An experimental investigation on the behaviour of steel fibre reinforced ternary blended concrete subjected to sustained elevated temperature.
2.1.2 Chemical transformations of concrete at high temperature

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hydrated cement paste. The matrix is highly porous and contains a relatively large amount of free water unless artificially dried. When exposed to high temperatures, concrete undergoes changes in its chemical composition, physical structure and water content. These changes occur primarily in the hardened cement paste in unsealed conditions. Such changes are reflected by changes in the physical and mechanical properties of concrete that are associated with temperature increase.

When concrete is subjected to elevated temperatures, the incompatibility of thermal deformations of the constituents of concrete initiates cracking. Internal stress is caused by a microstructure change due to dehydration and steam pressure buildup in the pores. The maximum exposure temperature, exposure time, heating and cooling rates are among the most important factors. In these processes, the removal of free water, absorbed and chemically bounded water affected the porosity, capillary and the microstructure of cements. In the temperature range (100 – 300°C), free and bound water from C-S-H gel is evaporated. Above 300°C a reduction in strength in the range of 15 – 40 % occurs. At 550°C, the reduction of strength in the range 55 – 70 % and dehydroxylation of Ca(OH)₂ takes place. The dehydration of calcium silicate hydrated and the thermal expansion increase internal stresses and micro cracks which are induced through the cementing material. Fire is generally extinguished by water and CaO turns into Ca(OH)₂ causing cracking and crumbling of concrete. The alterations produced by high temperatures are more evident when the temperature surpasses 500°C. CSH gel, which is the strength giving compound of cement paste, decomposes further above 600 – 800°C. At 400°C gel-like hydration products are decomposed. At 600°C, Ca(OH)₂ is dehydroxylated, and CaCO₃ dissociates to CaO and CO₂ accompanied with the recrystallization of non-binding phases from hydrated cement under re-combustion are dominant processes between 600°C and 800°C. This stage of concrete is characterized by the collapse of its structural integrity, revealing residual compressive strength. (21)

2.1.3 Effects of ingredients

2.1.3.1 Cement: Preliminary studies indicate that the amount of calcium hydroxide in concrete is of great importance in the resistance to high temperatures. Cements which release the least amounts of calcium hydroxide during hydration and hardening of the concrete are certainly to be favoured. For this reason slag cement or portland blast furnace slag cement are sometimes specified for this type of work. (19)
2.1.3.2 Aggregates: Studies of concrete heated to high temperatures indicate that the type of aggregate employed is critical. Nevertheless no standard specifications have been developed to define the aggregate properties desired for high temperature exposure. It seems obvious that aggregates with low coefficients of thermal expansion in the range of temperatures that the concrete is expected to experience would be preferable to those with high coefficients. A sizeable amount of expansion of the aggregates within the confines of a shrunken hardened cement paste would result in a disruption of the concrete mass. The conductivity of the aggregates employed will also be an important factor in determining the stability of the concrete.\(^{(19)}\)

Predominantly limestone (carbonate aggregate) provides higher fire resistance and better spalling resistance than that of siliceous aggregate predominantly quartz. This is mainly because carbonate aggregate possesses substantially higher heat capacity (specific heat), and this is beneficial for mitigating spalling and also increasing fire resistance. This increase in specific heat is caused by an endothermic reaction occurring around 600-750 deg centigrade due to dissociation of dolomite in carbonate aggregate concrete. This endothermic reaction absorbs energy supplied by fire and enhances the specific heat of concrete in that temperature range. In general, the fire resistance of the HSC columns made with carbonate aggregate concrete is about 10% higher than those made with siliceous aggregate concrete. Generally speaking, aggregates that contain a comparatively high proportion of silica exhibit a higher coefficient of thermal expansion. Therefore they should be avoided in concrete which is to be exposed to high temperatures.\(^{(64)}\)

Studies indicate that light weight aggregates, especially those manufactured in high temperature kilns or furnaces, exhibit greater dimensional stability under heat. In a comprehensive study reported in Volume 63 of the ASTM Proceedings expanded shale aggregates were the most stable. The expanded shale type retained approximately 20 percent of its original compressive strength after being heated to 1,000 degrees Fahrenheit; its thermal conductivity in concrete was also much lower than the other three types. This is probably explained by its glass like composition and high porosity. This type, therefore, retains a comparatively high amount of moisture, which is beneficial in dissipating heat within the concrete mass. Of course retention of water can be carried to an extreme wherein the generation of steam would be detrimental. The aggregate/ cement ratio appears to have an important effect on concrete strength exposed to high temperatures, the proportional reduction in strength being less for a lean mix than for a rich one.
2.1.3.3 Water:
The study reported in the August 1956 Magazine of Concrete Research indicated that the effect of temperature on the compressive strength is independent of the water/cement ratio within the range normally used in concrete.\(^{(19)}\)

2.1.3.4 Addition of fibers
The addition of polypropylene fibers minimizes fire induced spalling in the high strength concrete (HSC) members. One of the most accepted theory is that by melting at a relatively low temperature of 170 deg centigrade polypropylene fibers create 'channels' for the generated steam pressure (within the concrete) to escape, thus preventing the small 'explosions' that cause spalling. The amount of polypropylene fibers needed to mitigate spalling is about 0.1-0.15% (by volume). This technique is highly effective for concrete used in tunnel linings as tunnels are susceptible to fires with very high heating rates. Alternatively steel fibers can also be used to enhance fire resistance of HSC members. The addition of steel fibers enhances the tensile strength of concrete and reduces spalling. Also, hybrid (mixture of polypropylene and steel) fibers have been shown to be effective in minimizing spalling and thus enhancing the fire resistance of concrete structures.\(^{(36)}\)

2.1.3.5 Pozzolanic materials
The effect of high temperature on concrete containing fly ash or natural pozzolans has not been investigated in detail. Researchers and investigators differ in their opinion regarding the changes in the properties of concretes, particularly in the range of 100– 300\(^{\circ}\)C, whereas for temperature above 300\(^{\circ}\)C, there is uniformity in opinion concerning a decrease in mechanical characteristics.\(^{(43)},(57)\)

However, strength reductions which have been reported in the literature reveal significant quantitative differences due to the variety of high temperature condition tested, and the variety of constituent materials of concrete used.

The pozzolanic material such as silica fume, slag and ground clay bricks have been shown to improve the microstructure of cement paste by densifying the cement paste matrix and improving interfacial zone. This is due to the reaction between the amorphous silica of the pozzolana and the calcium hydroxide produced by the cement hydration reactions. In addition, the physical effect of the fine grains allows denser packing within the cement and reduces the wall effect in the transition zone between the paste and aggregate. This weaker zone is strengthened due to the higher bond developed between these two phases, improving the concrete microstructure and properties. In general, the pozzolanic effect depends not only on the pozzolanic reaction, but also on the physical or
filler effect of the smaller particles in the mixture. Therefore, the addition of pozzolans to
Portland cement increases its mechanical strength and durability when compared to the
blank paste, because of the interface reinforcement. The physical action of the pozzolans
provides a denser, more homogeneous and uniform paste. Natural pozzolans have been
used since antiquity with excellent results for production of durable concrete.

The hydrates, such as calcium silicate hydrate (CSH) phases produced as a result of
consumption of free Ca(OH)\textsubscript{2} by active silica fume, are deposited within the pore system
and around the grains of the concrete constituents. This leads to the formation of a denser
concrete microstructure.

2.1.4 High strength concrete (HSC) containing silica fume

High strength concretes containing silica fume have been found to be more susceptible to
explosive spalling in comparison to ordinary or lightweight concretes. This is caused by
the extreme reduction in the permeability of the concrete through the addition of the silica
fume. It has been found that the addition of as little as 5% silica fumes can reduce the
coefficient of permeability of the concrete by 3 orders of magnitude. This has the effect of
reducing the level of moisture content that may cause explosive spalling. Explosive
spalling has been noted in tests of concrete containing silica fume with water/cement
ratios of only 0.26. The extremely low permeability of concrete containing silica fume
also decreases the rate at which the evaporated moisture can pass through the concrete to
relieve the built up pore pressure.\textsuperscript{(36),(84)}

2.1.5 Effect of high temperature on properties of concrete

2.1.5.1 Compressive strength

One of the important requirements is that the structure shall resist collapse during fire.
The strength – temperature characteristics of concrete will greatly influence its resistance
to collapse.

All concrete’s loose strength at elevated temperature, but the rate of reduction differs with
the type of aggregate used. With the rise in temperature, the aggregates expand; the
expansion of the matrix takes place. The resultant expansion differential causes internal
cracking in the concrete and reduction in its stiffness. This phenomenon differs
considerably with the types of aggregates.\textsuperscript{(3)}

This phenomenon is most pronounced in case of concrete with siliceous aggregates,
which at very high temperature also undergoes physical changes accompanied by a
sudden expansion in volume, thus sometimes causing aggregates splitting and / or spalling.

Light-weight aggregates normally undergo heating process during manufacture and possess superior insulation properties. The physical compatibility between matrix and the aggregate with regard to deformability and expansion characteristics are also much better in light-weight concrete than in dense concrete and as a result much less damage and internal stresses are expected in light-weight concrete during heating. It can also withstand cooling shock much better than gravel concrete. Calcareous aggregates do not normally undergo physical changes during heating and are usually free from cracks and local damage. But at exceptionally high temperatures some chemical changes take place. During cooling, the expansion in volume causes cracks and damage.

2.1.5.2 Modulus of elasticity and shear modulus
It is observed that the aggregate type and concrete strength do not significantly affect modulus at high temperature. (3)

2.1.5.3 Poisson's ratio
Philleo and Cruz reported data on Poisson's ratio of concrete at high temperatures. Even though Philleo indicated a decrease in Poisson's ratio, both he and Cruz pointed out that results were erratic and no general trend of the effect of temperature was clearly evident. (3)

2.1.5.4 Stress - strain relationship
Stress-strain relationship in compression of light-weight masonry concrete (expanded shale aggregate) were reported. Fig 2.1 shows such a relationship. (3)
2.1.6 Spalling

Spalling can have insignificant or detrimental effects on the fire resistance of a concrete member depending on the type of spalling that occurs. Though most spalling that occurs from exposure to fire causes only superficial damage to a concrete member, the worst types of spalling cause the ejection of a large area of concrete from the exposed surface. This has the effect of reducing the protective cover or thickness of the concrete below that assumed in design calculations, which can lead to the premature insulation or structural failure of the member.\(^{(23), (24)}\)

The different types of spalling that have been observed during fire endurance testing have been grouped into categories based on the location, nature, and severity of the spalling.

- Explosive spalling is the ejection of large pieces of concrete from the surface of a member due to high pore pressures caused by the production of steam within the concrete.
- Surface spalling includes pitting, blistering and local removal of surface material
- Aggregate splitting is failure of the aggregate near the surface and is often accompanied by surface splitting
- Sloughing off occurs when the surface layer or corner of a concrete member is gradually eroded due to extended exposure to fire.

There are several factors that have been noted to influence the occurrence and scale of spalling.

- Moisture content of the concrete
- Compressive stress caused by restraint of thermal expansion or external load
- Aggregate type
- Rapid temperature rise at exposed surface
- Concrete density and permeability

From these five factors it is generally accepted that the first three are the most influential to spalling, though there is a much higher occurrence of explosive spalling in high strength concrete containing silica fume. This is due to the extremely low permeability of concrete containing silica fume.\(^{(65)}\)

To reduce the susceptibility of concrete to explosive spalling polypropylene fibres can be added to the concrete.
2.1.7 Thermal properties
The thermal properties like coefficient of thermal expansion, specific heat, density and thermal conductivity of concrete are important for evaluation of the performance concrete over the period of time.\(^{(14),(40),(84),(87)}\)

2.1.7.1 Coefficient of thermal expansion
Thermal expansion is a physical phenomenon common to all materials. It is however, complicated in concrete due to the differential expansion of its components producing high internal stresses. Thermal expansion has a significant effect on all types of concrete structures.

Concrete has a positive coefficient of thermal expansion and it depends on the compositions of mix and on the value of the coefficient of expansion of cement paste and aggregate and they have dissimilar thermal coefficients. The coefficient of thermal expansion of cement paste varies between about 11 x 10\(^{-6}\) and 20 x 10\(^{-6}\) per °C and is higher than the coefficient of aggregate.\(^{(87)}\)

Thermal expansion properties are important to the fire performance of concrete structures in two ways:

(i) The expansion of individual and adjacent members can induce stresses capable of buckling reinforced members while at high temperatures.

(ii) Differences in thermal expansion potential of the cement paste and the aggregate may produce stresses in the concrete. At sufficiently high temperatures these stresses can induce cracking within the paste and around aggregate margins. This cracking further accentuates the refractory effect of the damage surface layers, since air held in the crack voids is of lower thermal conductivity than the concrete.

It can be appreciated that the response of concrete to fire attack is such that heat penetration is reduced by the production of low thermally conductive surface layers. A consequence of low conductivity at the surface is the creation of high temperature gradients between the exposed surface and the concrete interior.

For ordinary concrete the value of coefficient of thermal expansion varies from 9 x 10\(^{-6}\) per °C to 12 x 10\(^{-6}\) per °C. (Fig. 2.2)
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Fig. 2.2 Thermal expansion of concrete at high temperature

The thermal expansion increases with increase in temperature. Fig. 2.2 shows the linear thermal expansion of different types of aggregates. The thermal expansion of concrete is influenced by, aggregate type, cement content, water content and age of concrete. (3)

2.1.7.2 Thermal conductivity

The thermal conductivity of concrete is one of the key parameters needed to predict temperature variation during hydration. This measures the ability of the material to conduct heat and is defined as the ratio of the flux of heat to temperature gradient. It is measured in joules per second per square meter of area of body when the temperature difference is 1°C per meter of thickness of the body. (87)

The conductivity of concrete is determined by the conductivities of its constituents. The major factors influencing the conductivity are the moisture content of concrete, the type of aggregate, the mix proportions, the type of cement and the temperature of the concrete. The conductivity of concrete is highly affected by its moisture content, as water has a higher conductivity than air. Though the effects a variation in the moisture content are not as large as those caused by the aggregate type for normal weight concrete, in light weight concrete the affects can be quite pronounced.

The thermal conductivity varies with the density of concrete, with heavier aggregates resulting in higher thermal conductivity. The conductivity of concrete is known generally to decrease with increased temperature, through the loss of pore water and the dehydration of cement paste. A concrete surface exposed to sufficiently high temperature will undergo these changes and effectively produce an insulating layer of lower thermal
conductivity, which acts as a refractory material and reduces the ingress of heat. The mineralogical character of the aggregate greatly affects the conductivity of concrete. Both light-weight and calcareous aggregate concrete possess low thermal conductivity (and hence low thermal diffusivity), which results in less temperature rise in light weight or calcareous aggregate concrete than in one with siliceous aggregate, after equal exposure to fire.

2.1.7.3 Thermal diffusivity
Thermal diffusivity is a measure of the rate at which temperature change within the mass take place. The larger the value of thermal diffusivity of a mass the faster the changes will occur. The value of thermal diffusivity is dependent on the aggregate type, moisture content, degree of hydration of the cement paste, and exposure to drying. Diffusivity can be determined by:

\[
D = \frac{K_Sd}{Sd}
\]

D = Thermal diffusivity (m²/s)
K = Thermal conductivity (J/s m K)
S = Specific heat (J/kg K)
d = Density of concrete ( kg/m³)

2.1.7.4 Specific heat
Specific heat represents the heat capacity of concrete. It increases with the moisture content of concrete and is affected by the mineralogical character of the aggregate, specific heat increases with an increase in temperature and also increases with a decrease in the density of concrete. Specific heat varies only 8 percent for different types of aggregates. An increase in water content from 4 to 8 percent resulted in a 12 percent increase in specific heat. While an increase in temperature from 10 to 65°C resulted in increase in specific heat of 24 percent.

Specific heat is the measure of the heat capacity of concrete. The type of aggregate has only a small affect on the specific heat of concrete, but it is greatly affected by the moisture content. This is due to the large difference between the values of specific heat of the concrete and water, 840 to 1170 J/kg °C and 4187J/kg°C respectively. This shows that a small change in the moisture content of the concrete causes a comparatively large change in the specific heat.
2.1.8 The Effect of temperature on steel

The effect of temperature up to about 400°C on the final strength and ductility of mild steel and hot-rolled high yield steel as from a practical point of view is negligible. This refers to strength and ductility after return to ambient temperature. The effect of the elevated temperature on the steel under load and the disruptive effect of expansion must be given careful consideration.

As the thermal expansion of the reinforcing steel is likely to be greater than the concrete bursting stresses and cracking of the concrete can occur around the steel, especially in heavily reinforced members. If the steel is subjected to design load stresses during the fire, deflection may occur due to the loss of strength at high temperature, also buckling of bars may occur due to compressive stresses induced by thermal expansion restraint. For prestressing tendons, the effect is much more critical as there is likely to be permanent loss of tension in the steel due to high temperature. The maximum temperature reached, duration, temperature distribution and other factors are to be considered in the assessment of fire damaged prestressed concrete. (3)

2.1.8.1 Bond strength

Bond strength is defined as the maximum force that can be transmitted between bar and the concrete per unit area of a specified cylinder concentric with the bar axis. The surface of the reinforcing steel bar and concrete strength play an important role in bond strength of reinforced concrete members when subjected to elevated temperatures. (3)

Bond strength is dependent upon the shape of the deformed bar and the properties of concrete. Deformed bars or plain bars with rusted rough surface show higher bond strength at high temperature. Concrete with lower thermal strain characteristics retains higher bond values. (3) The reduction in bond strength with temperature will be greater than the corresponding reduction in the concrete compressive strength. (Fig. 2.3)

![Fig. 2.3 Relative bond strength of various bars as a function of temperature](image)
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2.1.8.2 Anchorage capacity
The anchorage capacity of a reinforcing bar is the minimum of the splitting capacity and the bond capacity. The splitting capacity depends upon the geometry of the cross section, the transverse reinforcement and the quality of concrete.

The bond capacity is a property of the reinforcing bar embedded in particular concrete. The bond capacity often becomes of greater importance for structures exposed to high temperature because the transverse reinforcement regains its yield strength after the fire and that the bond capacity decreases at the same time are the reasons why bond failure becomes of special importance after a fire.

2.1.9 Reinforced concrete
In reinforced concrete structures, the weakening of the bond between reinforcement and concrete, which is the basis of reinforced concrete design, contributes to the total damage suffered by the structure during fire. The load-carrying capacity of the structure changes due to accumulation of irreversible damages of mechanical (fatigue, cracking, and plastic deformation etc.) and physico-chemical (corrosion, absorption etc.) origin.

When a flexural member-reinforced or prestressed - is exposed to fire from bottom, the bottom fibres of the members expand more than the top owing to the temperature differential and consequently a downward deflection occurs. In a continuous flexural member, downward deflection due to differential heating causes a rapid redistribution of moment until a hinge forms over the support by the yielding of the top steel.

Expansion of vertical members may increase the load in these members (and therefore of members below and above them) and in a localized fire the horizontal members near the top of the affected column may be deflected upwards. The expansion of the roof or floor at the top of the column may cause excessive lateral movement of the column and induce very high stresses in the column and result in appreciable shear distortion and ultimately in failure.

In concrete members subjected to heat, cracking occurs first due to differential thermal stresses and reduction in strength. As the temperature rises, the cover concrete loses its strength completely, the locked up moisture exerts pressure, and the cover spall off, thus exposing the reinforcing steel. The exposed reinforcing steel will now subjected to direct heat and can start expanding, losing its strength and can even buckle. Depending on the type of member and its end conditions, the member will then be subjected to deformations such as deflections, buckling or out of plumb. Concrete when subjected to temperature over 550°C induces distortion and residual thermal stresses. A restraint
caused at the ends will lead to excessive deformations, such as twisting and distortion. The loading through self-weight and imposed loads present on the member during fire also will aggravate the situation. The reinforcing steel embedded in concrete can survive well if the concrete has not spalled off. On the other hand, when exposed to temperatures over 800°C, yield strength reduces and quenching of steel during fire fighting can cause embrittlement. (3)

2.1.9.1 Codes and standards

IS:456 provides tabulated data on required minimum dimensions and minimum cover thickness to achieve desired fire resistance in structural members, such as beams, columns and slabs. The amount of concrete cover over reinforcing bars or prestressing tendons will also help determine the extent of damage to concrete exposed to high temperatures. The greater the cover, and therefore the greater the insulation afforded to the steel, the more delayed will be the contributory effect of deformation of structural members caused by loss of steel strength.

In a simply supported reinforced concrete slab, 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 strength of the concrete and steel near the bottom of the slab will decrease as the temperature increases. When the strength of the steel reduces to that of the stress in the steel, flexural collapse will occur, while in a two-span continuous beam whose underside is exposed to fire, the bottom of the beam becomes hotter than the top and tends to expand more than the top. This differential heating causes the ends of the beam to tend to lift from their supports, thus increasing the reaction at the interior support. This action results in a redistribution of moments, i.e. the negative moments at the interior support increases while the positive moments decreases. During course of fire, the negative moments reinforcement remains cooler than the positive moments reinforcements because of better protection. (3)

Thus, the fire resistance of a continuous reinforced concrete beam is generally significantly longer than that of a simply supported beam having the same cover and loaded to the same moment intensity. Thus a continuous beam or slab provides more resistance against fire than that of simply supported one. This is due to moment redistribution. And this is the reason why IS: 456 (2000) has provided lesser cover
requirement for continuous members. IS code has obviously suggested larger cover requirement for larger expected time of fire exposure. (90)

Concrete structures in the US are to be designed in accordance with the specifications of American Concrete Institute (ACI-318.2005) standard. While ACI 318 does not contain any fire provisions, it refers to ACI 216.1 (2007) standard which gives specifications for fire resistance ratings of concrete and masonry structural members. Similarly NBC (2005) for Canada, Eurocode 2 (2004) for Europe and AS 3600 (2001) for Australia provide fire resistance specifications.

2.1.10 Test methods: Types of loading test at elevated temperature

Mechanical properties of concrete at elevated temperature are determined by testing plain concrete specimens using one of three types of steady-state temperature tests: stressed tests, unstressed tests, and unstressed residual property tests. Briefly, in stressed tests, a preload (20 to 40% of the room temperature compressive strength) is applied to the specimen prior to heating and is sustained during heating. Heat is applied at a constant rate until a target temperature T is reached, and is maintained for a time t until a thermal steady state is achieved. Stress or strain is then increased at a prescribed rate until the specimen fails. In unstressed tests, the specimen is heated, without preload, at a constant rate to the target temperature, which is maintained until a thermal steady state is achieved. Stress or strain is then applied at a prescribed rate until failure occurs. In unstressed residual property tests, the specimen is heated without preload at a prescribed rate to the target temperature, which is maintained until a thermal steady state is achieved. The specimen is then allowed to cool, at a prescribed rate, to room temperature. The specimen is tested at room temperature. (41) These three types of test are schematically shown in Figure 2.4 a, b, and c.

Figure 2.4 Schematic temperature and load histories for steady-state temperature tests