

**ADDIS ABABA UNIVERSITY
INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIROMENTAL ENGINEERING**



**PERFORMANCE OF CONCRETE AND UNRESTRAINED REINFORCED CONCRETE
BEAM FOR FIRE**

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A THESIS SUBMITTED TO THE SCHOOL OF CIVIL AND ENVIROMENTAL ENGINEERING OF
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Last but not least for the huge moral support and dedication to make suitable situation for my work my family takes great thanks.

ABSTRACT

Fire accident is one of the dangerous accidents that could happen to any service structures in unexpected times, it could be ignited intentionally to attack enemies among human being aggression, it could be from the result of terrorism attack which of course common nowadays or it could be from war among enemies.

Fire accident by its behaviour a little source is enough to be ignited but its costs much to be controlled. In our country Ethiopia there were so many lives taking and damaging fire accidents occurring for instance in the near past an accident caused on TAITU HOTEL in piazza , an accident in Southern Ethiopia, Hawassa demolishing large number of homes and lives.

A repeated and hazardous fire accidents causing loss of valuable human life, failure of structures and the difficult circumstance to make fire accident under control within a shorter time, increase an interest in the design of structures for fire. Now a day there is a good development in using advanced analytical models to determine fire growth within a compartment and have used finite element models of structural components to determine temperatures within a component by heat transfer analysis but the experimental way of determining the performance of structural members for fire is more realistic one.

This paper focused in studying the performance of concrete and unrestrained reinforced concrete beams under fire. In this study different concrete surface temperature and duration of fire exposure was considered.

Experimental investigation on fire performance of concrete and unrestrained reinforced concrete were carried out and it is discovered compressive strength of concrete reduces up to 30% from initial compressive strength up on exposure to fire causing concrete surface temperature to rise to 246 °c for four hour duration, and residual shear and moment strength of unrestrained reinforced concrete beam reduce to 80% for 246 °c concrete surface temperature sustained for four hours.

Key words: Fire duration, Concrete surface temperature, Reinforced concrete beam, Fire rating, Bending moment capacity, deflection, Shear capacity, Compressive Strength, concrete cube.

1. INTRODUCTION

1.1 Background

Service structures could be built from different materials like wood, steel, Masonry, reinforced concrete and /or composite of the above. Whichever is the material made from the structure is expected to resist the loads coming to it during service periods.

The loads which most structures designed for are predictable from service type, location, dimension or history and they are easily modelled using highly developing software. But in case of fire it is difficult to speculate when it will happen, where and to what extent will affect the structure by causing strength reduction and imposing unexpected stress. This makes fire accident difficult in its nature.

Different construction materials for structural members or finishing part have different fire endurance capacity. One of the advantages of concrete over other building materials is its inherent fire-resistive property; however, concrete structures must still be designed for fire effects.

Structural components designed for desired fire rating are expected to be able to withstand design loads without collapse even though fire accident causes a decrease in the strength of the members. In addition, fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted.

For sound and safe design, fire considerations must be part of the preliminary design stage because of the dimension recommended for fire could be more than the minimum requirement provided for design load carrying capacity. Determining the fire rating for a structure member, can vary in complicity from extracting the relevant rating using a simple table provided in codes or books to a fairly complex and elaborate analysis.

In western countries, structural design for fire safety is more easy than in our country, which in our case unavailability of abundant data and recommendations in codes regarding fire design of structures makes it difficult. Unlike this in the western countries different sources are available starting from small study papers up to detailed codes, among them the International Building Code (IBC) [16], ACI 216.1 "Standard Method for Determining Fire Resistance of Concrete [1] and ASTM E 119 (Standard fire test) [2].

The performance of reinforced concrete for fire depends on the parameters of concrete, the reinforcing steel and the fire temperature- duration.

The parameters of the concrete affecting the fire endurance of reinforced concrete are

- ✓ Dimension
- ✓ Concrete grade
- ✓ Concrete cover to reinforcing steel
- ✓ The coarse aggregate type used whether it is silicate, carbonate or light weight.

The parameters of steel affecting fire endurance of reinforced concrete are

- ✓ Steel grade
- ✓ Time – temperature (fire) behaviour

The other parameter affecting fire endurance of reinforced concrete is

- ✓ Fire time – temperature

Here in Ethiopia, the shortest time to make under control of medium fire accident was three hours which is long. There could be many reasons why it becomes so, among them the main reasons are the time taking communication to inform the responsible authority or any responsible party to come and fight the fire, the over crowd of traffic ,difficult access infrastructure to point of interest and the limited capacity of fire fighting mechanism.

1.2 STATEMENT OF THE PROBLEM

Up to the date of the initiation to do this research, in our country building code there is no detailed and enough provisions existing about the performance of different kinds of construction materials for fire. With the afore mentioned limitations, growth of infrastructure and increasing interest of safety in our country, repetitive continuous experiments and studies on fire endurance and fire resistance property determination of different construction materials, different construction methods and different structural members must be given high value.

This experimental research considered concrete cube samples and small size simply supported beams on fire endurance determination of reinforced concrete beam and concrete exposed to fire of different temperature and duration, and it is found the residual strength of concrete and beam after fire exposure reduces up to 20% from initial strength.

1.3 RESEARCH OBJECTIVE

The design of structures specially here reinforced concrete beam for fire is not an easy task without the availability of supporting Codes and well organized literatures dictating the provisions from test and experiments.

Even though too much time , cost, effort and involvement of institutions is required to come up with a detailed provisions of data for fire design of any structural member, this research could be taken as one foot step initiating the long journey of fire safety in structure.

The objectives of this research are

- ✓ To determine the parameters affecting the performance of reinforced concrete beam on fire.
- ✓ How those parameters affect the performance of reinforced concrete beam on fire.
- ✓ To evaluate the current construction process on fire rating of beams.
- ✓ To come up with recommendations of fire resistance reinforced concrete beam for desired rating.
- ✓ To study how higher temperature and concrete is connected.
- ✓ To study the level of temperature penetrating through concrete cover to reach sensitive steel.
- ✓ To classify reinforced concrete beams about their safety and performance after exposure of fire accident for some duration.

Finally to increase the practice of making reinforced concrete beam resistive to fire damage for some rating or duration of emergency delivery and to give service after a fire accident.

1.4 THESIS HYPOTHESIS

At the end of this study hypotheses mentioned below will get answer.

- ✓ Concrete compressive strength will be affected under 500 °c temperature of fire exposure.
- ✓ Fire exposure duration affects the compressive strength of concrete.
- ✓ An increase in compressive strength of concrete will increase fire endurance.
- ✓ Lower temperature with higher duration will affect compressive strength of concrete than higher temperature with less duration. Will be justified positive or negative.
- ✓ How different fire temperature affect the fire endurance of reinforced concrete beam.

- ✓ How duration of fire affects strength of reinforced concrete.
- ✓ Thickness of concrete cover to reinforcement for good fire rating.
- ✓ The relevance of other recommendation on unrestrained reinforced concrete beam for fire resistance of desired duration.

1.5 RESEARCH APPLICATION

The construction of wider infrastructures including high rise buildings in our country Ethiopia is increasing now and will be expected to grow further. The design of such complex structures will need not only good software but also other inputs of researches, studies and review of foreign Codes used in our country.

As previous practices tells important findings and research results of important value comes from such type of fulfilment papers and the results of this experimental research will be useful.

Since this construction industry is huge it will need huge number of inputs. Based on this the results of this research could be used

- ✓ For the design of reinforced concrete beam for fire.
- ✓ To evaluate reinforced concrete beam after fire accident.
- ✓ By institutions working on fire safety of structures.
- ✓ To justify the recommendations in other literatures used.
- ✓ As a reference for further study.

1.6 LIMITATIONS

Even though this research could be taken as a good one foot step towards a huge field that needs many researches and studies, there are limitations which comes from level of study, resource capacity and from many others.

The followings are the limitations.

- ✓ The maximum concrete surface temperature considered is limited to 246⁰c.
- ✓ The maximum duration of fire exposure taken is four hours.
- ✓ Temperature measurement of concrete is only on its surface. Concrete internal temperature measurement gives accuracy.
- ✓ Moisture content effect not considered.
- ✓ Loading test is done after cooling.
- ✓ No simultaneous burning and loading test considered.

Additional limitations for the reinforced concrete beam are

- ✓ Only concentrated load on mid span of beam is considered.
- ✓ Effect of other dimension of samples not considered, single dimension considered.
- ✓ Only simple support condition considered.

1.7 CONTENT OF THE THESIS

This thesis is comprised of four chapters. Chapter one is an introductory chapter which discusses about the effect of fire accident on structures, reinforced concrete behaviour on fire, statement of problem, research goals and its application on current construction process with its limitations.

The second chapter assesses what literature discusses and presents about fire endurance of concrete and reinforced concrete. It discusses parameters affecting fire endurance of reinforced concrete, parameters of reinforced concrete affected during fire exposure, test method for fires, criteria of acceptance for fire endurance and recommendations for best fire endurance of reinforced concrete.

The third chapter contains the main part of this thesis. The experimental study of concrete and unrestrained reinforced concrete beam fire endurance is assessed here. Results of reduction in compressive strength of concrete and residual shear and moment strength of beam up on exposure of fire for different temperatures and duration is presented and discussed in this chapter.

The final and fourth chapter contains conclusion and recommendation of concrete and unrestrained reinforced concrete performance for fire.

2. LITERATURE REVIEW

2.1 General

Fire accident is an accident which happens in fire vulnerable areas during unexpected times. It could be categorized based on their covering area or their scale and development.

Classification based on their covering area

- a) Small scale fire
- b) Large scale fire
- c) Localized fire
- d) Wide spread fire

- a) Small scale fire accident is a type which covers small part of service structure or building. It could be controlled with little resources. The pattern it happens, the material existing in the fire zone are by chance not combustible and/or not highly combustible or the ability of the building or the structure to confine the fire makes the fire to be remained small scaled until it is controlled.

Some fires of potential damage could be said as small scale if they are controlled with in short period of time without causing considerable damage.

- b) Large scale fire accident is a category containing fire of potential damage in life and/or asset. It spreads over large area it could be due to material which the structure made like wood, due to highly combustible materials existing in the area, due to limitation in the fire fighting capacity or due to the building or structure is poorly designed for fire confinement.
- c) Localized fire type is more or less similar to small scale one but this type is based on the fire location and size but the former small scale could be based on the intensity of the fire for the damaged caused.
- d) Wide spread fire type is a fire accident covering large area it could be small scale or large scale. The damage could be considerable or not.

Any category of fire causing any significant damage to structural part at some location or a number of location could be structurally damaging since integrity of the structure system could be disturbed due to even a single part is failed.

Even though there is nothing in the world up to now that will assure the control of fire accident in service structures and buildings without causing significant damage, there exists variety of active fire fighting mechanisms and other manual options.

There are different types of fire fighting mechanisms some of them they are direct fighting systems others are alarming types for the people living inside prior to possible total damage or partial damage. Sprinkling system, fire detection and alarm system, fire Extinguishers, hose cabinet and stand pipes of water for fire fighting vehicle could be mentioned as examples of fire fighting mechanisms [3].

Compared to the loss of life and resources during fire accident, whatever it costs the design of structures for fire safety and fire resistance of desired rating should be implemented. In designing for fire, the “factor of safety” is contained within the fire resistance rating. Thus for a given situation, a member with a four hour resistance rating would have a greater “factor of safety” than one with a two hour resistance rating [1].

Structures made from stone masonry have a good behaviour on fire. They will have ability to confine a fire ignited within from spreading out to other parts. Stone masonry is also good in heat insulation. Still structure made from stone masonry is not fire proof, long duration of fire on stone masonry could make it brittle finally. Different types of stone masonry have different extent of being brittle on fire exposure.

Whatever the material structural systems or frames or parts of it is made it should be designed for fire resistance for a desired duration or rating to sustain the design load until all occupants exits before failure, until fire fighting mechanisms controlled the fire or until emergency is delivered [9].

2.2 BEHAVIOUR OF REINFORCED CONCRETE ON FIRE

Reinforced concrete is a widely used construction material around the world, as a construction material has a good behaviour in strength, sound insulation, heat insulation, durability, easiness in casting, not expensive in massive use and good fire resistance behaviour which of course focus of this paper. The universal nature of reinforced concrete and the wide availability of the constitute reinforcing bar, gravel, sand and cement, the relatively simple skilled labour required for construction are additional reasons for wide acceptance.

The behaviour of reinforced concrete on fire is highly dependent on the components used which are the concrete and the reinforcing steel bar [1]. The reinforcing steel bar which is the sensitive to heat or fire should be protected from direct contact with fire by the concrete covering it. Also the behaviour of concrete on fire is highly dependent on many parameters of the constitute. Both the reinforcing steel and concrete behaviours are studied in section 2.2.1 and 2.2.2.

The performance of reinforced concrete members could be studied from standard fire tests or now a days the performance could be found from numerical calculations and finite element modelling [1,2]. The standard fire test will be studied in detail under section 2.4. The calculative way of knowing the performance of reinforced concrete member for fire is based on the study of constitutes materials properties at high temperature, not discussed on this paper since this research paper is based on experimental tests.

In the study of reinforced concrete behaviour under fire different terms are used to express different terminology and concept. Among them three definitions are widely used in this paper and other literature

- a) Fire endurance
- b) Fire resistance
- c) Fire resistance rating

a) Fire endurance- A measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. Test and performance discussed under 2.4 [1].

b) Fire resistance- The property of material or assembly to withstand fire or to give protection from it [1].

- c) **Fire resistance rating**- Sometimes called fire rating, fire resistance classification or hourly rating. A legal term defined in different codes, usually based on fire endurance; fire resistance rating is assigned by different building codes for various constructions and occupancies and usually given in half-hour increments [1].

2.2.1 Concrete behaviour on fire

Concrete is made from coarse aggregate (gravel), fine aggregate (sand), cement and water. These constitute are mixed together in different proportion of interest to give a paste called concrete. Concrete is used in different parts of structure as reinforced concrete or only itself. Concrete is known in good compressive strength and lower tensile strength.

Concrete generally has good fire endurance. It can resist fire for a longer period of time without losing strength. 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 [1].

- ✓ 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.

As concrete is exposed to fire there are properties of it that will be affected. Some of the properties or relationships that will be affected are discussed below. Affection is highly dependent on which type of the three aggregate used.

- ✓ Compressive strength
- ✓ Thermal expansion
- ✓ Modulus of elasticity
- ✓ Stress relaxation and creep

2.2.1.1 Compressive strength

Compressive strength is the good quality of concrete and how it is affected by fire could be studied by a specimen similar to normal concrete compressive test specimen of different aggregate will be heated to target temperature with 5⁰c/min or 30⁰c/min temperature increment for a duration of until temperature of concrete interior becomes in steady state. Steady state during furnace burning is explained as either of the two criteria 1. Internal temperature of test samples varies with in 5⁰c measured by internally fixed thermocouples during heating or burning. 2. Internal temperature stays within +/- 5⁰c variation from target temperature [5].

Compressive strengths of concretes made with different types of aggregates are shown in Figures 2.1, 2.2 and 2.3 [1]. The sanded specimens were made with sand replacing 60 per cent of the lightweight fines (pumice), by volume. The “unsanded” concrete was the kind used in masonry block manufacture. Curves designated “unstressed” are for specimens heated to test temperature with no superimposed load and tested hot. Strengths of specimens heated while stressed to $0.4f'_c$ and then tested hot are designated “stressed to $0.4f'_c$ “. The “unstressed residual” strengths were determined from specimens heated to test temperature, cooled to room temperature, stored in air at 75 per cent relative humidity for six days and then tested in compression. Note that the “stressed” strengths are higher than the “unstressed” strengths. The “unstressed residual” strengths were in all cases lower than the strengths determined by the other two procedures. The original concrete strengths between 28 and 4.5 MPa have little effect on the percentage of strength retained at test temperature.

Where f'_c is the cylindrical compressive strength of concrete.

As it can be seen from figures in stressed test carbonate aggregate concrete tend to loss strength at higher temperature compared to the other two. Light weight concrete even though it starts to reduce its strength immediately after exposure of fire but it stays longer than the two types on fire before losing significant strength.

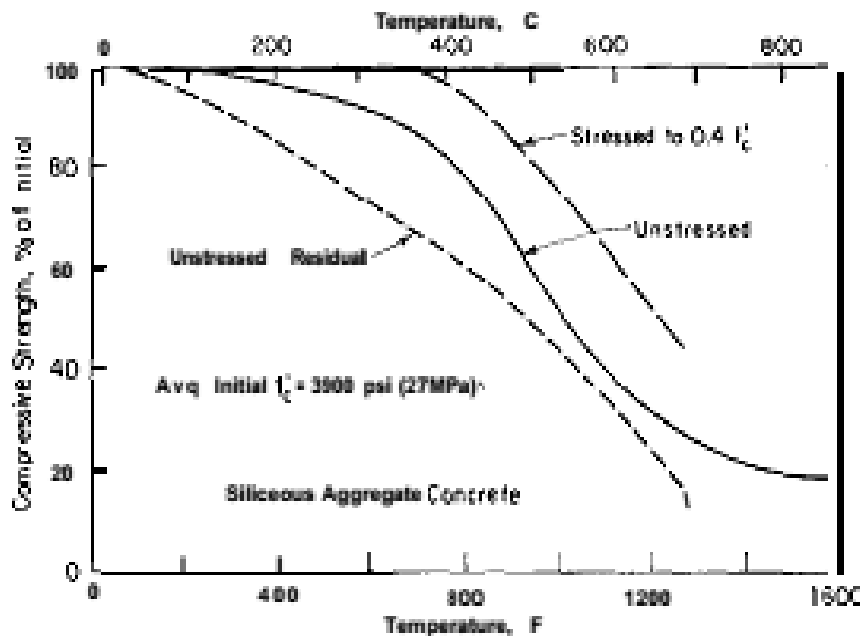


Fig. 2.1- Compressive strength of siliceous aggregate concrete at high temperature and after cooling [1]

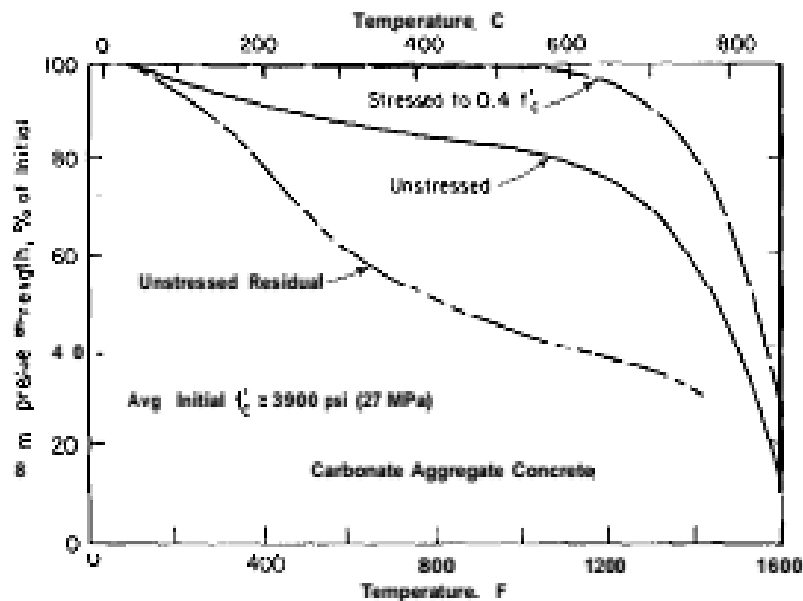


Fig. 2.2- Compressive strength of carbonate aggregate concrete at high temperature and after cooling [1]

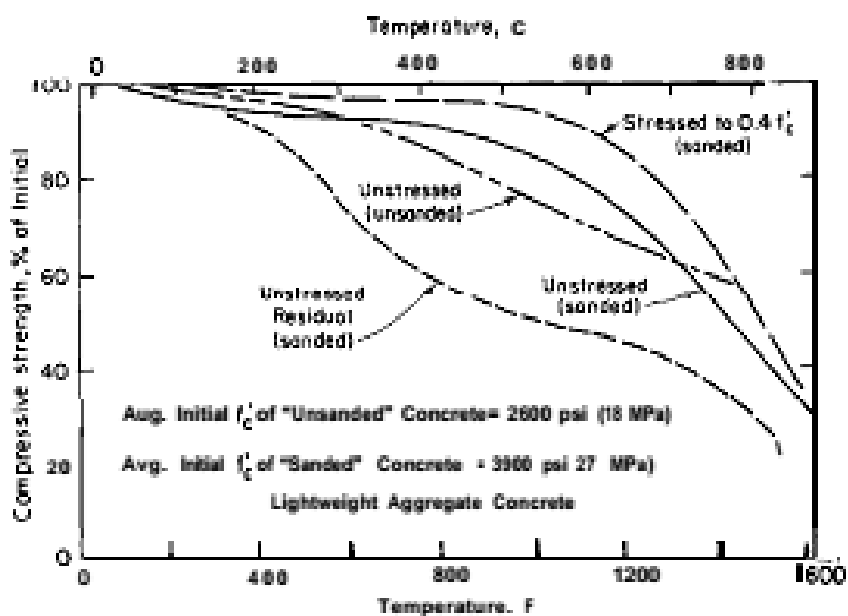


Fig. 2.3- Compressive strength of lightweight concrete at high temperature and after cooling [1]

2.2.1.2 Thermal expansion

Thermal expansion is an increase in dimension of concrete due to heating. Tests to study expansion of concrete under fire of high temperature were done for three different aggregate type and results are shown in Fig. 2.4 [1].

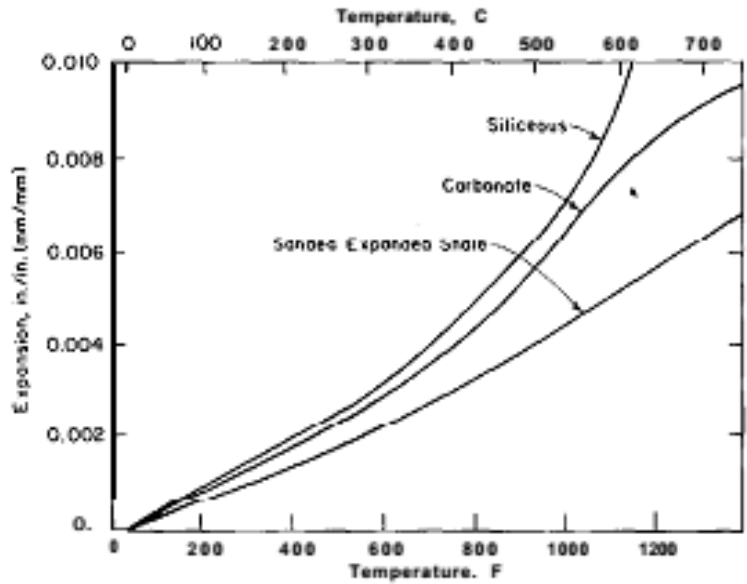


Fig. 2.4- Thermal expansion of concrete at high temperatures [1]

2.2.1.3 Modulus of elasticity

Modulus of elasticity of concrete can be defined in three ways using Fig. 2.5. The slope of a line which is tangent to a point on stress-strain curve is the tangent modulus of elasticity at that point. The slope of the curve at the origin is the initial tangent modulus of elasticity. The secant modulus of elasticity at a given stress is the slope of the line through the origin and the point on the curve representing that stress. Frequently the secant modulus of elasticity is defined by the point corresponding to $0.4f'_c$ [1].

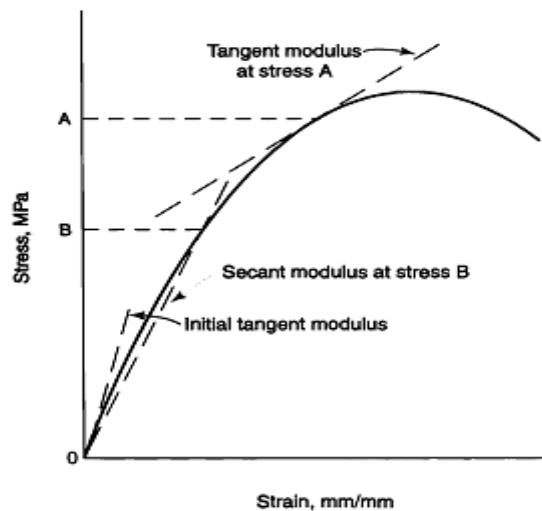


Fig.2.5- Stress-Strain curve used to define modulus of elasticity [1]

2.2.1.4 Stress relaxation and creep

Stress relaxation better explained by example. Consider a steel initially tensioned to some load, later this steel is heated to some higher temperature. The steel now become extended (relaxed) towards the tension direction to ease the initial stress now due to heating of particle. In similar way concrete rearranges its particle due to high temperature to sustain the load. Fig.2.6 shows this effect for carbonate aggregate. As temperature increases stress created with in the concrete reduces [1].

Creep strain is a strain created due to a load is kept for a longer time on concrete. This situation is due to a water particle inside the concrete transmitting stress tend to be removed through time this cause extra strain called creep strain [6]. As shown in Fig.2.7 creep strain increase as temperature increases.

Age, moisture condition, type and strength of concrete, and stress-strength ratio affect creep of concrete at high temperatures.

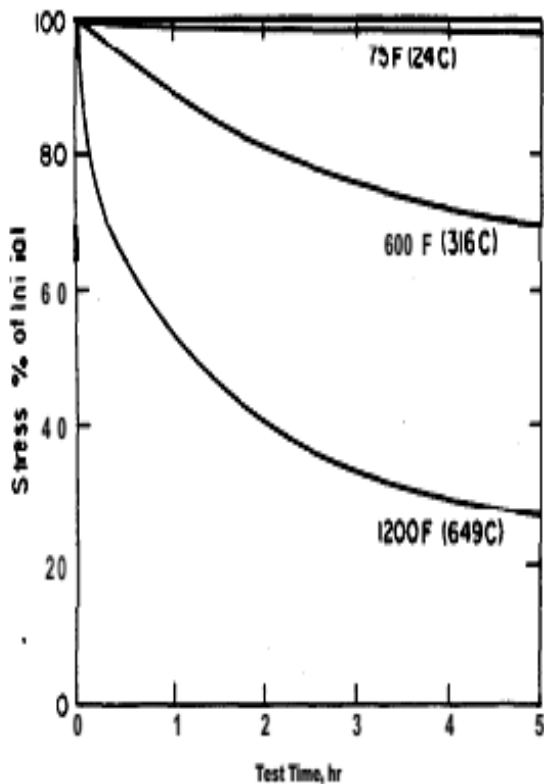


Fig.2.6- Stress relaxation of a carbonate aggregate concrete [1]

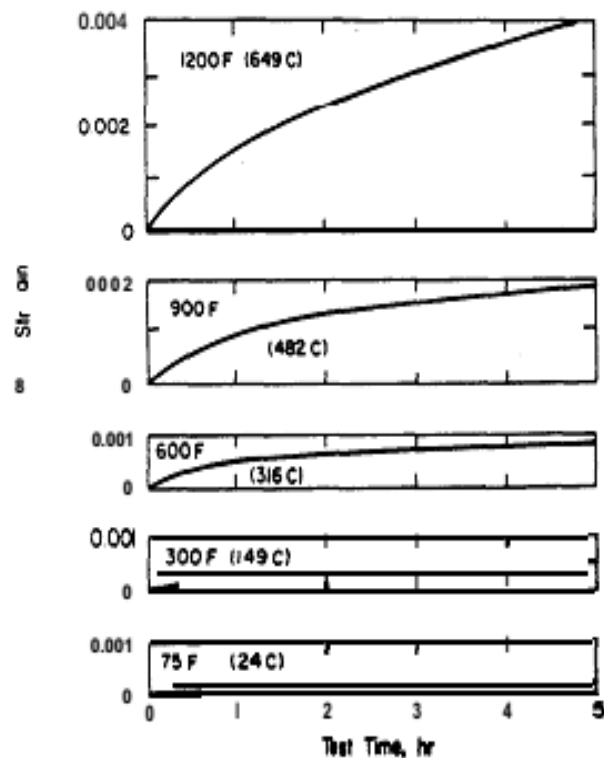


Fig.2.7- Creep of a carbonate aggregate concrete at various temperatures [applied stress $0.4f'_c = 12 \text{ MPa}$, $f'_c = 28 \text{ MPa}$] [1]

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. This process through time increases creep strain.

2.2.2 Behaviour of reinforcing steel on fire

Reinforcing steel is one of the components of reinforced concrete. Studying the properties of reinforced concrete on fire should include studying the properties of reinforcing steel bar on fire. Similar to the concrete there are some properties of reinforcing steel bar that will be affected during exposure to fire and they are discussed through 2.2.2.1 to 2.2.2.4 [1].

2.2.2.1 Strength

Strength is one of the property of reinforcing steel bar that will be affected by high temperature fire. Fig. 2.8 shows the influence of temperature on the strength of certain steels. Included are data on the yield stress of structural steels and ultimate strengths of cold-drawn steel.

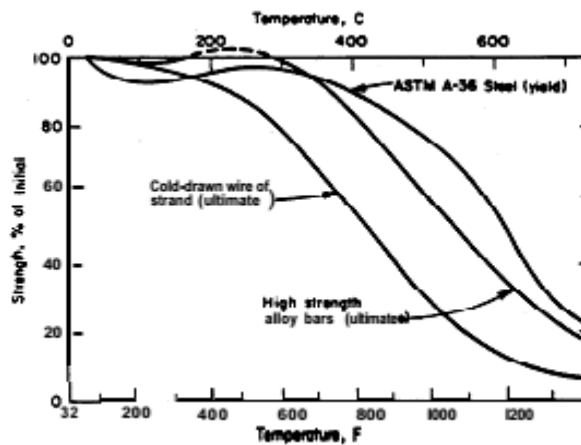


Fig. 2.8- Strength of certain steels at high temperatures [1]

2.2.2.2 Modulus of elasticity

The modulus of elasticity of steel decreases with increasing temperature as shown in Fig. 2.9. Modulus of elasticity for ferritic steels decreases linearly to about 750°F (400°C). Above 750°F (400°C) the modulus decreases at a higher rate. The curve in Fig. 2.9 is representative of the types of steels used in concrete construction, This curve was developed for the European Convention for Construction of Steel Structures (ECCS).

2.2.2.3 Thermal expansion

The average linear thermal expansion of ferritic steels over a temperature range of 200 to 650 °C is shown in Fig. 2.10.

The coefficient of thermal expansion is not constant over this temperature region but increases as temperature increases. The temperature dependence of the coefficient of thermal expansion α is approximated by the formula

$$\alpha = (6.1 + 0.002 \times \theta_1) \times 10^{-6} \text{ } ^\circ\text{F} \dots \dots \dots (2.1)$$

Or

$$\alpha = (11 + 0.0036 \times \theta_2) \times 10^{-6} \text{ } ^\circ\text{C} \dots \dots \dots (2.2)$$

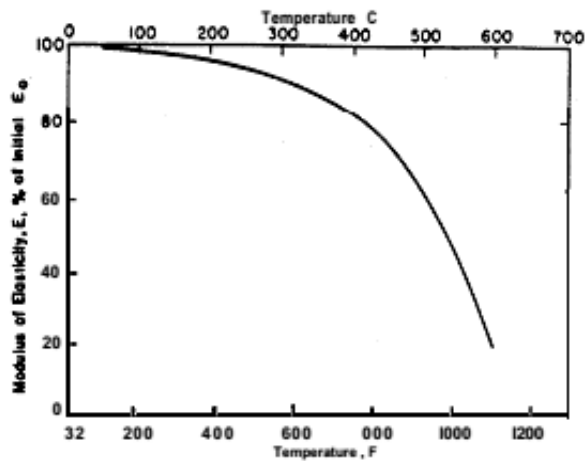


Fig. 2.9- Modulus of elasticity of steel at high temperatures [1]

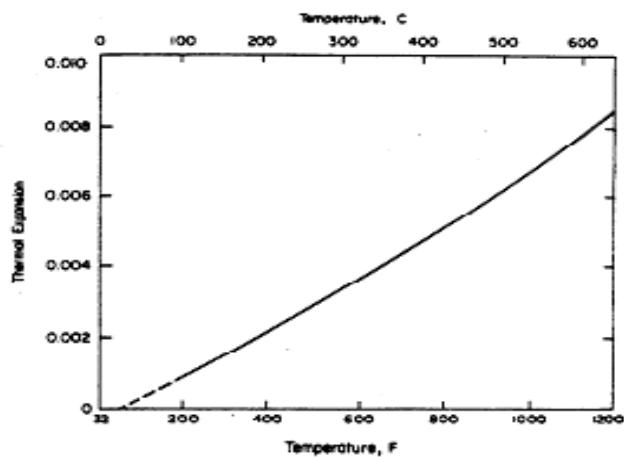


Fig. 2.10- Thermal expansion of ferritic steels at high temperatures [1]

2.2.2.4 Stress and strain

Stress-strain relationships for structural steel at different temperatures were developed. Such curves for an ASTM A 36 steel are shown in Fig. 2.11. Stress-strain relationship do not follow a regular trend up to a temperature of 427 °c but after that as temperature increases stress-strain relationship decreases.

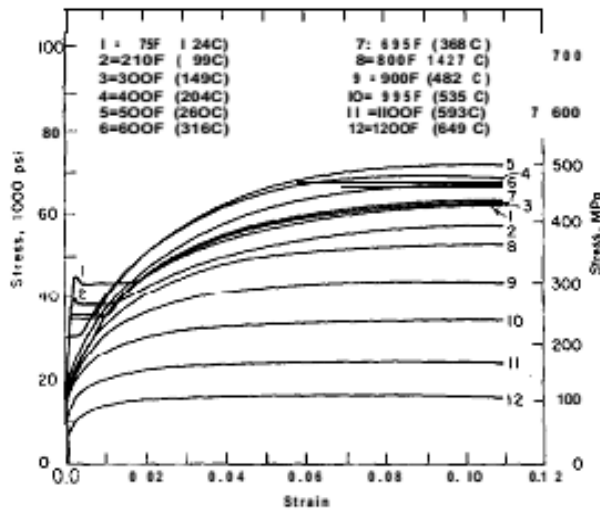


Fig. 2.11- Stress-strain curves for structural steels (ASTM A 36) at various high temperatures [1]

2.2.3 Action of fire on unrestrained reinforced concrete slabs and beams

Now after studying separately the behaviour on fire of concrete and reinforcing steel, the behaviour of reinforced concrete slab and beam on fire will be studied using illustrative Fig. 2.12. This figure illustrate a simply supported reinforced concrete slab and beam under fire. The rocker and roller supports indicate that the ends of the slab are free to rotate and expansion can occur without resistance. The reinforcement consists of straight bars located near the bottom of the slab. If the underside of the slab is exposed to fire, the bottom of the slab will expand more than the top, resulting in a deflection of the slab. The tensile strength of the concrete and steel near the bottom of the slab will decrease as the temperature increases. When the strength of the steel at elevated temperature reduces to that of the stress in the steel, flexural collapse will occur. If the reinforcement is straight and uniform throughout the length, the nominal moment strength will be constant throughout the length [1].

$$M_n = A_s \times f_y \times (d - a / 2) \dots \dots \dots (2.3)$$

Where

A_s : area of the reinforcing steel

f_y : yield strength of the reinforcing steel

d : distance from the centroid of the reinforcing steel to the extreme compressive fibre

a : depth of the equivalent rectangular compressive stress block at ultimate load, and is equal to $A_s \times f_y / 0.85 \times f_c' \times b$

Where f_c' : cylinder compressive strength of the concrete and b is the width of the slab

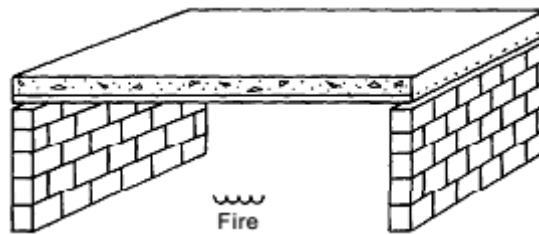


Fig. 2.12 - Simply supported reinforced concrete slab subjected to fire from below [1]

If the slab is uniformly loaded, the moment diagram will be parabolic with a maximum value at mid span.

$$M = w \times l^2 / 8 \dots \dots \dots (2.4)$$

Where w : dead plus live load per unit of length, and l is span length

During fire accident some of the live load will be removed for safety and emergency case but it is generally assumed that the dead and live loads remain constant for the reason of safety in calculation. However, the material strengths are reduced so that the retained nominal moment strength is

$$M_{n\theta} = A_s \times f_{y\theta} \times (d - a_{\theta} / 2) \dots \dots \dots (2.5)$$

in which θ - signifies the effects of elevated temperatures. Note that A_s and d are not affected, but $f_{y\theta}$ - is reduced. Similarly a_{θ} - is reduced, but the concrete strength at the top of the slab f_c' is generally not reduced significantly. If, however, the compressive zone of the concrete is heated, an appropriate reduction should be assumed.

Flexural failure can be assumed to occur when $M_{n\theta}$ - is reduced to M . From this statement, it can be noted that the fire endurance depends on the load intensity and the strength temperature characteristics of steel. In turn, the duration of the fire until the “critical” steel temperature is

reached depends upon the protection afforded to the reinforcement. Usually the protection consists of the concrete cover, additional protective layers of insulation might be present [1].

2.3 PARAMETERS AFFECTING PERFORMANCE OF REINFORCED CONCRETE ON FIRE

There are many factors affecting the performance of structural reinforced concrete for fire. These factors vary from members to members i.e one of the factor affecting the performance of reinforced concrete slab on fire could not be equally affecting the performance of reinforced concrete column under fire. So here we will discuss the factors (parameters) affecting the performance of reinforced concrete slab under fire. Even though these factors are discussed for reinforced concrete slab, they affect also the performance of other reinforced concrete members. For concrete slabs, the temperature rise of the top surface is dependent mainly upon the thickness, unit weight, moisture content, and aggregate type. [1,4] Other factors that affect temperature rise but to a lesser extent, include air content, aggregate moisture content at the time of mixing, maximum size of aggregate, water-cement ratio, cement content, and slump.

2.3.1 Effect of slab thickness and aggregate type on fire endurance

ASTM E 119 [2] limits the average temperature rise of the unexposed (top) surface of floors or roofs to 250 F (139 C) during standard fire tests (Standard fire test discussed under 2.4). Such limitations could be kept for a longer time of fire exposure by making the slab economically thicker. Fig. 2.13 shows the relationship between slab thickness and fire endurance for structural concretes made with a wide range of aggregates. The curves are for air-entrained concretes fire tested when the concrete was at the standard moisture condition (75 per cent relative humidity at mid-depth), made with air-dry aggregates having a nominal maximum size of 19 mm. [1,4]

On the graph, lightweight aggregates include expanded clay, shale, slate, and fly ash that make concrete having a unit weight of about 9.5 to 105 pcf (1520 to 1680 kg/m³) without sand replacement. The unit weight of air cooled blast-furnace slag aggregate was found to have little effect on the resulting fire endurance of the normal weight concretes in which it is used.

2.3.2 Effect of unit Weight of concrete for fire endurance

Fire endurance generally increases with a decrease in unit weight [1]. For structural concretes, the influence of aggregate type may overshadow the effect of unit weight. For low density concretes, a relationship exists between unit weight (oven-dry) and fire endurance, as shown in Fig. 2.14.

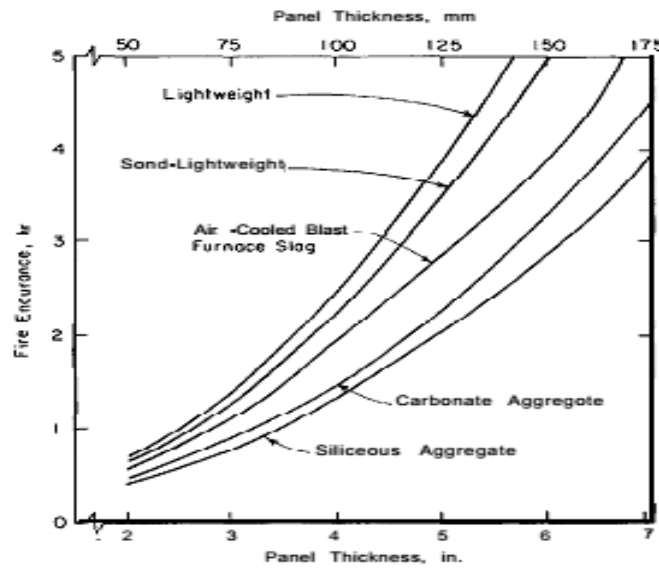


Fig. 2.13- Effect of slab thickness and aggregate type on fire endurance of concrete slabs. [Based on 250 F (139 °C) rise in temperature of unexposed surface] [1]

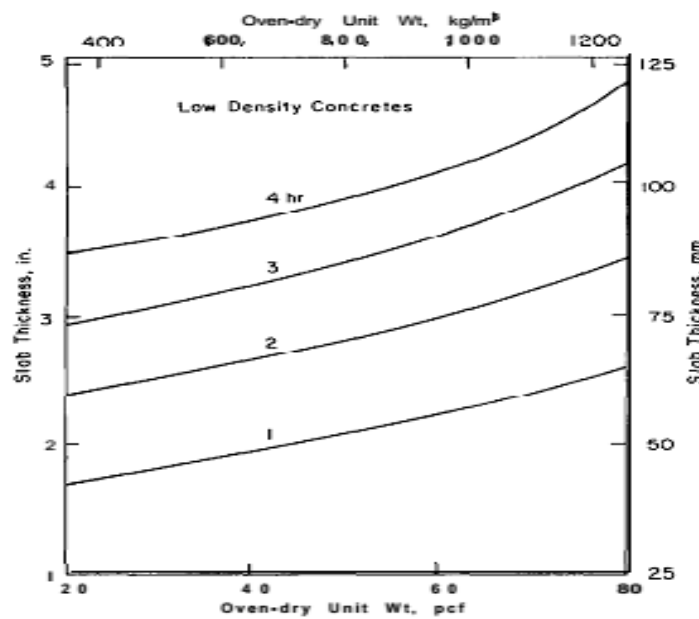


Fig. 2.14- Effect of dry unit weight and slab thickness on fire endurance of low density concretes. [Based on 250 F (139 °C) rise in temperature of unexposed surface] [1]

2.3.3 Effect of moisture condition on concrete fire endurance

The moisture content of the concrete at the time of test and the manner in which the concrete is dried affect fire endurance. Generally, a lower moisture content or drying at elevated temperature 120 to 200 F (49 to 94 °C) reduces the fire endurance.

A method is available for adjusting fire endurance of concrete slabs for moisture level and drying environment [2].

2.3.4 Effect of air content

The fire endurance of a concrete slab increases with an increase in air content, particularly for air contents above 10 per cent. Also, the improvement is more pronounced for lightweight concrete. This is due to variable thermal conductivity existing air in concrete.

2.3.5 Effect of sand replacement in lightweight concrete

As indicated in Fig. 2.13, replacement of lightweight aggregate fines with sand results in somewhat shorter fire endurance periods.

2.3.6 Effect of aggregate moisture

The influence on fire endurance of absorbed moisture in aggregates at the time of mixing is insignificant for normal weight aggregates but may be significant for lightweight aggregates. An increase in aggregate moisture increases the fire endurance. Thus, the fire endurances obtained from Fig. 2.13 represent minimum values.

2.3.7 Effect of water-cement ratio, cement content, and slump

Results of a few fire tests indicate that these factors, within the normal range for structural concretes, have almost no influence on fire endurance.

2.3.8 Effect of maximum aggregate size

For normal weight concretes, fire endurance is improved by decreasing the maximum aggregate size.

There are also parameters affecting the fire endurance behaviour of reinforced concrete. The reason why they are not discussed here is they are not applicable in our country by this time. Among those parameters floors or roofs may consist of base slabs of concrete with overlays or undercoating of either insulating materials or other types of concrete.

2.4 FIRE TEST OF REINFORCED CONCRETE

The process of designing reinforced concrete structural part for a fire of desired rating (fire endurance duration) involves first deciding the rating or fire endurance duration that we desire the structural parts to have. The next step in this process is how we do make the structural parts fire resistive for the decided duration. This can be achieved by varying the parameters that affect the fire endurance of structural parts. It is discussed under section 2.3 that some of the parameters are directly related to fire endurance that means an increase in some parameters increase the fire endurance performance, but some other parameters are inversely related to fire endurance that means increasing the behaviour of some parameters decrease the fire endurance performance.

The relationship among the fire endurance performance and the parameters affecting it whether it is direct or inverse as discussed in this section, was best studied by fire test of the structural part. The detailed procedures of fire endurance test of different structural parts, criteria of failure and different types of fire tests are discussed satisfactorily in ASTM [2].

The basic of a fire test is a specimen is exposed to a standard fire controlled to achieve specified temperatures throughout a specified time period. When required, the fire exposure is followed by the application of a specified standard fire hose stream. The test provides a relative measure of the fire-test-response of comparable assemblies under these fire exposure conditions. The exposure is not representative of all fire conditions because conditions vary with changes in the amount, nature and distribution of fire loading, ventilation, compartment size and configuration of the compartment. Variation from the test conditions or specimen construction, such as size, materials, method of assembly, also affects the fire-test-response. For these reasons, evaluation of the variation is required for application to construction in the field [2].

Important terms associated with fire test [2].

Test specimen- represent as closely as possible the actual construction in the field, subject to the limits imposed by the test facilities. All specimens are required to be conditioned so as to attain a moisture content comparable to that in the field prior to testing.

Standard fire- a fire controlled to achieve specified temperatures throughout a specified time period. It is not a representative of fire accidents on structures but accepted to be standard.

Time - Temperature curve of standard fire- a curve showing an increase in temperature of fire with time. Fig. 2.15 shows the variation of temperature with time of standard fire.

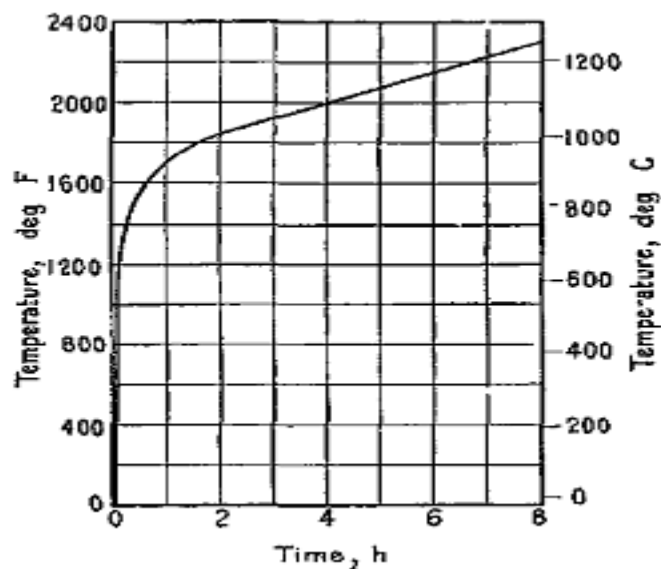


Fig. 2.15- Time-Temperature Curve [1]

Test furnaces- an assembly or arrangement place to test specimen for fire. This place is well equipped with temperature sensors (thermocouples) to measure the controlled temperature and it has a system of controlled fuel flow for burning.

2.4.1 Fire test of reinforced concrete floors and roofs

When it is mentioned here roof it means reinforced concrete roof. This test procedure is applicable to floor and roof assemblies with or without attached, furred, or suspended ceilings and requires application of fire exposure to the underside of the specimen under test. Two fire endurance classifications shall be developed from tests of assemblies restrained against thermal expansion and unrestrained assembly [2].

2.4.1.1 Size and Characteristics of Specimen

The area exposed to fire shall be not less than 180 ft²(16 m²) with neither dimension less than 12 ft (3.7 m). Structural members, if a part of the construction under test, shall lie within the combustion chamber and have a side clearance of not less than 8 in. (203 mm) from its walls.

Specimens representing forms of construction in which restraint to thermal expansion occurs shall be so restrained in the furnace [2].

2.4.1.2 Loading

Throughout the fire endurance test, apply a superimposed load to the specimen to simulate 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 and a corresponding reduced load is applied [2].

2.4.1.3 Temperature measurement

For specimens employing structural members (beams, open-web steel joists, etc.) spaced at more than 4 ft (1.2 m) on centers, measure the temperature of the steel in these structural members with four thermocouples at each of three or more sections equally spaced along the length of the members. For situations in which the protection material thickness is not uniform along the specimen length, at least one of the sections at which temperatures are measured shall include the point of minimum cover.

For specimens employing structural members (beams, open-web steel joists, etc.) spaced at 4 ft (1.2 m) on center or less, measure the temperature of the steel in these structural members with four thermocouples placed on each member. No more than four members shall be so instrumented. Place the thermocouples at locations, such as at mid-span, over joints in the ceiling, and over light fixtures. It shall not be required that all four thermocouples be located at the same section [2].

2.4.1.4 Evaluation of Specimen - Unrestrained assembly

The following conditions should be met to say a specimen has passed the test [2].

- ✓ The specimen shall have sustained the applied load during the classification period without developing unexposed surface conditions which will ignite cotton waste.
- ✓ The transmission of heat through the specimen during the classification period shall not have been such as to raise the average temperature on its unexposed surface more than 250 °F (139 °C) above its initial temperature.
- ✓ For specimens employing steel structural members (beams, open-web steel joists, etc.), spaced more than 4 ft (1.2 m) on centers, the temperature of the steel shall not have exceeded 1300°F (704°C) at any location during the classification period nor shall the average temperature recorded by four thermocouples at any section have exceeded 1100°F (593 °C) during the classification period.

- ✓ For specimens employing steel structural members (beams, open-web steel joists, etc.), spaced 4 ft (1.2 m) or less on center, the average temperature recorded by all joist or beam thermocouples shall not have exceeded 1100°F (593°C) during the classification period.

2.4.2 Fire test of reinforced concrete restrained beam

Reinforced concrete beam test for fire will be done in a similar way to that of reinforced concrete floors (slabs). It is discussed under 2.4.1 fire test of reinforced concrete slab lying on beams. The only difference coming here is the beam only will be considered but tested together.

The fire endurance classification so derived shall be applicable to the beam when used with a floor or roof construction which has a comparable or greater capacity for heat dissipation from the beam than the floor or roof with which it was tested. The fire endurance classification developed by this method shall not be applicable to sizes of beams smaller than those tested [2].

2.4.2.1 Size and Characteristics of specimen

The length of beam exposed to the fire shall be not less than 12 ft (3.7 m) and the member shall be tested in a horizontal position. For specimens tested with a representative section of a floor or roof construction, such sections shall be not more than 7 ft (2.1 m) wide and symmetrically located with reference to the beam [2].

Restrain the beam including that part of the floor or roof element forming the complete beam as designed (such as composite steel or concrete construction) against longitudinal thermal expansion in a manner simulating the restraint in the construction represented. Do not support or restrain the perimeter of the floor or roof element of the specimen, except that part which forms part of a beam as designed [2].

2.4.2.2 Loading

Throughout the fire endurance test, apply a superimposed load to the specimen to simulate 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 and a corresponding reduced load is applied.

2.4.2.3 Evaluation of Specimen

The following conditions should be satisfied to classify the specimen as fire resistant for the desired test duration [2].

- ✓ The specimen shall have sustained the applied load during the classification period.
- ✓ The specimen shall have achieved a fire endurance classification one half the classification of the assembly in 2.4.1.4 or 1 h, whichever is the greater. The temperature shall not have exceeded 1300°F (704°C) at any location during the classification period nor shall the average temperature recorded by four thermocouples at any section have exceeded 1100°F(593 °C) during the classification period.

2.5 MINIMUM THICKNESS AND CONCRETE COVER OF REINFORCED CONCRETE FOR FIRE

There are different parameters (dimensions) that affect the performance of reinforced concrete during a fire accident. A good knowledge of these parameters how do they affect the fire endurance behaviour of reinforced concrete will help us in the design process of making reinforced concrete fire resistance for the desired duration. Some of the parameters are either expensive or difficult to improve them for a better fire endurance, for example modulus of elasticity of reinforced concrete behaviour is the difficult one to vary easily for a better fire endurance. Parameters such as concrete cover to the reinforcing steel bar and thickness of a member are easier to alter them for increased fire endurance rating.

Test results show that fire resistance in concrete structures will vary in relation to the type of aggregate used [1,4]. 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 [4].

Another factor to be considered in complying with fire-resistive requirements is the minimum thickness of concrete cover for the reinforcement. The minimum concrete cover to the positive moment reinforcement is given in Table 2.3 for one-way or two-way slabs with flat under surfaces. [9] The minimum concrete cover to the positive moment reinforcement (bottom steel) in reinforced concrete beams is shown in Table 2.4 [1,4].

Table 2.1 Minimum thickness for cast in place floor and roof slabs, inch (mm)

Concrete type	Fire resistance rating				
	1 hr.	1.5 hr.	2 hr.	3 hr.	4 hr.
Siliceous aggregate	3.5 (88.85)	4.3 (109.15)	5 (127)	6.2(157.40)	7.0(177.70)
Carbonate aggregate	3.2 (81.25)	4 (101.55)	4.6 (116.80)	5.7(144.70)	6.6(167.60)
Sand-lightweight	2.7 (68.55)	3.3 (83.80)	3.8 (96.50)	4.6(116.80)	5.4(137.10)
Lightweight	2.5 (63.45)	3.1 (78.80)	3.6 (91.40)	4.4(111.70)	5.1(129.50)

Table 2.2 Minimum concrete column dimensions, inch (mm)

Concrete type	Fire resistance rating				
	1 hr.	1.5 hr.	2 hr.	3 hr.	4 hr.
Siliceous aggregate	8(203.10)	9(228.45)	10(253.85)	12(304.60)	14(355.35)
Carbonate aggregate	8(203.10)	9(228.45)	10(253.85)	11(279.20)	12(304.60)
Sand-lightweight	8(203.10)	8.5(215.80)	9(228.45)	10.5(266.50)	12(304.60)

Table 2.3 Minimum cover for floor and roof slabs, inch (mm)

Concrete type	Fire resistance rating					
	Unrestrained					Restrained
	1 hr.	1.5 hr.	2 hr.	3 hr.	4 hr.	4 hr. or less
Siliceous aggregate	0.75(19.10)	0.75(19.10)	1 (25.40)	1.25 (31.75)	1.625 (41.25)	0.75(19.10)
Carbonate aggregate	0.75(19.10)	0.75(19.10)	0.75(19.10)	1.25 (31.75)	1.25 (31.75)	0.75(19.10)
Sand-lightweight	0.75(19.10)	0.75(19.10)	0.75(19.10)	1.25 (31.75)	1.25 (31.75)	0.75(19.10)

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

Restrained or unrestrained	Fire resistance rating					
	Beam width, mm	1 hr.	1.5 hr.	2 hr.	3 hr.	4 hr.
Restrained	5(127)	0.75(19.10)	0.75(19.10)	0.75(19.10)	1(25.40)	1.25(31.75)
	7(177.70)	0.75(19.10)	0.75(19.10)	0.75(19.10)	0.75(19.10)	0.75(19.10)
	≥ 10(253.85)	0.75(19.10)	0.75(19.10)	0.75(19.10)	0.75(19.10)	0.75(19.10)
Unrestrained	5(127)	0.75(19.10)	1 (25.40)	1.25(31.75)	-	
	7(177.70)	0.75(19.10)	0.75(19.10)	0.75(19.10)	1.75(44.45)	3(76.15)
	≥ 10(253.85)	0.75(19.10)	0.75(19.10)	0.75(19.10)	1 (25.40)	1.75(44.45)

* Minimum cover for reinforcement in columns, for all aggregate types, is the smaller of, (25.40mm) times the number of hours of required fire resistance, or (50.80 mm) [4].

3. EXPERIMENTAL INVESTIGATION ON FIRE PERFORMANCE

The conventional method of testing any building construction and materials samples for fire performance is based in burning furnaces, which is well equipped with temperature measuring sensors thermocouples, controlled fuelling mechanism for burning and simultaneous loading way during burning [2]. This type of testing methodology is realistic but it is expensive to build it for individual research purpose.

In this research much easier way of fire testing procedure with commonly founded combustible materials and equipment are used. Samples are burned to a specified concrete surface temperature and duration then allowed to cool at room temperature and they are tested for failure.

❖ **Constitute materials used to produce the samples of concrete cubes and beams**

- ✓ The water used for mixing purpose is a tap water. Here also the water to cement ratio could affect the fire endurance behaviour of the concrete it could be studied separately not in focus here.
- ✓ Cement used to produce the test sample is Portland pozzolanas cement type available on market. The effect of other cement types on fire endurance could be studied as separate research not in focus here.
- ✓ Coarse aggregate used is crushed type of basaltic stone, which is classified as siliceous aggregate type. Actually the basaltic aggregate type is the most widely used coarse aggregate in our country for production of concrete.
- ✓ Fine aggregate called sand which comes from river side is used here for production of the test samples.

❖ **Tools and equipment for burning process**

There are different kinds of tools and equipment used for burning process, measuring process and sample handling process.

- ✓ Steel grill - A grill made from diameter 24 mm reinforcing bar which is be used to put the testing samples inside burning fire.
- ✓ Carrying bar - A bar which will be used to drag out and carry samples from burning place to testing laboratory place, made from reinforcing bar of 24mm.
- ✓ Old car tyres - These materials are chosen for facilitating and intensifying burning process because of their behaviour of long burning duration. For attaining the intended higher temperature fuel will be used parallel.

- ✓ Infrared thermometer – A thermometer is used to measure the temperature of burning fire to help keep the desired temperature of fire. Since it is fire test we could not use contact thermometer then it is chosen to be non-contact infrared thermometer having a measuring range of -50°C to 380°C shown in Fig. 3.1 . Actually there are other more ranging infrared thermometer this range and type is selected from optimization of time, cost and availability.



Fig. 3.1– Infrared thermometer

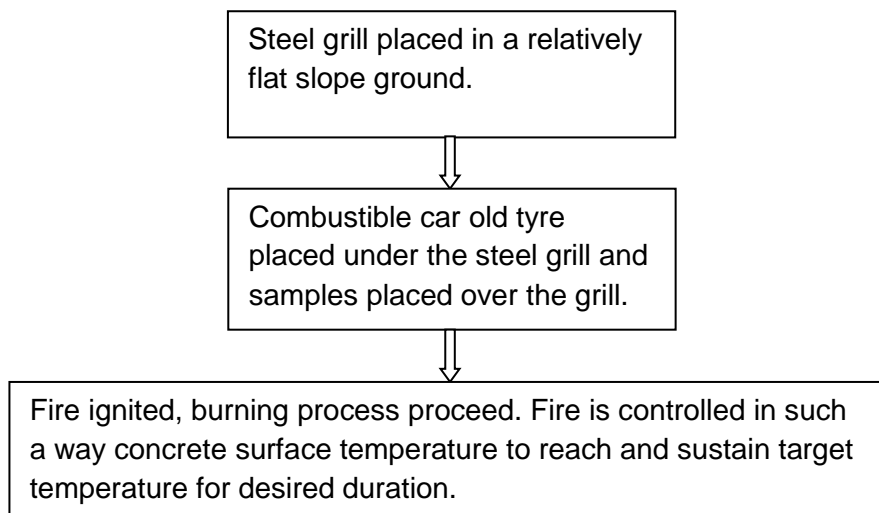


Fig.3.2- General burning process flow chart

3.1 Concrete Specimens for Compression

Concrete has good fire endurance behaviour, but it is not a fire proof. How a fire affects the compressive strength of concrete should be investigated well. Even though it is not common to use concrete only without reinforcement bars, performance of concrete under fire was studied since concrete in the compression zone is important and at high risk of fire exposure the results of this test will be used for fire design.

A good knowledge of how a fire of different temperature and duration affects the compressive strength of concrete will be useful in

- ✓ Economical fire design of concrete structures.
- ✓ Evaluating existing concrete structure its fire endurance.
- ✓ Evaluating concrete structure after fire accident whether it is re-usable with remedy or not.

In this section 3.1 performance of concrete for fire due to different burning temperatures and fire duration is presented.

3.1.1 Testing specimens

The specimen which is used in this test is concrete cube of 150mm size. To study the effect of varied compressive strength in fire performance two groups of concrete cube samples are produced, one group contains 21 cubes with presumed compressive strength of 25 MPa (group1). The other group contains 21 concrete cubes with presumed compressive strength of 30 MPa (group2). Figure 3.3 shows produced concrete cube samples and the mix design for concrete cubes production is shown in Table 3.1.



Fig. 3.3- Photo showing produced concrete cube specimens

Tables 3.1 Mix proportion of constitute materials for 25 MPa and 30 MPa cube specimen production

No	Material	Quantity 25 MPa	Quantity 30 MPa
1	Cement	360 Kg/m ³	400 Kg/m ³
2	Water	0.057 m ³ /m ³	0.063 m ³ /m ³
3	Fine aggregate	0.33 m ³ /m ³	0.32 m ³ /m ³
4	Coarse aggregate	0.49 m ³ /m ³	0.48 m ³ /m ³

The concrete cube samples as shown in Fig. 3.3, are hooked only for convenience of handling during burning, during removing from burning place and transporting to testing place. Samples are cured with water for seven days after removed from mould, kept under shed for one month and then exposed to open air until testing time.

3.1.2 Testing Procedures

Three concrete cube samples are tested to get representative value of compressive strength for different burning temperature and duration of fire exposure. Testing and burning process is expressed in the flow chart shown in Fig. 3.4 below.

Effect of varied concrete surface temperature on compressive strength of concrete is one of the parameter investigated in this paper, actually the concrete surface temperature does not tell the temperature inside the concrete but due to difficulty and sophistication to measure inside temperature in this study level it is decided to experiment by measuring surface temperature.

Duration of fire exposure is the other parameter investigated in this study. whether it affects the compressive strength of concrete or not and the extent of affection are studied in this paper for three hours and four hours duration.

There were three rounds of burning takes place, the first round of burning takes target concrete surface temperature to be 100⁰c for different duration, the second round is with target concrete surface temperature of 200⁰c and the third one is with target concrete surface temperature of 300⁰c.

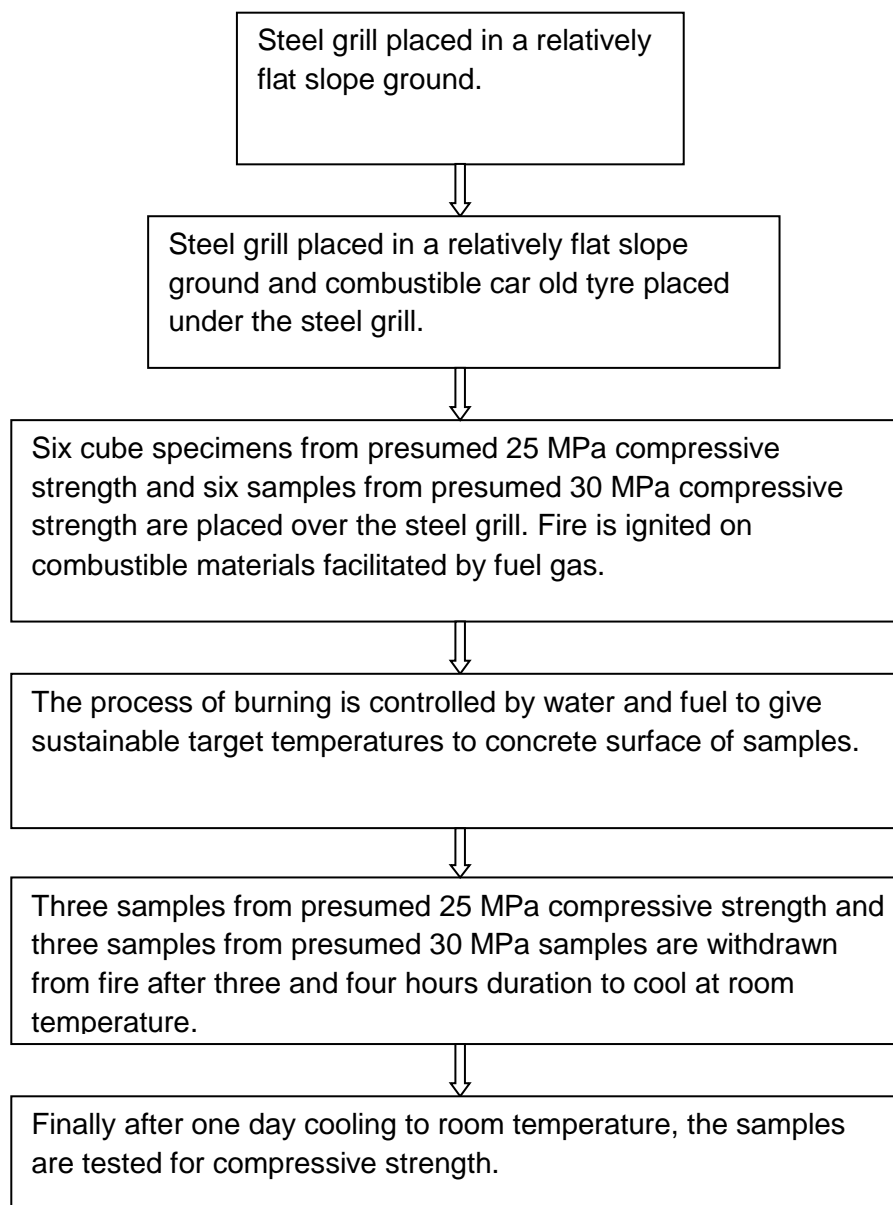


Fig.3.4- Flow chart showing steps of burning and testing cubes for all three rounds

The burning process was not easy especially in situations to give higher temperature to the concrete surface. It was difficult to handle samples and measure concrete surface temperature in closer distance because the burning fire heat was difficult to bear for human skin.

Under difficult situations like aforementioned the infrared thermometer will be used in a little bit far away distance from the flame by pulling out samples. Due to the nature of the infrared thermometer when the distance from temperature measuring place to the target objects increase the accuracy of temperature reading decreases in scale expressed in the manual of the instrument, that is why temperature expression in the burning process explanation stated as +/- 5⁰c. Temperature of concrete surface is controlled by letting the fire to intensify by adding fuel and reducing its burning by water whenever is required to achieve some targeted temperature. Figures from 3.5 up to 3.10 shows the burning process to testing stage.



Fig.3.5- Initial burning stage



Fig.3.6- Intensified stage of burning



Fig.3.7- Infrared thermometer measuring temperature of concrete surface.



Fig.3.8- Concrete cubes air cooled to room temperature ready for test



Fig.3.9- Concrete cubes on process of compression test



Fig.3.10- Excessive burning caused cement paste bond to spall of.

3.1.3 Results of Experiment

Air cooled samples are tested for compressive strength stress and the results for two sets of groups are presented in Table 3.2 and Table 3.3, respectively.

Table 3.2 Results concrete cubes test with presumed 25 Mpa compressive strength.

No	Number of Cubes	Concrete cubes samples with expected 25 mpa comp.					Remark
		Target Temperature °c	Actual temperature °c	Duration of Fire Exposure (hr.)	Compression stress (MPa) after burning		
1*	3	20	19	0	31.60		
		20	19	0	24.78		
		20	19	0	24.71		
Average Value		20	19	0	27.03		
2	3	100	113	3	20.89		
		100	113	3	22.96		
		100	113	3	24.70		
Average Value		100	113	3	22.85		
3	3	100	113	4	26.74		
		100	113	4	18.62		
		100	113	4	20.19		
Average Value		100	113	4	21.85		
4	3	200	172	3	28.58		
		200	172	3	26.51		
		200	172	3	29.76		
Average Value		200	172	3	28.28		
5	3	200	172	4	26.98		
		200	172	4	27.55		
		200	172	4	18.38		
Average Value		200	172	4	24.30		
6	3	300	246	3	24.15		
		300	246	3	19.44		
		300	246	3	21.79		
Average Value		300	246	3	21.79		
7	3	300	246	4	11.73		
		300	246	4	24.75		
		300	246	4	18.53		
Average Value		300	246	4	18.34		

* These samples are not burnt (reference sample @ 19.5 °c).

Table 3.3 Results concrete cubes test with presumed 30 MPa compressive strength.

No	Number of Cubes	Concrete cubes samples with expected 30 mpa comp. Strength test result				
		Target temperature °c	Actual temperature °c	Duration of Fire Exposure (hr.)	compression stress (Mpa) after burning	Remark
1*	3	20	19	0	51.27	
		20	19	0	40.93	
		20	19	0	38.00	
Average Value		20	20	0	43.40	
2	3	100	113	3	41.76	
		100	113	3	31.18	
		100	113	3	33.15	
Average Value		100	113	3	35.36	
3	3	100	113	4	38.98	
		100	113	4	37.38	
		100	113	4	36.50	
Average Value		100	113	4	37.62	
4	3	200	172	3	32.28	
		200	172	3	43.80	
		200	172	3	30.05	
Average Value		200	172	3	35.38	
5	3	200	172	4	45.56	
		200	172	4	37.40	
		200	172	4	29.78	
Average Value		200	172	4	37.58	
6	3	300	246	3	30.96	
		300	246	3	23.35	
		300	246	3	44.52	
Average Value		300	246	3	32.94	
7	3	300	246	4	31.99	
		300	246	4	19.20	
		300	246	4	36.78	
Average Value		300	246	4	29.32	

* These samples are not burnt (reference sample @ 19.5 °c).

The relationships between Concrete surface temperature, Duration of fire exposure and Compressive strength of group 1 and 2 cube specimens are shown in Fig. 3.11 and Fig 3.12, respectively.

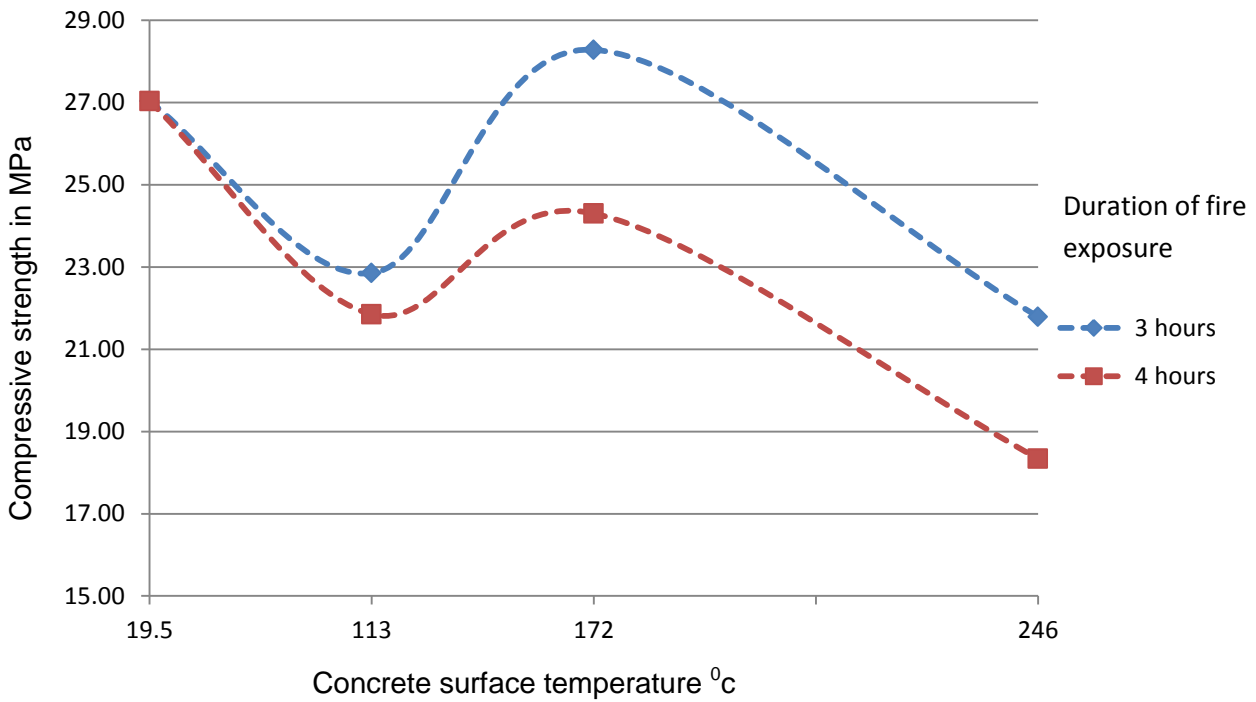


Fig.3.11- Variation of compressive strength in Mpa versus concrete surface temperature in °c for group 1 cube samples.

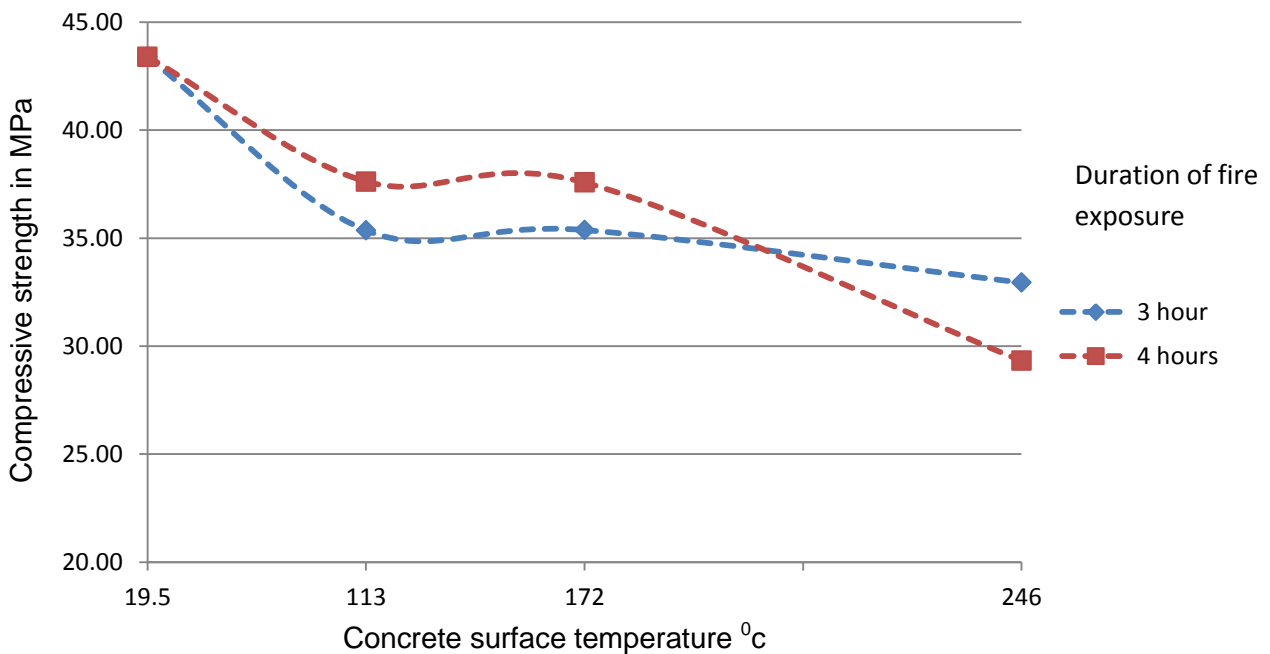


Fig.3.12- Variation of compressive strength in Mpa versus concrete surface temperature in °c for group 2 cube samples.

3.1.4 Discussion of Results

The concrete used to cast the cubes is constituted from basaltic coarse aggregate silicate derivate, fine aggregate, cement and water which are mixed in a proportion discussed under 3.1.1 in this paper. The concrete paste resulting from the mix of the above constitutes is put in to a cube mould by compacting in three equal layers. The day after casting the mould is removed and curing of the concrete cube samples started. There are different ways of curing, the way chosen in this research is spraying water two times a day in the morning and evening for consecutive seven days.

After seven days the concrete cubes are kept in shade avoiding direct sunlight water loss for additional twenty one days. Concrete is expected to achieve much of its strength with in twenty eight days so the concrete cube samples are exposed to open to sky environment condition after twenty eight days until the experiment time. Totally the concrete cubes aged two months before testing.

A concrete after hardening has two parts one is a bonded aggregates which is hard solid, the other part is the moisture (water particles) that exist in tiny gaps inside the former solid part. The same is true with the concrete cube samples. **It is very clear that when a compression stress or force is applied on the concrete cubes stress or force is carried and transmitted by the existing moisture water particle since it exist inside.**

The removal of such moisture (water particle) by any means like in our case high temperature of burning will let air to be entrained causing less strength [6]. This is one of the reasons for strength reduction in case of concrete fire exposure.

During the experiment it is observed that excessive burning of the concrete by fire makes the cement paste bonding the coarse aggregate to disintegrate by simple hand touch even in worse case by itself. This is the second critical reason for reduction of compressive strength during fire exposure; Fig.3.10 shows spall of concrete during fire exposure. The spalling of depth will be the same for large dimensioned samples but more strength could be recorded due to more surface area will not be affected this shows dimension of samples has effect on spalling of failure.

As we can see in figure 3.11, the compressive strength of concrete cube samples burnt for 172⁰c is higher than the compressive strength of cube samples burnt for 113⁰c, this looks conflicting with the finding of this study as temperature of fire increases compressive strength of concrete decreases, but a micro level study is necessary to explain this situation since the pattern is clearly observed on both groups results.

The plots in Fig.3.11 shows a concrete surface temperature of 246⁰c sustained for three hours duration caused 19.4% of compressive strength reduction, again the same concrete surface temperature sustained for four hours duration reduces compressive strength by 32.1%, these reductions show duration of fire exposure is also critical parameter affecting compressive strength of concrete up on fire exposure. The effect of raised concrete surface temperature due to fire on compressive strength of concrete intensifies more when it is accompanied with longer duration of fire.

It is observed in Fig.3.12 that a four hours duration of fire exposure for 113⁰c concrete surface temperature caused reduction in compressive strength of 13.3% , this is not large as compared to the reduction of 32.4% for a concrete surface temperature 246⁰c, this shows that as concrete surface temperature increases compressive strength of concrete significantly reduces.

3.1.4.1 Comparison of result

Even though the testing procedures and some methods of measurements do not much with this study procedures and measurement methods, the experiment results obtained by Abrahams 1971 on the effect of high temperature on compressive strength of concrete presented in broken line in figure 2.1 [1, 5] .

In that experimental set up samples heating will be done by a computer controlled electric split-tube furnace at selected rate of temperature rise up to a target temperature, then temperature kept there until whichever the two criteria happens first. 1. Internal temperature of test samples varies with in 5⁰c measured by internally fixed thermocouples during heating or burning. 2. Internal temperature stays within +/- 5 ⁰c variation from target temperature [5].

When any of the two criteria happens first samples withdrawn from furnace and air cooled to room temperature then tested by servo-controlled compression test machine the results or the name given to such test is unstressed residual test outcomes of their tests are plotted in figure 2.1 in broken lines. So here duration of fire or heating exposure is not prescribed, it is decided by the time whichever the two criteria comes first. But in my study, duration of fire exposure is prescribed as shown in result tables 3.2. and 3.3.

Considering three hours duration of fire exposure for group 2 concrete samples experimental results plotted in Fig.3.12 are compared in table below with ACI216R-89 [1] results approximate reading in Fig.2.1. The comparison shows good agreement of results despite difference in procedures and methodology.

Table 3.4- Comparison of result.

No.	For three hours fire duration		
	Concrete surface temperature in ⁰ c	This experiment percentage compressive strength	ACI216R-89 approximate result.
1	Room temp.	100	100
2	113	81.48	95
3	172	81.51	88
4	246	75.91	77

Experimental data obtained by Abrams 1971 G.C [5] were used to derive a conservative formula for residual compressive strength of concrete exposed to high temperatures:

Residual compressive strength after fire $f_{cr} = (1 - 0.001 \times T^{0c})$ of initial compressive strength. For temperatures less than 500 ⁰c.

$f_{cr} = (1 - 0.001 \times 246) \times 27.03 \text{ Mpa} = 20.38 \text{ Mpa}$ which is 75.40 %, this result agrees with this research result in the above table 75.91 %.

Concrete compressive strength is one of the parameters intended to be studied by this paper, on the effect of fire exposure. Two groups with two different presumed compressive strength of concrete were considered. As results presented in Tables 3.2 and 3.3 shows both concrete samples decreased their compressive strength on exposure of fire in closer scales, so it was not enough number of presumed compressive strength concrete samples considered here to reach at some conclusion on this parameter.

3.2 Unrestrained Reinforced Concrete Beam

The fire performance of unrestrained reinforced concrete beam is studied here experimentally by taking a sample of beams having dimension of $L= 1000$ mm, $W= 150$ mm $H= 250$ mm and exposing these beams to a fire of different duration and temperature. This dimension of the beam is selected for easiness of handling during burning and testing. The weight of each sample is tried not to exceed 100 Kg to be handled by two persons at a time for transporting from fire place to laboratory, accordingly the weight of one sample having a dimension of $L= 1000$ mm , $W= 150$ mm $H= 250$ mm is expected to be 99 Kg. Totally 24 beams are produced for the test. The sample beams are designed in order they fails in shear and bending at the same time, this is done by making shear capacity to be two times the moment capacity in magnitude in simple support case.

The parameters intended to be studied on the effect of moment and shear strength of beam are average concrete surface temperature and duration of fire exposure.

The maximum duration of fire exposure considered in this experiment to study its effect on shear and moment capacity of sample beams is four hours. As duration of fire exposure increase in an intensified fire the concrete surface temperature increases but to do so larger amount of combustible materials and time are required. The selection of maximum duration of fire exposure to be four hours in this study is more of arbitrary, but it is considered that working time before lunch and after lunch is four hours.

The concrete surface temperature during fire exposure is measured using a non-contact infrared thermometer. During a trial to give more concrete surface temperature the fire intensified makes it difficult to measure concrete surface temperature in closer distance and to manage the samples on fire.

3.2.1 Testing specimens

Two types of reinforced concrete beam samples with two different concrete cover of 15 mm (group 1) and 25 mm concrete cover (group 2) are produced for the test. The mix proportion of constitute materials for the production of the reinforced concrete beam samples is presented in Table 3.5. The reinforcing steel bar used is Turkey made S-500 diameter 8 mm three at the bottom and two on top, tied by stirrups of diameter 6 mm spaced centres to centres 200mm, the yield strength of the reinforcement is expressed from test and used in section capacity analysis presented in annex A, the sample beams are expected to resist a maximum load 54.67 KN with 1.90 mm deflection on mid span. Detail of samples are shown in Fig. 3.13.

Table 3.5 Mix proportion of materials for production of sample beams.

No	Material	Quantity
1	Cement	360 Kg/m ³
2	Water	0.057 m ³ /m ³
3	Fine aggregate	0.33 m ³ /m ³
4	Coarse aggregate	0.49 m ³ /m ³

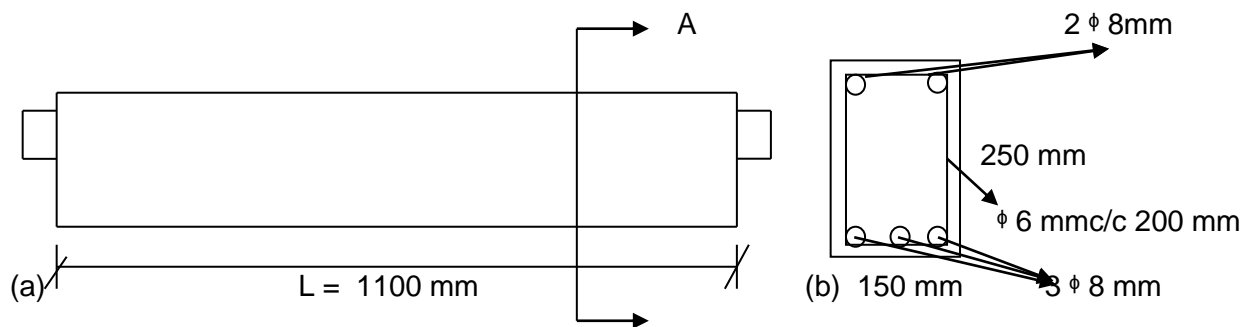


Fig.3.13 (a) - Longitudinal section of sample RC beams (b) - Cross section of sample RC beams

3.2.2 Testing Procedures

The testing procedures of beams for fire performance mentioned in American Society for Testing and Materials E119 [2] is a realistic one regarding simulating actual fire accidents, imposing loads during test and evaluation method for failure. The testing procedure used in here is quite different, samples are put on fire of specified average temperature for desired duration and drawn out from fire then tested for failure load after air cooled to room temperature. Load will not be imposed during exposure to fire except self-weight and dimension of sample is arbitrary. This procedure is similar with concrete cube testing procedure mentioned in section 3.1.2 except duration of fire exposure and representative value of test are varied. There were three rounds of burning in similar procedure shown below in flow chart for target temperature of 100°C , 200°C and 300°C .

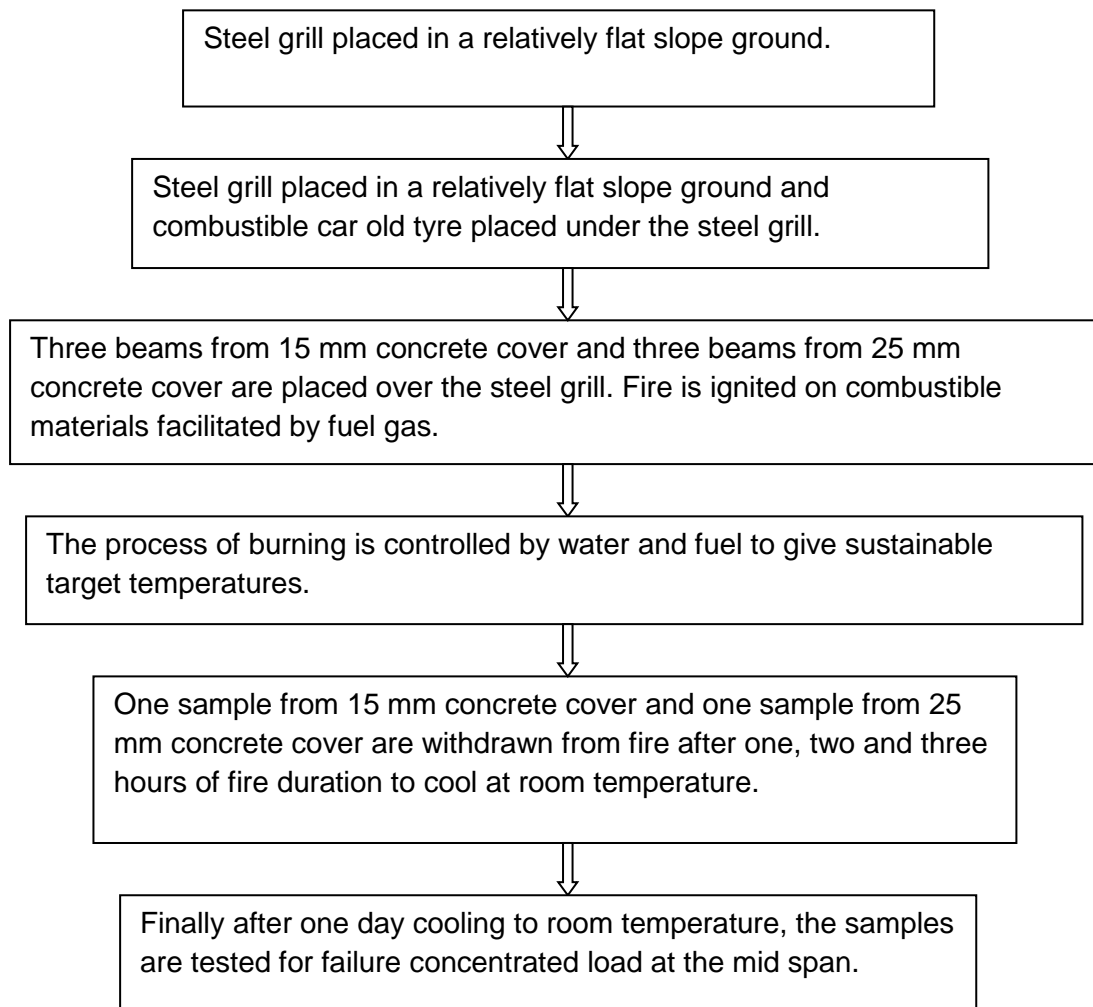


Fig.3.14- Flow chart showing steps of burning and testing beams for all three rounds.

The maximum temperature intended to give to the concrete surface was 300⁰c, but during burning procedures it was observed the flame created to give concrete surface temperature of 246⁰c was burning for skin when tried to get close to measure temperature and adjust samples on fire. In addition, the smoke which comes out of the fire was disturbing for peoples moving around fifty meters from burning place. Fig. 3.15 below express the intensified fire situation created during burning the sample beams.



Fig.3.15- sample beam under intensified burning

❖ **Loading condition**

The reinforced concrete beam is loaded at the mid-span and for the measurement of deflection, LVDTs are used. The deflections are measured at the midpoint on the side of the beams, the location of LVDTs is shown in Fig. 3.16 below.

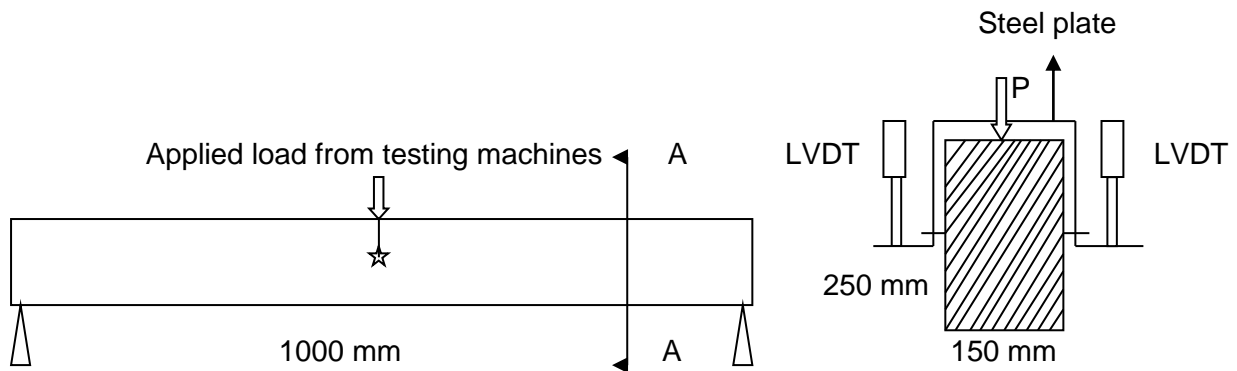


Fig.3.16- Representation of loading test of sample beam and deflection measuring method

Samples are burnt for desired durations starting from two hours up to four hours for different target concrete surface temperature from 100 °c up to 300°c then withdrawn from fire and air cooled to room temperature then tested for maximum concentrated load at the mid span and also deflection is measured, Fig. 3.17 shows actually loaded sample beam. Most of the samples except one sample beam all the rest failed in shear prior to full bending capacity develops. If it was samples were tested in hot conditions without air cooled to room temperature results will be different from results recorded in Tables 3.6 and 3.7 of this research. The reason is reinforcing steels will be affected by the temperature from fire when they are tested hot but the reinforcing steel restores when cooled.



Fig.3.17- Sample beam testing in loading machine after failure.

3.2.3 Results of Experiment

The results of tested sample beams for different concrete surface temperatures and different fire durations are presented in Tables 3.6 and 3.7. The results contains failure concentrated applied loads, failure moments, failure shear and deflections. Some specimens failed in shear without recorded deflection by the sensor used for deflection measurement mounted on the beam at mid span and on mid height shown in Fig. 3.16.

For determining the initial un-burnt strength of sample beams it is taken three beam samples for average strength value but for the test of different fire duration and concrete surface temperature it is taken one for each test to be representative.

The deflection measuring sensor is connected to the computer and record deflection from the beginning of the test up to the end or failure on prescribed time interval for one sample beam how it looks the time versus deflection in mm is presented in annex B.

Table 3.6 Test result of reinforced concrete beam samples with 15 mm cover after burning

No	Number of Beams	Beams with 15 mm of concrete cover dimension L= 1000 mm w= 150mm h= 250mm							
		Target temperature °c	Actual con. Surface temperature °c	Duration of Fire Exposure (hr)	Failure Load (KN) at mid span after burning	Maximum moment in PL/4 (KNm)	Failure shear load p/2 (KN)	Deflection at mid span (mm)	Mode of failure
1*	3	20	19.50	0	126.10	31.53	63.05	5.02	Bending failure
		20	19.50	0	88.20	22.05	44.10	0.00	Shear failure
		20	19.50	0	99.00	24.75	49.50	16.21	Shear failure
Average Value		20	19.50	0	104.43	26.11	52.22	7.08	
2	1	100	113	2	99.10	24.78	49.55	0.00	Shear failure
3	1	100	113	3	97.60	24.40	48.80	17.62	Shear failure
4	1	100	113	4	88.80	22.20	44.40	0.00	Shear failure
5	1	200	172	2	94.10	23.53	47.05	14.36	Shear failure
6	1	200	172	3	86.90	21.73	43.45	16.15	Shear failure
7	1	200	172	4	92.70	23.18	46.35	0.00	Shear failure
8	1	300	246	2	97.50	24.38	48.75	0.00	Shear failure
9	1	300	246	3	82.90	20.73	41.45	22.23	Shear failure
10	1	300	246	4	85.40	21.35	42.70	25.47	Shear failure

* These samples are not burnt (reference sample @ 19.5 °c).

Table 3.7 Test result of reinforced concrete beam samples with 25 mm cover after burning

No	Number of Beams	Beams with 25 mm of concrete cover dimension L= 1000 mm w= 150mm h= 250mm							
		Target temperature °c	Actual con. Surface temperature °c	Duration of Fire Exposure	Failure Load (KN) at mid span after burning (p)	Maximum moment (KNm) PL/4	Failure shear load p/2 (KN)	Deflection at mid span (mm)	Mode of failure
1*	3	20	19.5	0	96.60	24.15	48.30	0.00	Shear failure
		20	19.5	0	97.90	24.48	48.95	0.50	Shear failure
		20	19.5	0	98.90	24.73	49.45	0.00	Shear failure
Average Value		20	19.5	0	97.80	24.45	48.90	0.17	
2	1	100	113	2	96.40	24.10	48.20	0.00	Shear failure
3	1	100	113	3	90.20	22.55	45.10	0.00	Shear failure
4	1	100	113	4	73.20	18.30	36.60	0.00	Shear failure
5	1	200	172	2	92.10	23.03	46.05	13.02	Shear failure
6	1	200	172	3	98.70	24.68	49.35	19.47	Shear failure
7	1	200	172	4	90.20	22.55	45.10	22.26	Shear failure
8	1	300	246	2	95.10	23.78	47.55	16.97	Shear failure
9	1	300	246	3	94.40	23.60	47.20	0.00	Shear failure
10	1	300	246	4	80.30	20.08	40.15	19.94	Shear failure

* These samples are not burnt (reference sample @ 19.5 °c).

The relationship between concrete surface temperature, duration of fire exposure and failure load for both groups of specimens are plotted in Fig. 3.18 and Fig. 3.19, respectively.

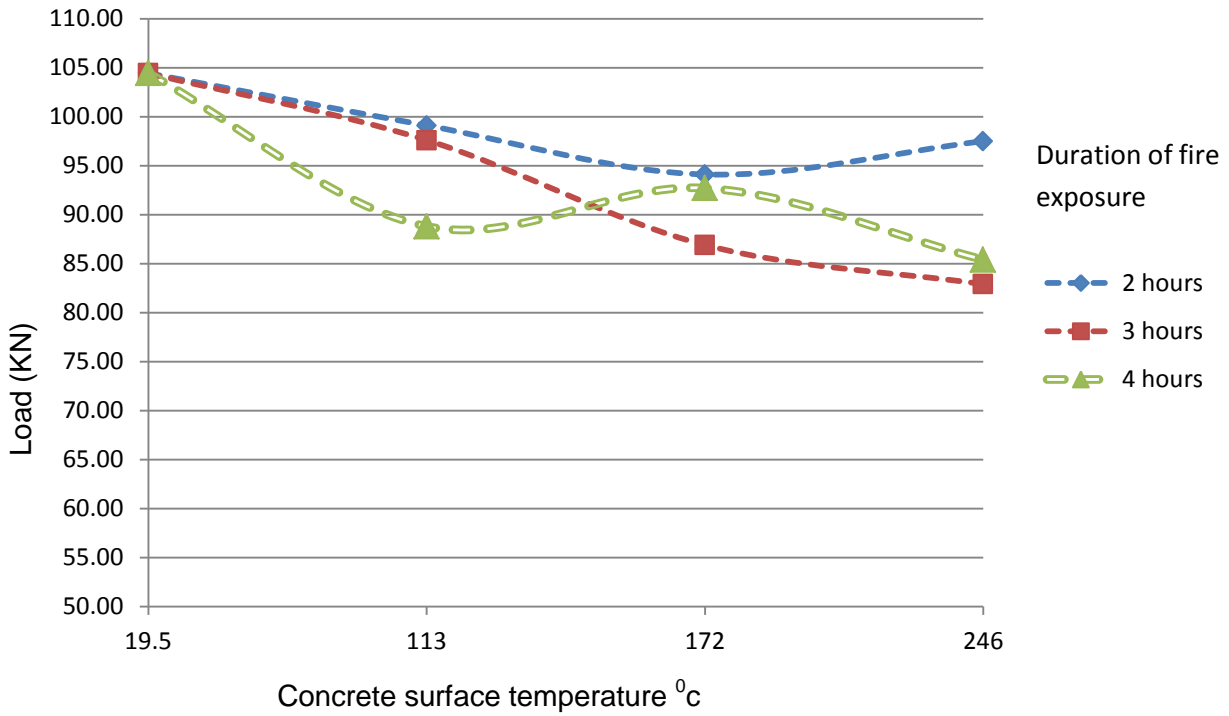


Fig.3.18- Variation of maximum concentrated load in KN versus concrete surface temperature in °C for group 1 beam samples.

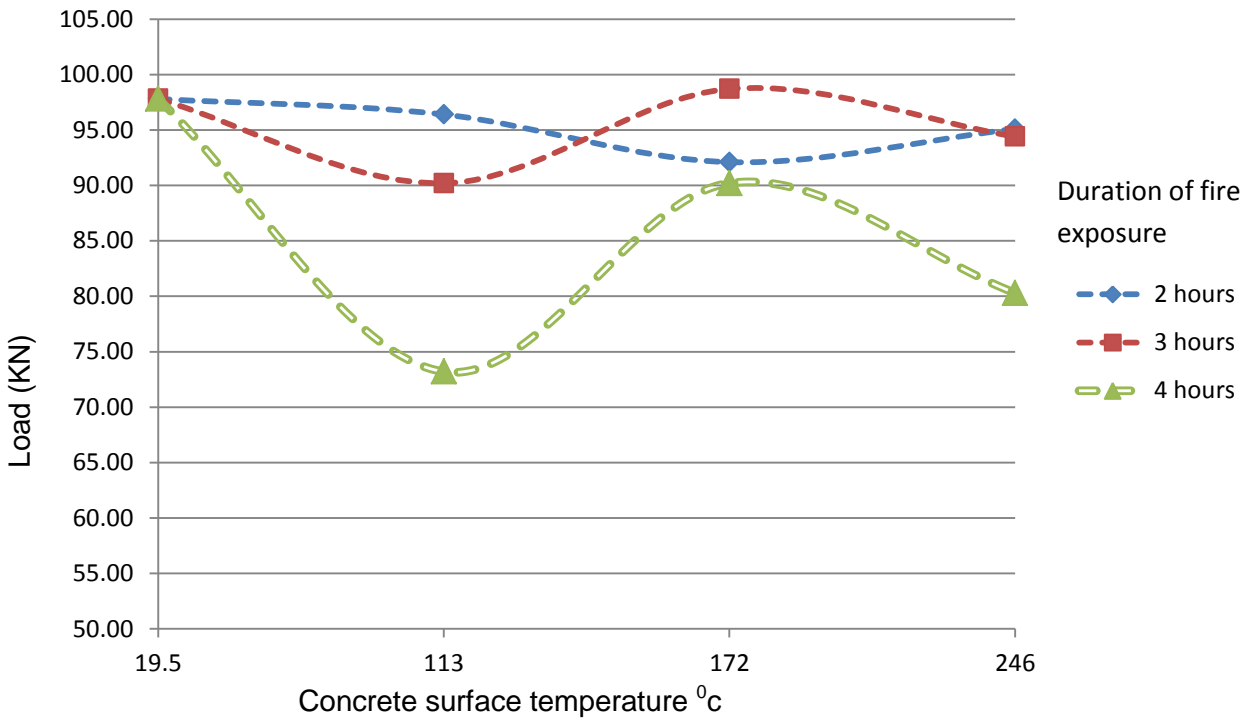


Fig.3.19- Variation of maximum concentrated load in KN versus concrete surface temperature in °C for group 2 beam samples.

3.2.4 Discussion of Results

The results from analysis of sample beam presented in annex A, shows moment capacity to be 27.33 KNm, shear capacity 54.67 KN and maximum deflection based on the limitation of strains in concrete and steel is 1.9 mm. This means moment and shear values from experiment on un-burnt samples in Tables 3.6 and 3.7 and analytical values more or less agree but not deflection. If we allow the strain limitations for concrete and steels to higher values in the analysis the deflection that we get will be larger and it coincides with the deflections recorded from experimental test. In experimental result when concrete and steels reaches the strain limits assumed in analysis the deflection recorded will be smaller than the maximum deflection recorded in the above table, even deflections could not be clearly visible due to small value at the time of the strain limits of concrete and steel reaches the 0.0035 and 0.0042.

More over the deflection calculated in analysis of sample beam is by considering bending failure and its value is 1.9mm but in the experimental results most of the sample beams failed in shear and its value of deflection reaches 22.23mm, which is why we do not have comparable results in deflection.

There are two types of reinforced concrete beam samples considered for the test one group is beams with 15 mm concrete cover and the other group is beams with 25 mm concrete cover to reinforcing steels. The reason to try two groups of beams with different concrete cover for the experiment is to study the effect of concrete cover to reinforcement on fire endurance rating but since the samples are tested after air cooled to room temperature due to

- ✓ Difficulties to handle samples from burning place to testing place when they are hot.
- ✓ Electric power interruption at the instance of hot testing.
- ✓ Difficulties and cooling during adjustment of deflection measurement on the sample during testing.

the results found for both groups of reinforced concrete beams does not tell any significant difference due to variation in concrete cover because of during Cooling after burning the samples reinforcing steels restores its mechanical properties. If conditions were suitable and samples were tested in hot state there will be some differences to observe due to this parameter, this is because of temperature rise in the reinforcing steel makes them to yield in relatively lesser loads and as the concrete cover is getting thicker the sensitivity of the reinforcing steel to increase temperature reduces and it yields in relatively larger load.

Deflection of sample beams as it is recorded in both Tables 3.6 and 3.7, some beams failing in shear have no recognizable deflections that means zero and others have deflections recorded up to 25.47 mm, the basic reason for this is the beam when it fails in shear it splits in two parts by diagonal cracking one part going down and the other part staying almost as it is, this failure type is completely different from bending failure deflection. When the deflection measuring sensor stays on the part that is going down it record deflection and when it stays on the other part remaining in almost initial position the deflection measuring sensor record zero.

As we can see in Fig. 3.18, a concrete surface temperature of 246⁰c sustained either for three or four hours reduces the residual shear or moment capacity to 80% from initial strength. The reason it is called residual is because of it is cooled after burning.

In Fig.3.19 it is visible that the unrestrained reinforced concrete beams exhibits an increase of residual shear and moment strengths as concrete surface temperature rise from 113 °c to 172 °c. To explain this situation clearly a micro level investigation is necessary.

The maximum reduction in shear and moment strength due to rise in concrete surface temperature is 20 % observed in both Figures 3.18 and Fig.3.19, this shows variation in concrete cover to reinforcing steel is not causing visible influence in shear and moment strengths in this study. So no observation is derived on this parameter on this stage.

3.2.4.1 Comparison of result

The sample burning process, testing procedure and failure criteria used in this experimental research are not conventional ones. The conventional way of testing structural members for fire endurance is the standard fire test [2]. The standard fire test of structural members and construction materials mentioned in literature survey under section 2.4 has a quite different testing procedures and acceptance or failure criteria. Due to this it is impossible to get results to discuss agreement or disagreement on the finding of this research on the effect of parameters on shear and moment strength of un-restrained beams. But the findings of this research on concrete cubes agree with the results presented in ACI 216R-89 [1] document discussed in section 2.2.1.1. this shows the experimental study in this paper is not under estimated.

Even though procedures like burning process , temperature measurement and loading methods are different from this experimental research but results of other research and results of analytical methods agrees with this research results as discussed below.

International Journal of Applied Science and Engineering in Taiwan has issued a paper entitled Residual Bearing Capabilities of Fire-Exposed Reinforced Concrete Beams [7] which is done by two persons named J. H. Hsu and C. S. Lin in 2006, this paper uses both analytical modelling and experimental ways to calculate the residual shear strength of reinforced concrete beam after fire exposure. Based on this paper for two hours duration of fire exposure the reinforced concrete beam sample reduces 20 % of the initial shear strength and reaches 80 %, despite differences in procedure the result in Fig.3.18, in this experimental study gives residual shear strength after fire exposure to be 79.38 % which agrees with the Taiwan paper.

Even more severe reduction in shear capacity is discovered by a thesis paper done in western Ontario University for Master of Engineering fulfilment [8], which is based experimentally, the paper indicates the shear capacity of reinforced concrete beam reaches 42 % of initial shear capacity after 1.72 hours fire exposure.

4. CONCLUSIONS AND RECOMMENDATIONS

This study presents the effects of concrete surface temperature and duration of fire exposure on the compressive strength of concrete and on shear and moment resistance for un-restrained reinforced concrete beams both tested in residual state, that means after air cooled. According to the results observed during experimental tests concrete or reinforced concrete losses their strength significantly up on even small scale fires exposure for longer durations.

In Ethiopia, it is common to observe after a fire accident happens on service structure and controlled, most people abandoned the structures even if main structural elements such as beams and columns survive without severe effect. According to the results of this research their decision is acceptable because concrete losses about 20 % of its strength in compression and shear even in fire exposure up to four hours.

The time needed to control a fully developed fire in our country is mostly more than four hours even it could take a day (this is due to resource limitation, infrastructure of access and means of communication from fire place to fire fighting authority). All these reasons together with rising economy and interest of safety fire endurance test, classification of structure for fire rating and including fire safety factors in the design process is necessary since fire accident severity on structural members is high.

4.1 Conclusions

One of the advantages of concrete or reinforced concrete over other building materials like timber and steel is its inherent fire-resistive properties; however, concrete structures must still be designed for fire effects since it is not fire proof. Based on this research, the following conclusions are drawn.

- ✓ An increase in duration of fire exposure decreases compressive strength of concrete and residual shear strength of reinforced concrete beam.
- ✓ Concrete surface temperature rise to higher level reduces compressive strength of concrete and residual shear strength of reinforced concrete beam.
- ✓ Concrete surface temperature of 246 °c due to fire sustained for four hours duration, reduces the initial compressive strength of concrete to 70%.
- ✓ Concrete surface temperature reaching 246 °c staying for four hours duration , reduces the shear capacity of reinforced concrete beam up to 81 % of its initial strength.
- ✓ Compressive strength of concrete reduce by 15% for small concrete surface temperature of 113 °c.
- ✓ Spalling of failure in concrete starts around 100 °c.
- ✓ Duration of fire exposure up to four hours reduces initial shear strength of reinforced concrete beams to 80 % if they burnt under a temperature 246 °c.
- ✓ More investigations are needed to see effect of compressive strength variation on fire performance.
- ✓ Since samples are tested air cooled, the contribution of concrete cover to reinforcement in fire resistance of beams is not clearly observed, further investigations needed to see the effect.

4.2 Recommendations

The interest of to make service structure more fire resistive and safe surely will develops in our country Ethiopia following an economic growth. In near future it will be true cost of structures for sale depends on fire resistance rating of it and insurances will set payments lesser for those assets having high fire resistance rating.

So far there are no provisions and analysis method for fire resistance stated in our Ethiopian Building Codes for reinforced concrete. This experimental research shows fire accidents to service structures can cause total collapse and hence loss of lives. So due to mentioned and unmentioned reasons there should be a building rules and regulations to set either a factor of safety or allowances for fire resistance rating of structural members and methodology for determining fire resistance rating for existing structures.

To assess the followings, further studies are recommended.

These include:

- ✓ Effect of different cement types for fire resistance.
- ✓ Influence of using different aggregate types on fire resistance.
- ✓ Effect of water to cement ratio or moisture content in fire endurance of structural members.
- ✓ Exposure of extra higher temperature and its effect on concrete and reinforced concrete members strength.
- ✓ Effect of more duration of fire exposure on shear and moment capacity reduction.
- ✓ Contribution of concrete cover to reinforcement in fire resistance of structural members.
- ✓ Fire resistance test for different loads applied concentrated and distributed.
- ✓ Fire resistance test of specimens for different support conditions and restrain.

Moreover in order to have a more realistic fire test results on fire resistance of structural members, it is recommended proportionally reduced samples to be tested for failure load simultaneously.

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Annex A

Analysis of a sample beam

In addition to determining the moment capacity of not burned beams through experiment the sample beams section moment, mid span deflections and shear capacities are computed below for study and comparison purpose. The sample beams prepared are two types one with 15 mm concrete cover and the other with 25 mm concrete cover. The moment capacity, mid span deflection and shear capacity are calculated for the 15 mm concrete covered sample beam, dimensions and section parameters are presented below.

Considering balanced failure and the center line of strain occur at a distance of x measured from top fiber of concrete. The parabolic like distribution of stress in the compression zone concrete is simplified to equivalent rectangular stress block with height of $0.8x$ measured from the top compression concrete fiber with stress magnitude of $0.85f_{ck}$ as shown below.

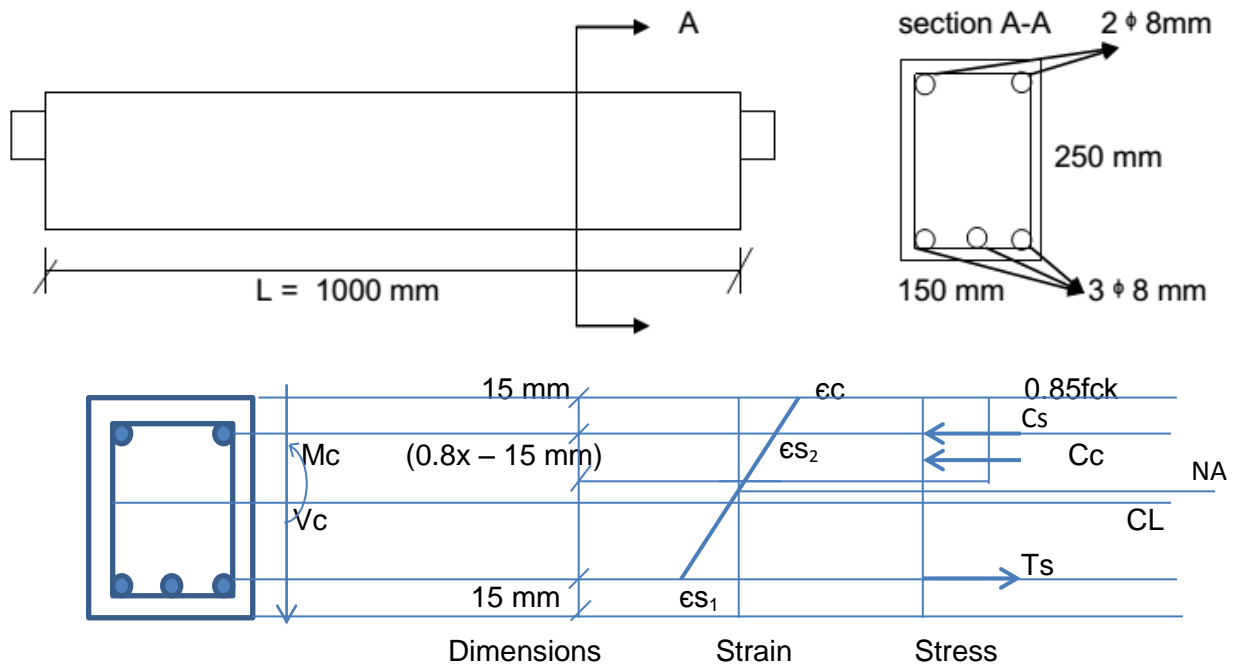


Fig. A.1- Sample beam, stress and strain diagrams.

Where

M_c : un-factored moment capacity of the section for balanced failure.

V_c : un-factored shear capacity of the concrete section.

V_s : shear resistance from stirrups.

V_r : total shear capacity gained from concrete and stirrups.

CL : section center line.

NA : neutral axis.

E : modulus of elasticity of steel 200Gpa.

Ec : modulus of elasticity of concrete, $E_c = 9.5 \times (f_{ck} + 8)^{1/3}$

Ig : gross moment of inertia of concrete $I_g = b \times h^3 / 12 = 1.95 \times 10^8$

ϵ_c : strain in the top fiber of concrete.

ϵ_{s1} : strain in bottom reinforcement level.

ϵ_{s2} : strain in top reinforcement level.

ϵ_y : yield strain of reinforcing steel. $\epsilon_y = f_y / E = 0.84/200 = 0.0042$

Ts : tension stress from bottom reinforcement.

As₁ : area of tensile reinforcement. As₁= 150.72 mm²

As₂ : area of compression reinforcement. As₂= 100.48 mm²

Cs : compression stress from top reinforcement.

Cc : equivalent compression stress of concrete.

fck : characteristic compressive strength of concrete. From test result in this research table 3.2. first sample average value 27.03 MPa.

f_y : yield strength of reinforcing steel. From test 840.13 MPa

d : distance from top fiber to center of tensile reinforcing steel

$$d = 250\text{mm} - 15\text{mm} - 4\text{mm} = 231 \text{ mm}$$

d' : distance from top fiber up to the center of compression reinforcement

$$d' = 15\text{mm} + 4\text{mm} = 19 \text{ mm}$$

b : width of beam 150 mm

I : moment of inertia of the cross section. It is calculated below.

The reinforcement used for the sample production is Turkey made S-500 steel bars.

1. Moment capacity

Taking the concrete yields and its strain reaches to $\epsilon_c = 0.0035$ and from similarity of triangles in the strain diagram two equations below will be obtained.

$$0.8x / (231\text{mm} - 0.8x) = 0.0035 / \epsilon_{s1} \quad \text{from the similarity of two larger triangles.}$$

$$\epsilon_{s1} = (0.8085 - 0.0028x) / 0.8x \dots\dots\dots (A -1)$$

$$0.8x / (0.8x - 15\text{mm}) = 0.0035 / \epsilon_{s2} \quad \text{from the upper two triangles in strain diagram}$$

$$\epsilon_{s2} = (0.0028x - 0.0525) / 0.8x \dots\dots\dots (A-2)$$

Taking summation of forces perpendicular to the section is balanced we can get

$$0.8x b \times 0.85 \times f_{ck} + E \times \epsilon_{s2} \times A_{s2} = E \times \epsilon_{s1} \times A_{s1} \dots\dots\dots (A-3)$$

Up on substitution and simplifications

$x = 80.06 \text{ mm}$ using this value ϵ_{s1} and ϵ_{s2} solved from equations A-1 and A-2

$$\epsilon_{s1} = (0.8085 - 0.0028 \times 80.06) / 0.8 \times 80.06$$

$$\epsilon_{s1} = (0.8085 - 0.224) / 64.05$$

$$\epsilon_{s1} = 0.0091$$

As we can see this result $\epsilon_{s1} > \epsilon_y$ this means $0.0091 > 0.0042$ so the reinforcing steel at the bottom yields and the capacity T_s is calculated $T_s = E \times \epsilon_y \times A_{s1} = 200 \text{KN/mm}^2 \times 0.0042 \times 150.72 \text{ mm}^2 = 126.60 \text{ KN}$

Similarly $\epsilon_{s2} = (0.0028x - 0.0525) / 0.8x = (0.224 - 0.0525) / 64.05 = 0.0027 < \epsilon_y$ so the reinforcing steel at the top not yielding so $C_s = E \times 0.0027 \times A_{s2} = 200 \text{ KN/mm}^2 \times 0.0027 \times 100.48 \text{ mm}^2 = C_s = 54.26 \text{ KN}$

Using these two values of $\epsilon_{s1} = 0.0042$ and $\epsilon_{s2} = 0.0027$ in to equation A-3 new revised value of x can be found like it follows

$$0.8x b \times 0.85 \times f_{ck} + E \times \epsilon_{s2} \times A_{s2} = E \times \epsilon_{s1} \times A_{s1}$$

$$(0.8 \times 150 \times 0.85 \times 0.02703)x + 200 \times 0.0027 \times 100.48 = 200 \times 0.0042 \times 150.72$$

$$2.78x + 54.26 = 126.60$$

$$x = 26.02 \text{ mm}$$

Compressive force from upper concrete is $C_c = 0.8x b \times f_{ck} = 0.8 \times 26.02 \times 150 \times 27.03 \text{ N}$

$$C_c = 71738.70 \text{ N} \quad C_c = 71.74 \text{ KN}$$

Taking summation of moments about the center line of strain, moment capacity of the section will be found.

$$M_c = C_c \times (d - 0.8x/2) + C_s \times (d - d')$$

$$M_c = 71.74 \text{ KN} \times (0.231 - 0.8 \times 0.02602 / 2) + 54.26 \text{ KN} \times (0.231 - 0.019)$$

$$M_c = 15.83 \text{ KNm} + 11.50 \text{ KNm}$$

$$M_c = 27.33 \text{ KNm}$$

2. Maximum deflection of the sample beam.

The maximum deflection is expected to occur at the mid of the span of the beam. The maximum deflection occurring at the mid span in the beam due to a concentrated load applied at the mid span is given by

$$\Delta = p \times L^3 / (48 \times E \times I) \dots\dots\dots(A-4)$$

Where: p : applied concentrated load from test it was 104.43 KN from test result in table

3.6 first three samples average failure load before burning.

L : length of loaded beam

E : modulus of elasticity of the material

I :moment of inertia of the beam

When the material with which the beam is made is single one it is easy to calculate EI value but now our beam is made from concrete and reinforcing steel in such case it is necessary to transform one material to the other, in our case the common one is to transform the section to all concrete beam. In addition to section transformation I have decided to calculate and use the cracked section properties because of the observation during loading test of the beam it started to crack in the early stage of loading moreover it is safe to use the lesser value of EI to calculate maximum deflection of beam.

Cracked transformed section properties calculation

$$\text{Modular ratio } n = E_s / E_c = 200\text{Gpa} / (9.5 \times (f_{ck} + 8)^{1/3}) = 200/31.08 = 6.435 \approx 6$$

$$A_{s1} = 150.72 \text{ mm}^2$$

$$A_{s2} = 100.48 \text{ mm}^2$$

Replacing areas of concrete

Bottom bars $A_{s1} = n \times 150.72 \text{ mm}^2 = 904.32 \text{ mm}^2$ since bottom bars in tension zone replaces no concrete on action, so we use the whole modular ratio.

Top bar $A_{s2} = (n-1) \times 100.48 \text{ mm}^2 = 502.40 \text{ mm}^2$ but here the top reinforcements were originally in place of concrete having an area equal to their area so we deduct 1 from modular ratio.

Let the depth to the neutral axis be c, and sum the moments of the areas about the neutral axis to compute c:

Parts	Area(A) mm ²	centroidal depth from top (y) mm	A × y mm ³
Compression concrete	150c	c/2	75c ²

Top steel	502.40	$c - 1.5$	$502.4c - 753.6$
Bottom steel	904.32	$c - 231$	$904.32c - 208897.92$

$\sum Ay = 0$ for balance issue.

$$75 \times c^2 + 1406.72 \times c - 209651.52 = 0$$

$$c^2 + 18.76 \times c - 2795.35 = 0 \text{ solving } c \text{ from quadratic equation}$$

$$c = (-18.76 \pm (18.76^2 + 4 \times 2795.35)^{1/2})/2$$

$$c = (-18.76 \pm 107.39)/2 \text{ neglecting negative value which is meaningless}$$

$$c = 44.32 \text{ mm}$$

Computing moment of inertia

Parts	Area(A) mm ²	centroidal depth from top (y) mm	Inertia own axis mm ⁴	$A \times y^2$ mm ⁴
compression concrete	6648	22.16	$1.09e10^6$	$3.26e10^6$
Top bars	502.40	42.82	-	$9.21e10^5$
Bottom bars	904.32	-186.68	-	$3.15e10^7$

$$I_{cracked} = I_{cr} = I_{own \text{ axis}} + \sum A \times y^2 = (1.09 + 3.26 + 0.921 + 31.5)e10^6 = 3.68 e10^7 \text{ mm}^4$$

So now the cracked transformed EI is $E_c I_{cr}$ and $\Delta = pL^3 / 48E_c I_{cr}$

$$\Delta = 104.43 \text{ KN} \times 1\text{m}^3 / (48 \times 31.08 \text{ KN/mm}^2 \times 3.68e 10^7 \text{ mm}^4)$$

$$\Delta = 104.43 / 54899.71 \text{ m} = 0.0019 \text{ m}$$

$\Delta = 1.90 \text{ mm}$

3. Shear capacity analysis of the beam

Shear capacity of the sample beam is resulted from the concrete and the reinforcement. The stirrups are tied in vertical direction spaced 200 mm , based on this and previously provided section parameters shear capacity will be calculated as follows.

$$V_c = 0.25 \times f_{ctk} \times k_1 \times k_2 \times b \times d$$

$$f_{ctk} = 0.7 \times f_{ctm}$$

$$f_{ctm} = 0.3 \times f_{ck}^{2/3} = 0.3 \times (27.03)^{2/3} = 0.3 \times 9 = 2.7 \text{ Mpa}, f_{ctm} = 2.7 \text{ Mpa}$$

$$f_{ctk} = 0.7 \times 2.7 \text{ Mpa} = 1.89 \text{ Mpa}$$

$$k_1 = (1 + 50 \times \rho) \leq 2.0, \quad \rho = A_s / (b \times d) = 150.72 / (150 \times 231), \quad \rho = 0.0043$$

$$k_1 = (1 + 50 \times 0.0043) = 1.215$$

$$k_2 = 1.6 - d \geq 1.0, \quad k_2 = 1.6 - 0.231 = 1.37$$

$$V_c = 0.25 \times 1.89 \text{ Mpa} \times 1.215 \times 1.37 \times 150 \text{ mm} \times 231 \text{ mm}$$

$$V_c = 27252.22 \text{ N}$$

$$V_c = 27.25 \text{ KN from concrete}$$

Shear resistance from stirrups

$$V_s = A_v \times d \times f_y / s$$

Where

s : spacing of stirrups

$$A_v : \text{area of stirrups with in the spacing } s, \quad A_v = \pi \times r^2 = 3.14 \times 36 \text{ mm}^2 = 113.04 \text{ mm}^2$$

f_y : the yield stress of the stirrups bar equals 210 Mpa which is locally produced steel.

$$V_s = 113.04 \text{ mm}^2 \times 231 \text{ mm} \times 210 \text{ N/mm}^2 / 200 \text{ mm}$$

$$V_s = 27.42 \text{ KN}$$

Then the total shear capacity is the sum of V_s and V_c

$$V_r = V_c + V_s$$

$$V_r = 27.42 \text{ KN} + 27.25 \text{ KN}$$

$$V_r = 54.67 \text{ KN}$$

Annex B

Table B-1 Tabular representation of LVDTs deflection reading of reinforced concrete beam sample under testing.

LVDTs Reading of sample beam deflection under test mounted in two channels				
Reading No.	Time (dd:hh:mm:ss)	Time min	Deflection mm	Deflection mm
14	00.00.00.36	0.605	0	0
22	00.00.00.57	0.947	0	0
23	00.00.01.00	0.992	0	0.01
24	00.00.01.02	1.033	0	0.01
48	00.00.02.04	2.068	0	0.01
49	00.00.02.07	2.109	0	0.01
50	00.00.02.09	2.154	0	0.01
74	00.00.03.11	3.184	0	0.03
75	00.00.03.14	3.23	0	0.03
76	00.00.03.16	3.271	0	0.03
77	00.00.03.19	3.311	0	0.03
78	00.00.03.21	3.357	0	0.02
107	00.00.04.36	4.602	0	-0.01
108	00.00.04.39	4.648	0	-0.01
109	00.00.04.41	4.689	0	-0.01
110	00.00.04.44	4.735	0	-0.02
111	00.00.04.47	4.776	0	-0.02
112	00.00.04.49	4.816	0	-0.03
179	00.00.07.42	7.7	0	-0.08
180	00.00.07.44	7.741	0	-0.06
181	00.00.07.47	7.787	0	-0.04
182	00.00.07.50	7.827	0	-0.02
183	00.00.07.52	7.873	0	0
214	00.00.09.12	9.204	-13.9	-16.21
215	00.00.09.15	9.25	-24.08	-27.95
216	00.00.09.17	9.291	-26.77	-29.07
217	00.00.09.20	9.332	-26.77	-29.08
220	00.00.09.28	9.464	-26.77	-29.08
221	00.00.09.30	9.505	-26.77	-29.08
222	00.00.09.34	9.566	-26.77	-29.08
223	00.00.09.35	9.592	-26.77	-29.08
224	00.00.09.38	9.638	-26.77	-29.08

DECLARATION

I, THE UNDERSIGNED, DECLARE THAT THIS THESIS IS MY ORIGINAL WORK AND HAS NOT BEEN PRESENTED FOR A DEGREE IN ANY OTHER UNIVERSITY. ALL SOURCES OF MATERIALS USED FOR THE THESIS HAVE BEEN DULY ACKNOWLEDGED.

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