.1
18	119.8	68.6	656.5
19	126.9	70.8	660.7
20	129.4	73.8	665.3
21	138.3	77.1	666.3
22	148.2	80.2	665.4
23	158.9	81.6	666.8
24	171.0	78.8	643.5

Table A.2- Time-Temperature Reading of 25 mm Cement Plaster Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	27.1	26.5	27.0
1	23.8	23.6	224.5
2	17.3	20.6	390.7
3	25.1	21.5	464.8
4	38.1	21.5	525.6
5	49.1	22.5	558.4
6	61.5	24.6	595.2
7	70.9	27.6	599.3
8	72.4	32.1	593.9
9	75.0	35.3	604.0
10	80.4	40.4	634.3
11	82.3	45.0	667.0
12	85.4	47.4	669.2
13	88.9	49.0	677.8
14	91.4	59.1	680.2
15	104.2	62.7	687.1
16	104.7	65.1	687.6
17	108.2	68.7	690.9
18	112.5	71.8	696.6
19	116.4	73.6	694.6
20	120.2	76.5	689.7
21	123.8	78.7	690.0
22	126.4	81.6	692.9
23	130.1	84.0	688.6
24	145.3	87.1	687.5
25	149.5	90.0	688.7
26	156.6	93.4	685.4
27	165.7	96.2	674.3

Table A.3- Time-Temperature Reading of 35 mm Cement Plaster Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	25.8		29.8
1	32.9		300.9
2	37.8		435.6
3	76.5		556.7
4	68.1		582.3
5	68.8		591.1
6	68.8		591.1
7	66.8		637.0
8	90.3		672.7
9	73.3		687.3
10	79.7		681.4
11	89.3		685.7
12	98.5		695.6
13	109.6		692.0
14	117.8		685.0
15	122.2		682.2
16	99.1		680.9
17	97.2		678.5
18	101.5		683.7
19	97.8		675.3
20	98.0		676.1
21	96.7		676.2
22	97.2		665.1
23	98.2		673.2
24	99.1		662.6
25	114.8		665.5
26	119.0		658.2
27	120.2		663.0
28	123.7		663.8
29	126.2		656.8
30	130.0		657.7
31	138.2		653.3
32	144.5		650.2
33	153.0		647.2
34	160.5		644.1
35	167.1		641.1

APPENDIX B

TEMPERATURE DISTRIBUTION ALONG TH CROSS SECTION OF 100X200X1000 mm COLUMNS COATED WITH PERLITE FOR EQUAL INCREMENT OF ONE MINUTE

Table B.1- Time-Temperature Reading of 15 mm Perlite Coated Concrete Columns

Time (min.)	Temperature (˚C)		
	Under plaster	Center	Oven
0	22.7	24.4	31.8
1	28.2	26.3	228.1
2	26.6	25.0	534.1
3	20.0	24.2	597.1
4	26.3	24.0	657.0
5	23.8	23.8	647.7
6	50.1	24.7	640.5
7	70.0	24.2	645.0
8	89.3	24.2	667.8
9	111.8	29.7	633.2
10	117.3	26.6	670.0
11	114.1	26.8	672.0
12	118.2	29.5	658.0
13	120.5	27.2	637.0
14	122.7	25.9	638.0
15	123.4	26.3	667.0
16	123.0	26.2	669.0
17	126.4	26.0	660.0
18	129.2	26.3	668.0
19	129.1	26.2	675.0
20	130.0	25.2	672.5
21	130.0	18.1	656.6
22	130.7	27.9	656.0
23	133.8	25.8	676.6
24	134.8	26.6	640.0
25	134.0	27.3	660.2
26	134.9	20.8	702.6
27	134.9	25.6	619.6
28	135.2		669.0
29	135.9		687.3
30	136.1		625.3
31	136.1		656.2

32	136.7		657.8
33	137.3		653.8
34	137.8		653.5
35	138.0		673.0
36	137.7		667.6
37	137.6		666.3
38	138.2		683.0
39	139.7		685.0
40	140.1		630.3
41	141.5		668.0
42	142.7		667.0
43	143.5		672.3
44	147.2		681.2
45	153.1		628.5
46	153.2		629.5
47	157.6		620.9
48	158.6		669.5
49	158.2		644.3
50	164.3		645.8
51	168.6		631.5

Table B.2- Time-Temperature Reading of 25 mm Perlite Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	27.4	25.4	29.4
1	32.2	26.6	33.2
2	40.5	27.7	261.6
3	44.3	28.8	521.9
4	50.5	29.1	635.4
5	55.8	27.7	663.0
6	59.8	26.7	665.0
7	65.1	28.7	680.0
8	67.1	29.0	680.3
9	69.4	31.7	679.6
10	70.7	31.8	688.0
11	74.5	31.8	687.9
12	76.6	35.0	638.3
13	77.1	34.9	663.3
14	79.5	37.8	622.7
15	81.3	38.8	614.3
16	83.3	42.6	621.7
17	85.4	42.8	636.8
18	86.5	46.3	620.1
19	87.8	47.6	625.0
20	90.0	50.7	624.3
21	92.0	52.1	622.1
22	93.3	55.1	622.1
23	94.8	56.6	620.5
24	96.0	57.5	623.4
25	97.1	60.1	626.1
26	98.0	62.3	628.4
27	98.7	63.4	627.1
28	99.7	64.8	620.4
29	99.8	67.7	631.2
30	100.1	70.0	635.1
31	100.3	71.7	632.1
32	100.5	72.0	628.8
33	100.5	72.7	630.0
34	100.8	75.2	624.5
35	101.5	78.0	628.7
36	101.6	79.0	623.1
37	102.3	79.1	621.2
38	104.4	83.1	627.8

39	106.6	85.0	630.0
40	106.5	85.5	639.7
41	108.8	86.8	638.7
42	109.8	86.6	638.0
43	113.2	92.5	645.5
44	114.7	92.1	646.0
45	114.7	91.6	651.6
46	116.1	95.1	641.0
47	117.5	95.0	627.6
48	118.9	97.1	637.5
49	119.2	97.5	630.6
50	120.3	97.0	618.7
51	121.3	98.1	625.5
52	122.6	97.5	620.8
53	122.3	95.2	645.1
54	124.8	98.6	636.1
55	127.4	102.1	640.5
56	127.2	99.0	622.6
57	128.1	100.1	622.5
58	129.4	100.9	620.9
59	131.2	105.4	622.1
60	135.7	107.7	647.3

Table B.3- Time-Temperature Reading of 35 mm Perlite Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	24.7		26.2
1	30.8		34.8
2	26.7		39.5
3	26.6		468.5
4	24.5		485.7
5	24.8		500.1
6	25.1		598.1
7	30.0		678.8
8	58.0		682.8
9	91.1		672.7
10	92.5		658.6
11	29.0		629.1
12	35.4		647.4
13	39.1		662.8
14	44.3		694.0
15	45.9		692.6
16	47.8		674.2
17	50.1		688.7
18	51.0		665.6
19	121.0		689.5
20	75.0		660.2
21	93.0		665.4
22	120.0		650.1
23	129.0		655.2
24	134.1		653.4
25	172.0		644.1

APPENDIX C

TEMPERATURE DISTRIBUTION ALONG TH CROSS SECTION OF 100X200X1000 mm COLUMNS COATED WITH VERMICULITE FOR EQUAL INCREMENT OF ONE MINUTE

Table C.1- Time-Temperature Reading of 15 mm Vermiculite Coated Concrete Columns

Time (min)	Temperature (°C)		
	Under plaster	Center	Oven
0	22.8	22.9	23.8
1	22.6	25.3	106.8
2	24.6	21.5	241.7
3	41.3	24.1	338.7
4	63.4	24.3	410.6
5	71.6	23.7	405.6
6	74.6	24.5	489.0
7	76.4	25.7	467.0
8	78.3	28.2	458.0
9	79.5	30.5	427.7
10	82.8	33.8	474.2
11	90.5	36.3	622.2
12	95.8	39.3	647.1
13	105.4	39.2	621.1
14	112.9	46.1	670.0
15	115.3	45.9	692.2
16	119.6	48.9	637.0
17	124.1	54.3	668.7
18	131.0	57.3	640.5
19	136.0	59.6	622.8
20	141.5	63.4	658.8
21	148.1	67.0	659.9
22	150.2	68.1	660.4
23	155.4	69.1	662.5
24	160.4	70.8	665.7
25	171.4	75.8	668.7

Table C.2- Time-Temperature Reading of 25 mm Vermiculite Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	24.1	24.2	25.0
1	23.8	19.7	393.8
2	24.8	21.9	446.3
3	24.5	21.7	477.2
4	25.5	23.2	520.6
5	28.0	23.1	555.5
6	39.8	23.4	559.9
7	55.5	22.9	579.6
8	68.8	22.8	620.4
9	79.2	24.8	650.7
10	83.1	25.2	657.4
11	86.5	28.5	660.8
12	92.0	30.5	645.7
13	96.3	31.5	621.5
14	102.3	34.0	620.3
15	108.1	35.2	619.7
16	116.8	40.6	624.2
17	121.2	44.5	651.5
18	123.0	50.1	610.0
19	119.0	55.9	633.5
20	112.7	62.4	624.9
21	113.7	69.7	610.4
22	115.4	77.3	617.9
23	98.0	85.5	654.2
24	99.0	95.2	633.4
25	104.8	100.3	645.0
26	114.7	99.3	636.0
27	125.4	95.8	656.0
28	123.5	97.1	672.0
29	139.5	96.8	640.3
30	142.3	99.7	622.8
31	155.4	99.1	635.7
32	166.7	98.2	642.3

Table C.3- Time-Temperature Reading of 35 mm Vermiculite Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	27.1	26.9	27.4
1	28.1	18.7	224.8
2	29.1	19.0	550.5
3	31.7	19.7	635.9
4	41.3	19.3	638.6
5	59.5	24.7	658.1
6	61.1	25.6	662.5
7	72.1	25.6	663.3
8	77.2	24.1	676.8
9	75.5	22.8	673.7
10	74.0	36.4	667.6
11	80.2	35.1	674.7
12	79.9	39.3	662.4
13	79.2	46.2	655.5
14	80.2	48.1	644.6
15	77.2	53.1	658.5
16	82.0	58.6	650.3
17	79.6	63.7	654.6
18	83.1	65.2	619.5
19	85.3	64.8	635.4
20	84.5	66.7	622.1
21	87.7	75.2	624.1
22	87.7	74.6	624.2
23	90.7	74.7	617.8
24	91.7	76.1	623.8
25	91.6	83.0	659.7
26	93.2	82.9	658.2
27	92.4	91.8	659.8
28	94.8	91.3	652.3
29	93.2	89.7	686.2
30	94.6	91.1	651.4
31	96.7	95.5	653.2
32	103.4	95.1	685.0
33	110.0	97.4	657.6
34	96.7	91.3	654.2
35	103.1	81.5	658.4
36	95.5	82.7	638.5
37	104.5	100.6	628.6
38	103.2	100.1	662.1
39	96.0	83.0	679.6

40	96.1	83.8	674.7
41	108.8	92.9	691.6
42	99.4	94.2	678.9
43	118.6	100.2	684.3
44	149.5	100.5	647.8
45	186.4	105.1	641.1

APPENDIX D

TEMPERATURE DISTRIBUTION ALONG TH CROSS SECTION OF 100X200X1000 mm COLUMNS COATED WITH ROCK WOOL FOR EQUAL INCREMENT OF ONE MINUTE

Table D.1- Time-Temperature Reading of 15 mm Rock wool Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	29.6		26.7
1	28.1		574.3
2	36.5		588.1
3	43.5		639.5
4	50.7		688.7
5	60.9		666.3
6	65.5		657.6
7	72.6		659.2
8	77.6		655.2
9	80.3		654.9
10	82.4		655.4
11	86.3		654.1
12	89.8		689.6
13	95.2		650.2
14	92.5		625.1
15	100.7		621.1
16	101.6		624.8
17	107.3		627.1
18	113.1		620.1
19	118.1		623.8
20	117.4		651.2
21	118.1		659.8
22	119.7		660.7
23	123.1		646.8
24	123.0		654.7
25	128.1		654.6
26	129.5		637.8
27	135.6		633.1
28	131.8		630.1
29	135.5		633.3
30	139.6		626.5
31	144.6		650.2

32	149.1		653.3
33	156.2		656.4
34	158.3		659.5
35	159.7		654.1
36	163.3		650.2
37	165.7		634.5

Table D.2- Time-Temperature Reading of 25 mm Rock wool Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	25.1		23.9
1	27.1		235.4
2	34.1		409.8
3	46.4		449.6
4	50.0		485.9
5	52.2		555.2
6	58.4		617.0
7	59.1		660.8
8	59.1		634.3
9	60.0		631.5
10	65.7		639.1
11	70.1		652.4
12	75.4		648.2
13	78.1		685.8
14	82.3		699.1
15	84.7		683.8
16	89.7		701.5
17	96.1		697.3
18	95.4		696.3
19	91.1		691.4
20	95.4		673.0
21	96.3		684.8
22	93.6		685.4
23	96.1		681.8
24	102.1		677.8
25	105.3		661.9
26	107.8		672.6
27	111.8		673.8
28	113.7		650.9
29	115.1		660.8
30	120.5		675.2
31	124.7		680.4
32	126.2		683.2
33	131.1		670.8
34	134.2		684.3
35	136.4		686.1
36	138.7		684.0
37	139.2		681.8
38	142.1		663.1

39	145.8		674.6
40	147.5		675.6
41	150.7		660.4
42	152.3		655.3
43	154.2		665.6
44	157.1		665.2
45	160.4		660.7
46	167.4		655.7

Table D.3- Time-Temperature Reading of 35 mm Rock wool Coated Concrete Columns

Time (min.)	Temperature (°C)		
	Under plaster	Center	Oven
0	24.6		26.8
1	22.3		163.0
2	26.1		590.7
3	27.4		679.0
4	29.2		681.1
5	30.1		689.2
6	32.3		685.2
7	30.3		679.2
8	31.1		680.4
9	32.2		682.4
10	34.6		689.4
11	37.5		655.4
12	40.3		651.5
13	42.5		643.1
14	47.8		636.7
15	49.1		621.7
16	51.1		619.1
17	56.7		619.6
18	60.3		625.5
19	63.4		624.8
20	64.3		635.9
21	65.1		638.3
22	67.8		620.8
23	70.9		627.2
24	74.3		618.1
25	73.0		622.1
26	72.7		629.6
27	72.9		625.1
28	74.8		624.3
29	75.9		616.0
30	77.1		620.2
31	79.8		622.1
32	81.7		617.1
33	85.5		627.0
34	86.3		633.8
35	87.1		631.8
36	88.5		620.5
37	90.0		629.9
38	91.1		635.1

39	90.2		640.1
40	91.9		633.5
41	93.5		639.3
42	95.4		620.2
43	94.8		627.6
44	94.0		619.2
45	95.9		625.8
46	96.0		624.7
47	97.9		635.1
48	98.2		640.5
49	99.4		642.3
50	99.0		645.5
51	98.9		650.5
52	101.9		655.8
53	103.4		655.8
54	105.1		660.1
55	107.3		662.3
56	109.8		662.3
57	111.4		650.1
58	113.5		655.1
59	114.8		660.8
60	117.8		663.4