Chapter Two

Literature Review

2.1 Introduction

One of the advantages of concrete over other building materials is its inherent fire-resistive properties; however, concrete structures must still be designed for fire effects. Structural components still must be able to withstand dead and live loads without collapse even though the rise in temperature causes a decrease in the strength and modulus of elasticity for concrete and steel reinforcement. In addition, fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted.

In the design of structures, building code requirements for fire resistance are sometimes overlooked and this may lead to costly mistakes. It is not uncommon, to find that a concrete slab floor system may require a smaller thickness to satisfy ACI 318 strength requirements than the thickness required by a building code for a 2-hour fire resistance. For sound and safe design, fire considerations must, be part of the preliminary design stage. Determining the fire rating for a structure member, can vary in complicity from extracting the relevant rating using a simple table to a fairly complex and elaborate analysis. In the United States, structural design for fire safety is based on prescriptive approach. Attempts are being made to develop performance based design approach for structural design for fire. State and municipal building codes throughout the country regulate the fire resistance of the various elements and assemblies comprising a building structure. The 2006 International Building Code (IBC) (1) contains prescriptive requirements for building elements in Section 720. This section is based on ACI 216.1 “Standard Method for Determining Fire Resistance of Concrete and Masonry Construction

Assemblies and contains tables describing various assemblies of building materials and finishes that meet specific fire ratings.

2.2 Effect of Fire on Building Materials

A relatively new method for determining fire exposure used by fire protection engineers is to first calculate the fire load density in a compartment. Then, based on the ventilation conditions and an assumed source of combustion determine the compartment temperature at various times.

Another factor considered in the analysis is the effect of active fire protection systems e.g. sprinklers or fire brigades on the growth of the fire. The size and timing of the fire growth determined by fire analysis is sensitive to changes in the fuel load over time and changing ventilation conditions during the fire. This method of fire analysis requires special software and extensive training and is used only in very large or unusual buildings.

Once the temperature time relationship is determined using a standard curve or from the method described above, the effect of the rise in temperature on the structure can be determined.

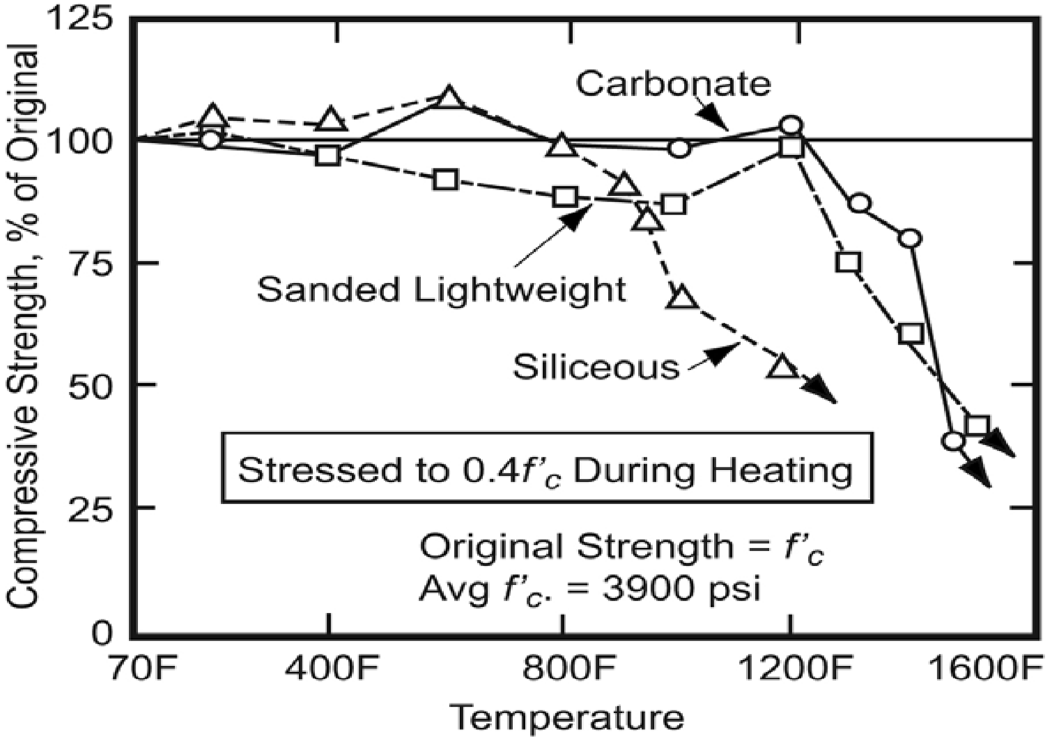
The rise in temperature causes the free water in concrete to change from a liquid state to a gaseous state. This change in state causes changes in the rate with which heat is transmitted from the surface into the interior of the concrete component.

The rise in temperature causes a decrease in the strength and modulus of elasticity for both concrete and steel reinforcement. However, the rate at which the strength and modulus decrease depends on the rate of increase in the temperature of the fire and the insulating properties of concrete. Note that concrete does not burn.

2.2.1 Concrete

The change in concrete properties due to high temperature depends on the type of coarse aggregate used. Aggregate used in concrete can be classified into three types: carbonate, siliceous and lightweight. Carbonate aggregates include limestone and dolomite. Siliceous aggregate include materials consisting of silica and include granite and sandstone. Lightweight aggregates are usually manufactured by heating shale, slate, or clay Figure (2.1) shows the effect of high temperature on the compressive strength of concrete. The specimens represented in the figure were stressed to 40% of their compressive strength during the heating period. After the designated test temperature was reached, the load was increased gradually until the specimen failed. The figure shows that the strength of concrete containing siliceous aggregate begins to drop off at about 800 °F and is reduced to about 55% at 1200^{o}F.

Concrete containing lightweight aggregates and carbonate aggregates retain most of their compressive strength up to about 1200 ^{o}f. Lightweight concrete has insulating properties, and transmits heat at a slower rate than normal weight concrete with the same thickness, and therefore generally provides increased fire resistance.



Figure(2.1): Effect of high temperature on the compressive strength of concrete.

Figure (2.2) shows the effect of high temperature on the modulus of elasticity of concrete. The figure shows that the modulus of elasticity for concretes manufactured of all three types of aggregates is reduced with the increase in temperature. Also, at high temperatures, creep and relaxation for concrete increase significantly.

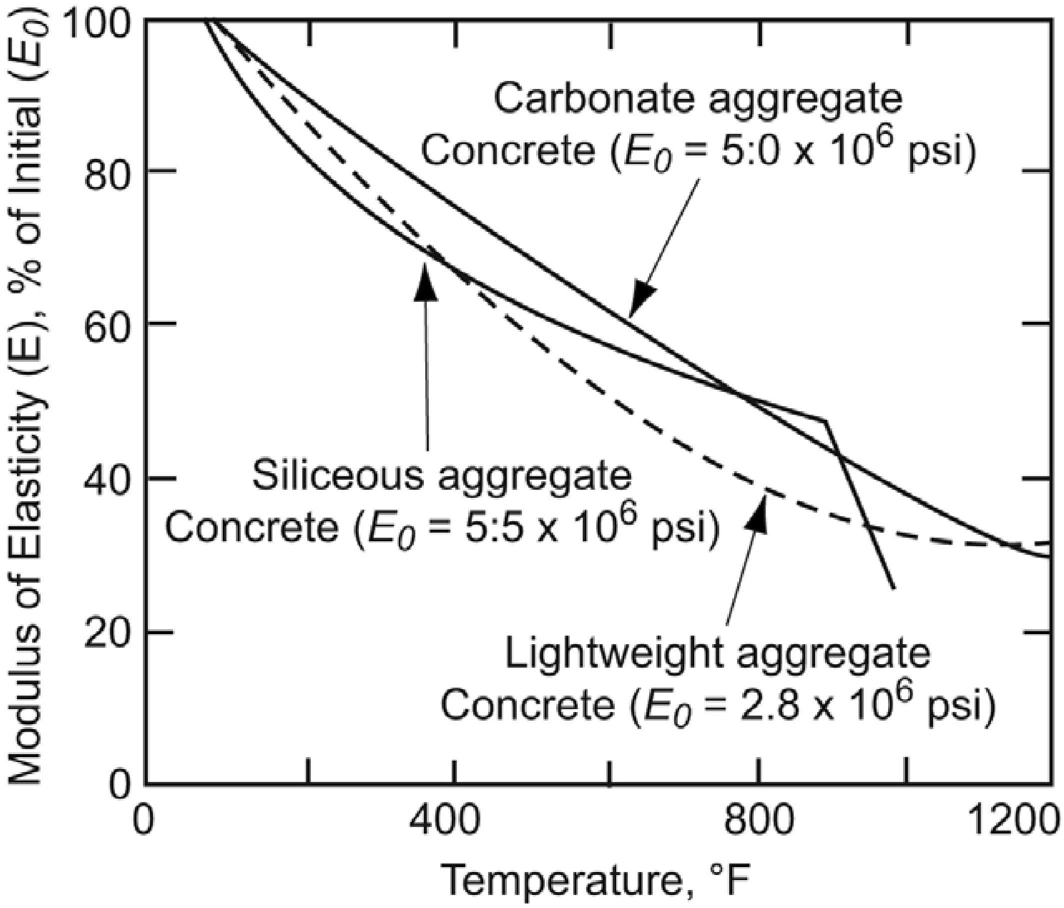


Figure (2.2): Effect of high temperature on the modulus of elasticity of concrete.

2.3 Fire Resistance Rating

Fire resistance can be defined as the ability of structural elements to withstand fire or to give protection from it . this includes the ability to confine a fire or to continue to perform a given Structural function, or both. Fire Resistance Rating (or fire rating), is defined as the duration of time that an assembly (roof, floor, beam, wall, or column) can endure a “standard fire” as defined in ASTM E 119 .

2.4 Fire Endurance of Structures

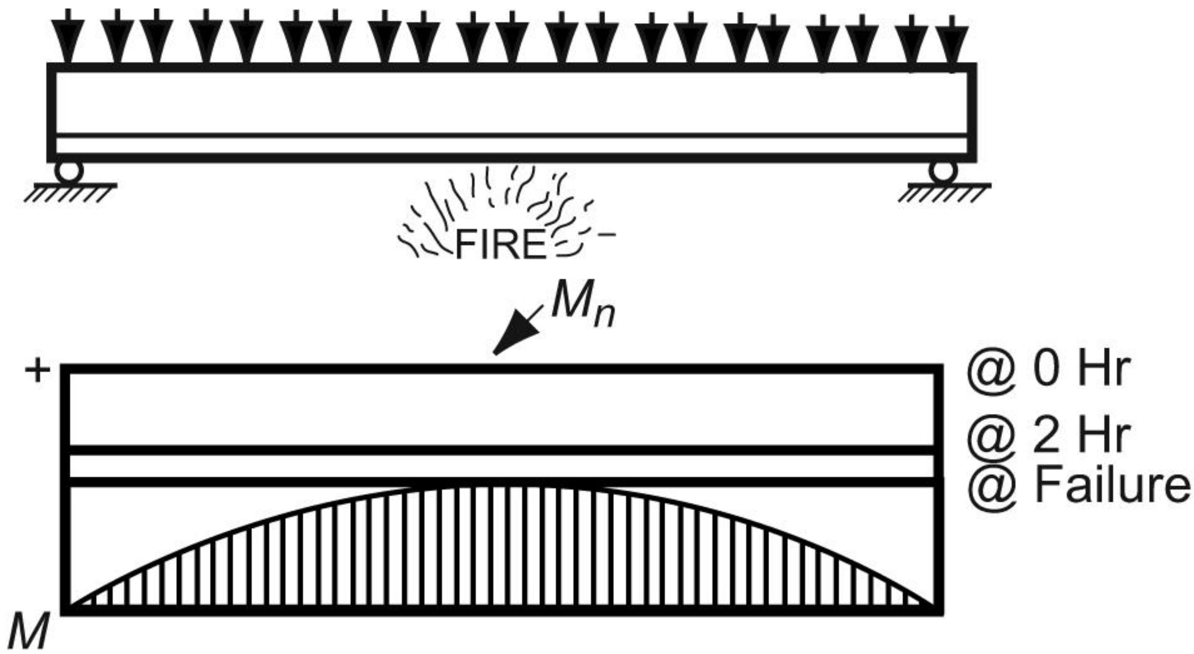


Figure (2.3): Effect of fire on the resistance of a simply supported reinforced concrete slab.

If the bottom side of the slab is subjected to fire, the strength of the concrete and the reinforcing steel will decrease as the temperature increase. However, it can take up to three hours for the heat to penetrate through the concrete cover to the steel reinforcement. As the strength of the steel reinforcement decreases, the moment capacity of the slab decreases. When the moment capacity of the slab is reduced to the magnitude of the moment caused by the applied load, flexural collapse will occur. It is important to point out that duration of fire until the reinforcing steel reaches the critical strength depends on the protection to the reinforcement provided by the Concrete cover.

The behavior of structures exposed to fire is usually described in terms of the concept of fire resistance, which is the period of time under exposure to a standard fire time-temperature curve at which some prescribed form of limiting behavior occurs. In performance-based design this limiting behavior may be defined as real structural collapse or as a failure of integrity (which allows fire-spread to occur), but is more usually defined in terms of a deflection limit. Current design codes [1, 2] have taken a step towards full performance-based design by allowing designers to treat fire as one of the basic design limit states, taking account of:

• Non-uniform heating due to partial protection, which may be inherent in the framing system or specially applied,

• The level of loading in the fire limit state, using partial safety factors lower than those used for ultimate limit states, because of the relative improbability of such accidental conditions,

• Realistic stress-strain characteristics of materials at elevated temperatures.

The main limitation of these codified approaches is that they are based on the behavior under test of isolated simply supported members, usually heated according to the standard ISO834 time-temperature curve. In real buildings structural elements form part of a continuous assembly, and building fires often remain localized, with the fire-affected region of the structure receiving significant restraint from cooler areas surrounding it. The real behavior of these structural elements can therefore be very different from that indicated by standard furnace tests.

2.5 ASTM E119 Standard Fire Test

The fire-resistive properties of building components and structural assemblies are determined by fire test methods. The most widely used and nationally accepted test procedure is that developed by the American Society of Testing and Materials (ASTM). It is designated as ASTM E 119,Standard Methods of Fire Tests of Building Construction and Materials. A standard fire test is conducted by placing a full size assembly in a test furnace. Floor and roof specimens are exposed to a controlled fire from beneath, beams are exposed from the bottom and sides, walls from one side, and columns are exposed to fire from all sides. The temperature is raised in the furnace overran given period of time in accordance with ASTM E 119 standard time-temperature curve as shown in Figure(2.6). This specified time-temperature relationship provides for a furnace temperature of1000^{o}F at five minutes from the beginning of the test, 1300^{o}F at 10 minutes, 1700^{o}F at one hour,1850^{o}F at two hours, and 2000^{o}F at four hours. The end of the test is reached and the fire endurance of the specimen is established when any one of the following conditions first occurs:

1. For walls, floors, and roof assemblies, the temperature of the unexposed surface rises an average of 150^{o}F above its initial temperature of 325^{o}F at any location. In addition, walls achieving a rating classification of one hour or greater must withstand the impact, erosion and cooling affects of a hose steam test.
2. Cotton waste placed on the unexposed side of a wall, floor, or roof system is ignited through cracks or fissures which develop in the specimen during the test.
3. The test assembly fails to sustain the applied service load.
4. For certain restrained and all unrestrained floors, roofs and beams, the reinforcing steel temperature rises to 1100^{o}F.

The complete requirements of ASTM E 119 and the conditions of acceptance are much more detailed than summarized above. Experience shows that concrete floor/roof assemblies and walls usually fail by heat transmission (item 1); and columns and beams by failure to sustain the applied loads (item 3), or by beam reinforcement failing to meet the temperature criterion (item4).

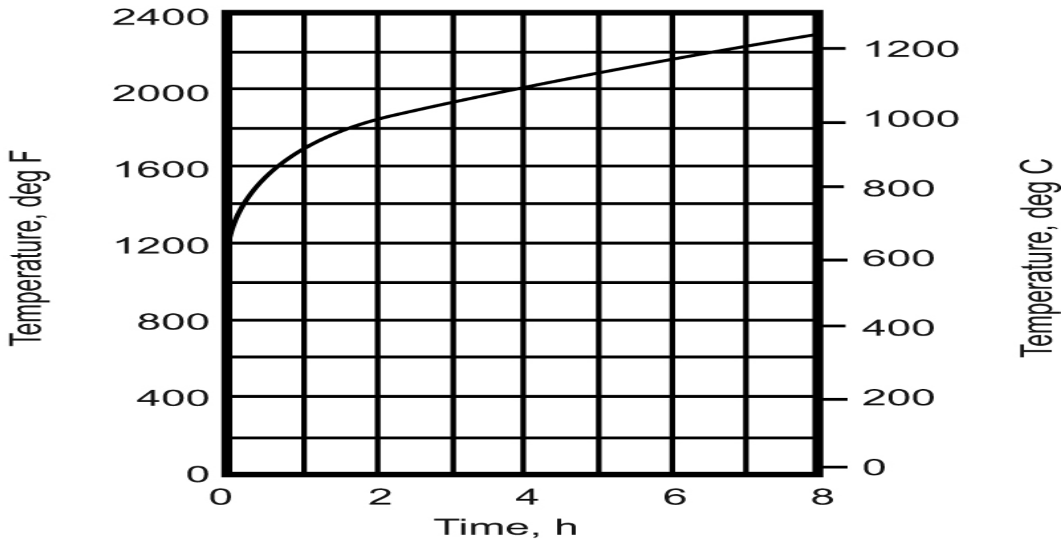


Figure (2.4): ASTM E 119 Time temperature curve.

2.6 Advanced Analytical Models

Recently some engineers have suggested using 3D finite element software to calculate the change in spatial temperatures over time in structural components using as input the time, temperature, and pore pressure data from the fire analysis described in previous sections. The software has to be able to model the non-linear non-isotropic behavior of reinforcement steel and concrete including crack development and crushing of the concrete. In addition to the external service loads, the model has to be able to include the following: (1) internal forces due to restraints that prevent free expansion, (2) internal forces due to pore pressure changes, (3)internal forces due to redistribution due to degradation of the mechanical properties of the steel reinforcement and concrete, (4) internal forces due to second order effects from the interaction of external loads and the deformations due to the three types of internal forces mentioned above .CTL Group performed a 3D analysis using the software DIANA for the Portland Cement Association and was able to obtain a fair correlation to actual ASTM E119 tests on high strength concrete columns.

Needless to say, this type of analysis is very complex and expensive and therefore is not suitable for general structural design.

2.7 ACI 216 Method

Although testing according to ASTM E 119 is probably the most reliable method, the time and expense required to build and test the assemblies makes this method impractical and is actually Unnecessary for most situations. The methods contained in ACI 216.1 (2) are based on fire research performed from 1958 through 2005 and are by far the most commonly used in typical design situations. The fire resistance (based on the heat transmission end point) of a concrete member or assembly is found by calculating the equivalent thickness for the assembly and then finding the corresponding rating in the charts and tables provided. The equivalent thickness of solid walls and slabs with flat surfaces is the actual thickness. The equivalent thickness of walls and slabs that have voids, undulations, ribs, or multiple layers of various materials (for example, a sandwich of concrete, insulation, and concrete) must be calculated using equations found in ACI 216.1.

An analytical method of calculating fire resistance for flexural members is contained in ACI216.1 [4]. This method involves estimating the actual temperatures of the concrete and reinforcing steel and using the properties of the materials at those temperatures in the analysis.

The method assumes that the bottom, positive moment steel will reach elevated temperatures and begin to weaken before the top concrete and reinforcement. This allows the moment in the member to be redistributed from the weaker, positive moment region to the negative moment region where little reduction in strength will have occurred.

Once it is established that the member or the assembly has enough equivalent thickness to satisfy the heat transmission end point, it must also be determined whether there is enough cover on the reinforcing steel to prevent excessive heat from reducing the yield strength to the point where it can no longer carry the loads. The cover requirements for slabs are functions of the required fire rating, aggregate type, restrained or unrestrained construction, and pre stressed or non-pre stressed reinforcement.

2.8 The Code Approach

State and municipal building codes throughout the country regulate the fire resistance of the various elements and assemblies comprising a building structure. Structural frames (columns and beams), floor and roof systems, and load bearing walls must be able to withstand the stresses and strains imposed by fully developed fires and carry their own dead loads and superimposed loads without collapse for the specified duration. The 2006 International Building Code (IBC) (1)contains prescriptive requirements for building elements in Section 720. This section contain stables describing various assemblies of building materials and finishes that meet specific fire endurance ratings. The tables in the 2006 IBC are compatible with the tables in ACI 216.1 except for the provisions for the use of high strength concrete columns found in ACI 216.1-07.

2.9 Thickness Requirements

Test results show that fire resistance in concrete structures will vary in relation to the type of aggregate used. Table (2.1) shows a summary of the minimum thickness requirements for floor slabs and cast in place walls for different concrete types and for different fire resistance ratings. Table(2.2) summarizes the minimum column dimensions for different concrete types and different fire resistance ratings. Tables (2.1) and (2.2), show that there may be economic benefits to be gained from the selection of the type of concrete to be used in construction. The designer is encouraged to evaluate use of the alternative materials.

Table(2.1): Minimum thickness for cast in place floor and roof slabs, in.

Fire resistance rating					
Concrete type	1 hr.	1.5 hr	2 hr.	3 hr	4 hr
Siliceous aggregate	3.5	4.3	5.0	6.2	7.0
Carbonate aggregate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

Table (2.2): Minimum concrete column dimensions, in.

Fire resistance rating					
Concrete type	1 hr.	1.5 hr	2 hr.	3 hr	4 hr
Siliceous aggregate	8	9	10	12	14
Carbonate aggregate	8	9	10	11	12
Sand-lightweight	8	8.5	9	10.5	12

2.10 Cover Requirements

Another factor to be considered in complying with fire-resistive requirements is the minimum thickness of concrete cover for the reinforcement. The concrete protection specified in ACI 318for cast-in-place concrete will generally equal or exceed the ACI 216.1 minimum cover requirements, but there are a few exceptions at the higher fire ratings. The minimum concrete cover to the positive moment reinforcement is given in Table (2.3) for one-way or two-way slabs with flat undersurfaces. The minimum concrete cover to the positive moment reinforcement (bottom steel) in reinforced concrete beams is shown in Table (2.4).

Table(2.3): Minimum cover for floor and roof slabs, in.

	Fire resistance rating					
	Unrestrained					Restrained
Concrete type	1 hr	1.5 hr	2 hr	3 hr	4 hr	4 hr. or less
Siliceous aggregate	0.75	0.75	1	1.25	1.625	0.75
Carbonate aggregate	0.75	0.75	0.75	1.25	1.25	0.75
Sand-lightweight	0.75	0.75	0.75	1.25	1.25	0.75

Table(2.4) Minimum cover requirements to main reinforcement in beams (All types), in.

		Fire resistance rating				
Restrained or unrestrained	Beam width, in.	1 hr	1.5 hr	2 hr	3 hr	4 hr.
Restrained	5	0.75	0.75	0.75	1	1.25
	7	0.75	0.75	0.75	0.75	0.75
	≥ 10	0.75	0.75	0.75	0.75	0.75
Unrestrained	5	0.75	1	1.25	-	0.75
	7	0.75	0.75	0.75	1.75	3
	≥ 10	0.75	0.75	0.75	1	1.75

2.11 Concrete as a structural material:

Concrete is the most widely used construction material in the world today, and it rise to this position has played a major role in the shaping of civilization as long time ago. The earliest known illustration of concrete work being carried out and that can be seen in mural form Thebes in Egypt dating back to about 1950b.c, the art of making concrete eventually spread from Egypt and by 500b.c was being used in ancient Greece. ` 6 By the 1890s, concrete was being used extensively for docks, river banks, and bridge; in 1899 one of the longest bridges at that time was constructed in western highland of (Scotland) it was constructed entirely in concrete[1].

2.11.1 Concrete ingredients.

In general concrete is the result of mixing together the various ingredients (water, aggregates, cement and any additives) and the proportion of the main ingredients gives the required properties of both fresh and hardened state.

I. Aggregates.

Aggregates were originally viewed as an inert material dispersed throughout the cement paste largely for economic reasons and it is normally occupy about 70% to 80% of the total concrete volume. In order to obtain the maximum amount of aggregates into a given volume, it's necessary to use varying size of aggregates to fill as many of the space as possible.

The aggregates are usually split into at least two different portions for ease of batching and the common dividing point is 4 mm, materials larger than 4 mm is termed coarse aggregate or gravel and materials less than or equal 4 mm is termed fine aggregate or sand.

The particles size distribution is extremely important in the design of any concrete mix, in order to obtain a reasonable workability and minimum segregation it is important to use well-graded aggregates[1].

II. Cement.

Cement can be described as a material with adhesive and cohesive properties which make it capable of bonding minerals. There are many different types of cement available, the most common of which is Portland cement. Four primary compounds usually regarded as the major constituent of cement and they are:

Table(2.5) : The cement components

Name Symbol	composite oxide	installation manual
Calcium silicate triple	$3CaO.SiO_2$	C_3S
Calcium silicate bilateral	$2CaO.SiO_2$	C_2S
Calcium aluminates triple	$3CaO.AL_2O_3$	C_3A
Calcium silicate iron	$4CaO.AL_2O_3Fe_2O_3$	C_4AF

2.11.2 Hydration of cement.

Hydration is a chemical reaction being involving the silicates and Aluminates in the cement and these reactions take place when water and cement are mixed. During hydration, capillary voids are form, these capillary are the large residual pore spaces originally filled by the water that have not been filled by hydration product, Higher water/cement (w/c) ratio result in greater distance between cement grains and therefore a greater volume of capillary pore.

The capillary pores are irregular in shape and size and form a complex interconnected network through which liquids and gases can pass; this lead to a weaker and more permeable hardened cement paste (HCP).

2.11.3 Strength of concrete.

Strength of concrete is commonly considered to be the most valuable property, although in many practical cases other characteristics such as durability, impermeability and volume stability may in fact be more important. Never less, strength usually gives the overall picture of the quality of concrete because it's directly related to the structure of cement paste. Strength as well as durability and volume changes of hardened cement paste, appears to depend not so much on the chemical composition as on the physical structure of the products of hydration of cement and on their relative volumetric proportions. It is necessary to relate strength to measurable parameters of structure of hydrated cement paste. Porosity is a primary factor in strength and this can be viewed as sources of weakness, also other sources of weakness rise from aggregates, which itself may contain flaws in addition to being the cause of micro cracking at the interface with the cement paste [1].

2.11.4 Modulus of elasticity

The modulus of elasticity and Poisson ratio of concrete are fundamental parameters necessary in structural analysis for the determination of the strain distributions and displacements, especially when the design is based on elasticity considerations.

Static modulus of elasticity of concrete (Ec) is defined as the slope of the (stress vs. strain) relationship at origin, according to ASTM C 318–92 the ratio of the stress to the corresponding elastic strain.

The modulus of elasticity and Poisson ratio are estimated from compressive strength of concrete, which increases with age.

The values of modulus of elasticity of concrete (Ec) and of Poisson ratio of concrete (μc) depend on the values of modulus of elasticity of paste (Ep) and ` 11 Poisson ratio of paste (μP) also in modulus of elasticity of aggregates (EA) and of Poisson ratio of aggregates (μA).

Since the micro structure of the paste changes with age, the values of (Ep) and (μP) in concrete increase with an increase in compressive strength of concrete, several investigators and standards have proposed empirical equations for the estimation of (Ec) and (μc) on the basis of their correlation to compressive strength. [7]

The modulus of concrete increase with (gel/space) ratio and decrease with an increase in the voids, therefore, the factors that affect concrete strength have similar effects on its modulus, the code of practice BS 8110: part 2 gives the relations between strength and modulus of elasticity as shown in table below:

Table (2.6): Modulus of Elasticity of concrete by (BS 8110: part 2)

Compressive strength of cubes (MPa)	Mean value of modulus of elasticity Ec (GPa)
20	24
25	26
30	28
40	30
50	33
60	35

Where Ec in (GPa) for various value of cube strength in (MPa) and it can be related by the following expression:

Ec = 9.1fcu0.33 ……………………………………………………..(2.1)

The expression is valid only in general terms and affected by the conditions of specimen during testing, the relation between modulus of elasticity and strength depends on mix proportions since the aggregates generally has a higher modulus than cement paste, and the age of specimen (at later ages the modulus increase more rapidly than paste).

During the vibration of the specimen a negligible stress only is applied, the dynamic modulus refer to almost purely elastic effect and is unaffected by creep, dynamic modulus is approximately equal to the initial modulus determined in the static test.

According to British code CP 110: 1972, the moduli expresses in (GPa) are related by the expression:

Ec = 1.25Ed -19 ……………………………………………………(2.2)

Where (Ec) and(Ed) are the static and dynamic moduli respectively, the relation does not apply to concrete containing more the 500 kg of cement per cubic meter, for the later the expression is:

Ec = 1.04 Ed – 4.1 ……………………………………………….(2.3)

The relation between the static and dynamic moduli is a function of density of concrete, just as in the case with the relation between the static moduli and strength.

The relation between the dynamic modulus of elasticity and its strength can be derived from the British code CP 110: 1972 using the following equation:

Ed = 7.6fcu0.33 +14 ……………………………………………..(2.4)

Where: Ed is in (GPa) and fcu in (MPa).

Poisson ratio may be determined experimentally by measurement of the longitudinal and lateral strains of concrete specimen subjected to an axial compression. Poisson ratio usually lies within the range of (0.1 to 0.2) and it's slightly lower for high strength concrete. For design calculation a value of 0.2 is usually assumed.

2.12 The impact of elevated temperature on concrete ingredients.

Under normal conditions, most concrete structures are subjected to a range of temperature no more severe than that imposed by ambient environmental conditions. However, there are important cases where these structures may be exposed to much higher temperature as: building fires, chemical and metallurgical industrial applications in which the concrete is in close proximity to furnaces, etc. ` 14 Concrete's thermal properties are more complex than for most materials because not only is the concrete a composite material whose constituents have different properties, but its properties also depending on moisture and porosity. Exposure of concrete to elevated temperature affects its chemical and physical properties. Elements could distort and displace, and under certain conditions the concrete surfaces could spall due to the buildup of steam pressure.

A complete understanding of the behavior of concrete under long term elevated temperature exposure as well as both during and after a thermal excursion resulting from a postulated design basis, accident condition is essential for reliable design evaluations and assessments. Because the properties of concrete change with respect to time and the environment to which it is exposed, an assessment of the effects of concrete aging is also important in performing safety evaluations [6]. Presented in the following sections a review of the effects of elevated temperature on concrete ingredients:

2.12.1 Impact of elevated temperature on ordinary Portland cement

Portland cements are manufactured by mixing finely divided calcareous materials (lime) and argillaceous materials (clay). The four compounds that make up more than 90% of the dry weight of the cement are:

i. Tri-calcium silicate (3CaO.SiO□).

ii. Di-calcium silicate (2CaO.SiO□).

iii. Tri-calcium aluminates (3CaO.Al□O□).

iv. Tetra-calcium alumino-ferrite (4CaO.Al□O□.Fe□O□).

Mature cement paste is normally composed of 70–80% layered calcium silicate-hydrate (C-S-H) gel and 20-30% of Ca.(OH)□ , and other chemical compounds[6]. The heating of cement paste results in drying water, it gradually evaporates from the paste, and the order in which water is removed from heated concrete paste depends on the energy that binds the water and the solid. Thus, free water evaporates first followed by capillary water and finally by physically bound water. The process of removing water that is chemically bound with cement hydrates is the last to be initiated. The mechanical properties of cement paste are strongly affected by chemical bonds and cohesion forces between sheets of calcium silicate hydrate (C-S-H), it is assumed that approximately 50% of cement paste strength comes from cohesion forces of C-S-H gel; therefore, the evaporation of water between C-S-H gel sheets strongly affects the mechanical properties of the cement paste[4]. The main products of hydration of Portland cement including Portland ite, ettringite, calcite, lime, larnite, and hydrated calcium silicate (C-

S-H gel). During C°heating, ettringite decomposes at first even before the temperature reaches 100 also the C-S-H gel dehydration is progressive and takes place from the very ` 16 beginning of concrete heating. It is worth noting that the structure of the cement C, which is°paste is partially damaged due to dehydration at the temperature of 105 standard for the drying of materials. C, the portlandite°As soon as cement paste is heated to temperature of 500–550 content rapidly drops, as it decomposes according to the following reaction: Ca(OH) □ Ca.O + H□O. The portlandite decomposition reaction explains the observed increase in C.°(CaO) content in cement paste at the temperature of approximately 550 The (CaO) created in this reaction makes the elements made of the Portland cement practically redundant after cooling. The dehydration process of the C-S-H gel reduces its volume, which in turn increases the porosity of the cement matrix. Moreover, during heating, the cement paste experiences a slight expansion up C, although the intense to shrinkage begins as°to temperature of approximately 200 C, This significantly contributes to the°soon as this temperature is exceeded 200 porosity evolution of the cement paste. Due to heating total the pore volume increases, as does the average pore. [8] and [9]

2.12.2 Impact of elevated temperature on Aggregates.

Aggregates occupy 70–80% of the volume of concrete and thus heavily influence its thermal behavior. The term (thermal stability of aggregates) is to describe aggregates effect on concrete performance at high temperature. Thermally stable aggregates are characterized by chemical and physical stability at high temperature, which is determined by thermo-gravimetric and differential thermal test .Considering concrete behavior at high temperature, a suitable aggregate would be one with a low thermal strains coefficient as well as negligible residual strains. ` 17 Mineralogical composition determines aggregate thermal strains, since all minerals differ in their thermal expansion properties; the type of minerals governs the chemical and physical changes that take place during heating. For example, C due to the quartz inversion. (10)°quartz aggregates and sands change at 574 C. At°The carbonate stones (limestone and dolomite) are stable up to 600 C.°higher temperature, carbonate aggregate decomposes into CaO and CO_2 at 700 additionally; the CaO formed during de-carbonation may hydrate when cooling, with a consequent 44% expansion. The poly-mineral stones may be prone to the disintegration that results from the thermal incompatibility of its components. For those stones differences in thermal strain can cause inter-crystalline stresses and failure.

The further heating of aggregate leads to its melting, the melting temperature varies along the mineralogical composition, for most igneous rock it is above C, while basalts melt at1050°C. The melting temperature of granites is 1210–1250°1000 C, which is accompanied by gas release and expansion [10].

2.13 Previous Studies

2.13.1 Fire and Concrete Structures

Concrete's excellent fire resistance has been proven by many tests performed for over 60 years. The American Concrete Institute and various building codes have developed prescriptive and analytical methods based on the fire tests on concrete components of structures. These methods provide architects and engineer a relatively easy way to select member proportions and reinforcement requirements for all but the very unusual structures. For the very unusual structures, alternate methods are available to adequately model or to test the complex behavior of reinforced concrete components subject to fire [5].

2.13.2 The effect of fire on concrete

The behavior of concrete in fire depends on its mix proportions and constituents and is determined by complex physicochemical transformations during heating. Normal-strength concretes and high-performance concretes micro structurally follow similar trends when heated, but ultra-high-performance concrete behaves differently. A key property unique to concrete amongst structural materials is transient creep. Any structural analysis of heated concrete that ignores transient creep will yield erroneous results, particularly for columns exposed to fire. Failure of structural concrete in fire varies according to the nature of the fire; the loading system and the type of structure. Failure could occur from loss of bending or tensile strength; loss of bond strength; loss of shear or tensional strength; loss of compressive strength; and spelling of the concrete. The structural element should, therefore, be designed to fulfill its separating and/or load-bearing function without failure for the required period of time in a given fire scenario. Design for fire resistance aims to ensure overall dimensions of the section of an element sufficient to keep the heat transfer through this element within acceptable limits, and an average concrete cover to the reinforcement sufficient to keep the temperature of the reinforcement below critical values long enough for the required fire resistance period to be attained. The prediction of spelling – hitherto an imprecise empirical exercise – is now becoming possible with the development of thermo hydro mechanical nonlinear finite element models capable of predicting pore pressures. The risk of explosive spelling in fire increases with decrease in concrete permeability and could be eliminated by the appropriate inclusion of polypropylene fibers in the mix and/or by protecting the exposed concrete surface with a thermal barrier. There are three methods of assessment of fire resistance: (a) fire testing; (b) prescriptive methods, which are rigid; and (c) performance-based methods, which are flexible. Performance-based methods can be classified into three categories of increasing sophistication and complexity: (a) simplified calculations based on limit state analysis; (b) thermo mechanical finite element analysis; and (c) comprehensive thermo hydro mechanical finite element analysis. It is only now that performance-based methods are being accepted in an increasing number of countries[6].

2.13.3 BEHAVIOUR OF REINFORCED CONCRETE STRUCTURES IN FIRE

In 1995-96 six large fire tests were carried out on a full-scale composite building at the BRE Fire Research Laboratory at Cardington[4]. The tests made it clear that unprotected steel members could have significantly greater fire resistance within real multi-storey buildings than when tested as isolated members. This was undoubtedly due to interaction between the heated members within the fire compartment, the concrete floor slabs (both heated and unheated) and the adjacent composite frame structure. If such interactions are to be used by designers in specifying fire protection strategies, as part of an integrated limit state design process, then this cannot practically be based on testing because of the extremely high implicit costs. It is therefore becoming increasingly important that software models be developed to enable the behavior of such structures under fire conditions to be predicted with sufficient accuracy.

A number of researchers have developed numerical modeling approaches to the behavior of reinforced concrete structures in fire conditions. Ellinwood and Lin(5), and Huang and Platten [6], developed planar modeling software for reinforced concrete members in fire, and a simpler model has been developed by Lie and Clicked[7] for the high-temperature analysis of circular reinforced concrete columns. In the major general-purpose finite element codes this kind of numerical modeling is often attempted, but the degradation of material properties tends to be simplified, and the finite element formulations used are often inappropriate for efficient set-up and analysis of concrete and composite buildings under fire attack.

The specialized finite element program *Vulcan* has been progressively developed over the past decade[8-11] at the University of Sheffield for three-dimensional modeling of the structural behavior of composite and steel-framed buildings in fire. In this program a non-linear layered finite element procedure has been developed for predicting the structural response of reinforced concrete slabs subjected to fire [9, 10]. Also a more robust three-dimensional 3-noded beam-column element with general cross-section has been developed for Modeling of steel and reinforced concrete frames in fire conditions[11]. These developments have provided a powerful tool to carry out 3D analysis of reinforced concrete structures in fire.

In this study a generic 37.5m x 37.5m normal-weight reinforced concrete structure comprising four floors has been considered, with realistic loading conditions and structural layout. In order to develop a better understanding of the interactions between the cool and hot zones of the structure, a series of analyses has been carried out for different extents and positions of localized fire compartments.