# Performance of Concrete During Fire Exposure-A Review

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***Abstract-*** **Construction of high-rise buildings becomes most common due to land scarcity, higher land cost, urbanizations as well as rapid increase in population specifically in cities. In the design of the high rise building, in addition to strength, serviceability is an imperative parameter. Consequently, the behavior of concrete need to be well known in every exceptional situations. One of these exceptional situations is fire resistance of concrete. When concrete is exposed to high temperature during fire, properties of concrete were found to be considerably changed. The changes in properties of fire affected concrete need to be thoroughly understood to achieve proper assessment. A comprehensive review on the changes in concrete and performance during fire is not reported in the available literature. This paper integrates the information from various earlier research studies on the performance of concrete against fire. Moreover, suitable recommendation is highlighted on the later part of this paper.**

***Keywords: Fire Resistance, Concrete, Spalling, Colour, Thermal conductivity.***

## I. INTRODUCTION

Concrete is one of the most widely used materials in construction field. Concrete has its inherent fire resisting properties. However, this advantage cannot neglect the consideration of fire effect in the design of concrete structures. When concrete exposed to fire, it adversely affects various physical and mechanical properties of concrete. Furthermore, high quality concrete structures which were designed for higher strength and less permeability were found to severely affected due to fire accident and led to collapse of the structure. Although several fire accidents including recent incidents on concrete structures, emphasize on the fire resistance concept is considerably limited. Significant degradation of concrete due to fire that compromised with the safety of the structures in the earlier fire accidents specifically tunnels of the English Channel (1996 and 2008), Mont Blanc tunnel (1999), Fréjus forest (2005) in France, Storebealt (1994) in Denmark, the Gotthard tunnel (2001) in Switzerland, World Trade Centre, New York (2001)[1], and the Windsor Tower Fire, Madrid_(2005)[2]. Therefore, special considerations need to be attained on fire resistance and when concrete is exposed to fire, the structural component should be able to withstand the dead load and live load without collapse.

The fire resistance of concrete depends on the duration of fire as well as on the exposure temperature. A longer exposure time has an enhancing effect on strength for lower heating temperature. On the other hand, a deteriorating effect for high heating temperature. The deteriorating effect can be attributed to the fact that a longer exposure time along with high temperature causes reduction in Young's modulus and Poisson's ratio. A longer exposure time has an enhancing effect on all the strengths and fracture toughness for lower heating temperatures but a deteriorating effect for high heating temperatures[3]. Moreover, the high temperature concrete behavior is strongly linked to the properties of the cement paste. For example, one of the causes of deterioration of concrete is dehydration and expulsion of water, which is primarily the property of cement. However, it does not denote that aggregates play insignificant role in concrete. As aggregates occupy a large volume in concrete (around 60–80%), it is generally recognized that the heat transfer of the concrete depends mainly on the aggregates characteristics [4]. The mineralogical characteristics of the aggregates greatly affect the thermal conductivity of the concrete. Basalts and dolerites have a low thermal conductivity, limestones and granites are in the middle range while quartzite and sandstone exhibit the highest conductivity. A lesser propagation of heat causes a higher thermal gradient in the material that can increase thermal stress which is the primary reason for spalling [5, 6]. Consequently, the aggregate selection is important in the fire resistance structure because, different types of aggregates show evidence of different resistances to elevated temperatures in the earlier research studies.

Several studies have been carried out, even in recent times, on the performance of concrete at high temperature, and the most relevant parameters have been investigated. Still, a congregated description of the important parameters affecting the concrete behavior at elevated temperatures is not reported in the current literature. This paper mainly focuses the discussion on the variation some of the physical and mechanical properties of concrete at high temperatures. The purpose of this review is to summarize previous research progress and to suggest further guidelines to reach scientific insight on the performance of fire resistant concrete

## II. VARIATIONS IN PHYSICAL AND CHEMICAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURES

### *A. Influence of dehydration*

The dehydration process of concrete is related to the characteristics of hydrated products. Water, in hydrated cement paste, is present either as free water or as chemically bonded water. Due to increase in surrounding temperature, water is released and a large amount of energy is consumed. Free water commonly evaporates at around 100 °C and is completely removed at 120 °C. There is a loss of the water which is chemically bound in hydrated calcium Silicate, above 150 °C, with a peak rate of loss at 270°C [7-9]. As there is difference in thermal coefficients of expansion of the cement paste and aggregate, due to which thermal stresses are induced between the aggregate (is in expanding stage) and cement paste (is in shrinking state). The induced stress results in breakdown of the interfacial bond between the aggregate and the surrounding cement paste, that results in strength loss of concrete specimens. On increasing the temperature above 300°C, micro cracks are induced through the material. As a result, mechanical strength and thermal conductivity are found to be considerably degraded. Approximately at 550°C temperature can be denoted as critical temperature for the reason that the dehydration of calcium hydroxide takes place. In addition to this, aggregates were found to be started to deteriorate at this temperature range this leads to shrinkage of concrete [10]. It is interested to note that the effect of water which may be sprayed to extinguish the fire at this stage involved in the conversion of calcium oxide into calcium hydroxide. Moreover, it through the pores and forms white spots on the surface after the fire. Moreover, increase in volume has been reported. As a result of volume expansion, cracks occur, and concrete becomes porous. At temperatures above 600°C, C-S-H gel decomposes, and spalling behavior is widely reported [8].

At 800 °C→ Concrete gets crumbled.

At 1150 °C→ Cement paste is transformed into glass phase which results in serious deterioration in strength and durability [11].

### *B. Changes in Colour*

According to Omer Arioz [7], it is not feasible to generalize the intensity of white colour for different elevated temperature variations. The intensity with respect to temperature is shown in Fig.1. As the temperature increases, intensity of white colour is not changing significantly. Although a concluding remark can be made about the yellow colour from earlier research studies that its intensity increases with increase in exposure temperature. When concrete is exposed to a temperature beyond 200 °C (Fig.2-3), it experiences petite change in colour. After 650 °C, concrete colour changed to insipid yellow and presence of few micro-cracks and holes was reported. After exposure to a temperature above 800 °C, light brown appears with whitish gray around the perimeter [12]. After exposure up to 1200 °C, the colour of the concrete was found to be red with some of the coarse aggregates were seen as melting attributable to their chemical composition.

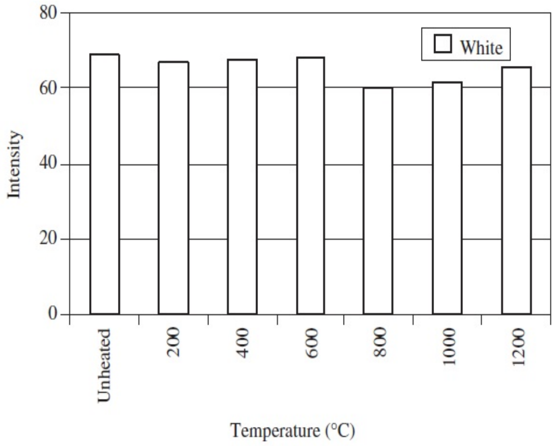


Fig. 1: Result of colour image analysis (white colour)[7]

### *C. Spalling*

It is defined as separating of fragments of concrete from the surface of a concrete member when it is exposed to elevated and swiftly increasing temperatures as encountered during fire conditions. In other words, fragments of concrete separate from the concrete member when it is subjected to rapidly increasing temperatures. When concrete is exposed to fire, spalling is one of the major problems that needs to be properly addressed. Because it have a severe effect destroying the complete cross section and decreasing the load bearing capacity of construction to a greater extent. This unique property of concrete has a deterministic effect on the fire resistance of concrete member. Therefore, spalling is one of the important considerations while designing for the performance under the fire.

Normal spalling [13] - This type of spalling happens when the tensile stresses in concrete at the surface reaches the ultimate tensile strength during heating. As a result cracks are formed and to end with concrete falls off. Normal spalling is a ductile failure.

Explosive spalling [13] -This type of spalling happens because of the stresses and strains applied on the gel structure of concrete. It generates great strain energies, and if there is a defect in the gel pore, there is an abrupt release in energy which creates the violent failure. The stresses can be tensile or compressive or a combination of both.

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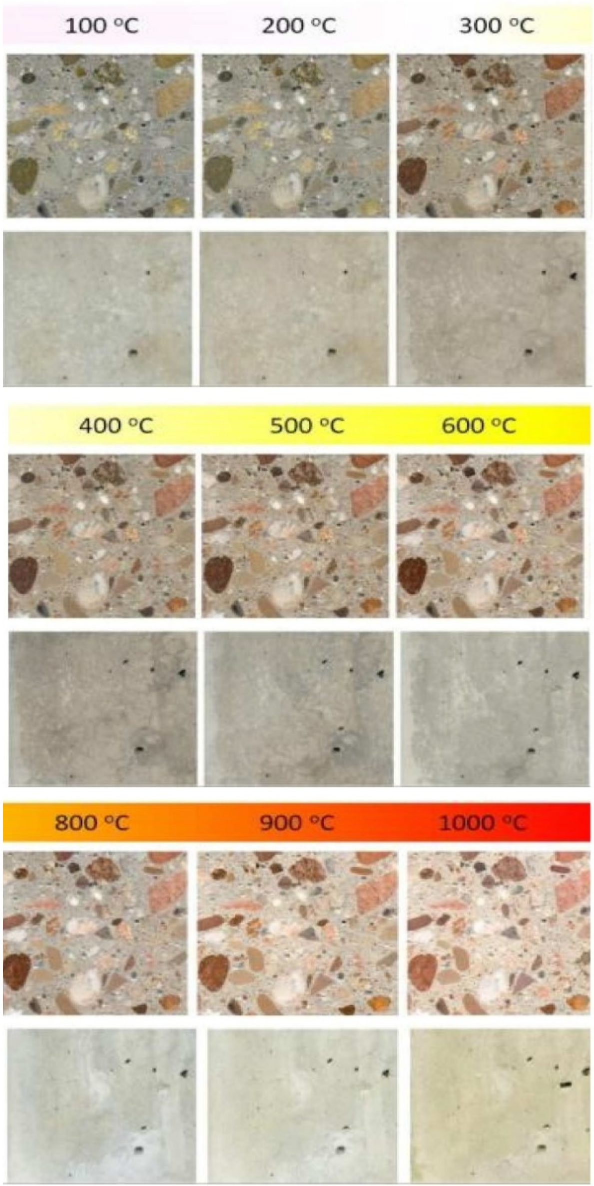


Fig. 2: Colour change of concrete at elevated temperature (in exposed aggregate surface and external surface of structure) [38]

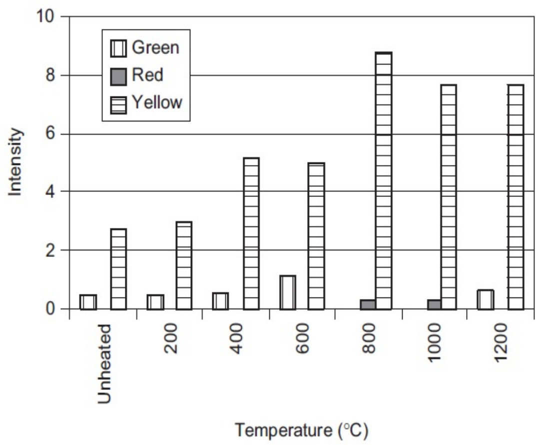


Fig. 3: Results of colour image analysis (Green, Red, Yellow colour) [7]

Theories of Spalling:

*(a) Pore Pressure*

Pore pressure is also one of the important factors that should be considered in the study of spalling [14]. Generally, concrete has many phases which consist of a porous solid skeleton, adsorbed water, and different types of gases. When these elements are exposed to higher temperature various compound phenomenon's take place such as dehydration of cement paste and thermal expansion of skeleton etc. which results in a build-up of pore pressure along with the thermal stresses. When pore pressure is increased to considerable level, causes loss of material from the surface of the member. This built up pore pressure begin the progressive failure, ultimately leading to the separating of fragments of concrete from the concrete member which can be explosive in nature.

*(b) Restrained thermal dilatation*

When concrete is subjected to rapidly rising temperatures as in the case of fire, compressive stresses are developed parallel to the heated surface and which are liberated by the brittle failure. As a consequence, chunks of concrete get separated from the main concrete member and leads to spalling of concrete.

*D. Mont Blanc Tunnel Fire Case study:*

The major fire damage to the tunnel structure included damage of tunnel roof of over 900 m long due to spalling (Fig. 4). The spalling of the tunnel roof concrete lining was due to the dehydration of concrete. As the tunnel was exposed to fire for a long duration (50 hours), significant adverse effect on strength and stiffness were found in the evaluation. Furthermore, the molecular links which bind together the materials of concrete got destroyed due to dehydration. Consequently, the concrete failed in cohesion and got weakened, pushing pieces of the concrete off the tunnel linings layer by layer. In that fire accident, a part of the tunnel roof lining was completely collapsed and exposed the rock layer as shown in Fig 4.

Fig. 4: Spalling due to fire in the Mont Blanc Tunnel fire (1999)


Fig. 5: Fire induced Spalling in 1) Normal strength concrete 2) High strength concrete [15]

### E. *Thermal conductivity*

Thermal conductivity is a significant property to determine the behavior of concrete at high temperature. It describes the inward progression of temperature rise on increase in temperature. When the concrete is subjected to elevated temperature, its thermal conductivity decreases progressively with temperature. This thermal conductivity decrease is dependent on its linear variation with moisture content [15]. However, moisture content is not the only factor which affects thermal conductivity. Some of the other factors are type and quantity of aggregate, permeability and internal hydrated products. The aggregate dependency of thermal conductivity in normal strength concrete has already been investigated by ASCE [22] and Eurocode [21].

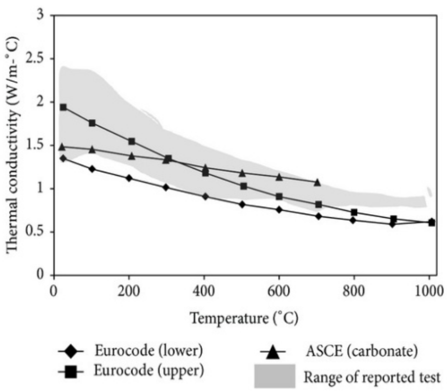


Fig. 6: Variation in thermal conductivity of normal strength concrete as a function of temperature [15]

Thermal Conductivity variation with temperature as per The American Society of Civil Engineers: (Based on ASCE [22])

| **THERMAL CONDUCTIVITY ($k_c$), W-m/°C.** | ***TEMPERATURE RANGE*** |
|---|---|
| ***Siliceous aggregate concrete*** | |
| **$k_c$=-0.000625T+ 1.5**<br>**$k_c$=1.0** | **200°C < T < 800°C**<br>**T > 800°C** |
| ***Calcareous aggregate concrete*** | |
| **$k_c$ = 1.355**<br>**$k_c$ = -0.001241T + 1.7162** | **20°C < T < 293°C**<br>**T > 293°C** |
| ***For high strength concrete and Siliceous aggregate concrete*** | |
| **$k_c$ = 0.85(2-0.0011T)** | **20°C < T < 1000°C** |
| ***For high strength concrete and calcareous aggregate concrete*** | |
| **$k_c$ = 0.85(2-0.0013T)**<br>**$k_c$ = 0.85(2.21-0.002T)** | **20°C < T < 300°C**<br>**T > 300°C** |

Thermal Conductivity variation with temperature as per Eurocode [21]: (For all types of concrete aggregates)

| THERMAL CONDUCTIVITY ($k_c$), W-m/°C. | *TEMPERATURE RANGE* |
|---|---|
| *Upper limit-* | |
| $k_c = 2 - 0.2451(T/100) + 0.0107(T/100)^2$ | $20°C \le T \le 1200°C$ |
| *Lower limit-* | |
| $k_c = 1.36 - 0.136(T/100) + 0.0057(T/100)^2$ | $20°C \le T \le 1200°C$ |

## III. VARIATIONS IN MECHANICAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURES

### A. *Compressive strength*

Reduction in compressive strength of concrete at high temperatures is inevitable in spite of different mixture proportions, specimen size, stressed or unstressed.

The residual compressive strength of concrete post heating experiences has three stages [17]:

1) Room temperature to 300°C→ Compressive strength of concrete remains constant or increases to some extent.

2) 300-800°C→drastic decrease in the compressive strength

3) Temperature >800°C→ Almost major reduction in compressive strength of concrete. Bamonte and Gamborova [18-19] tested the compressive strength of two types of concrete, self-compacting concrete and high strength durable concrete at hot state and after heating.

According to the results when the temperature was:

<300 °C→Compressive strength of both the concretes at hot condition was inferior to the residual ones.

When the temperature was increased to 600°C, results were contrary.

In an another study, compressive strength of normal and self-compacting concretes were investigated by Seshu and Pratusha [20] from temperatures in upwards of 800°C and the results that obtained, followed a similar trend with the previous studies. The primary mechanism for the decline of compressive strength is believed to be the vapor pressure caused by evaporation of free water in capillary pores. The pores get pressed during the compressive test, which increases the vapor pressure at hot state and then escalating the damage of concrete. Consequently the compressive strength at hot state decreases at a larger rate than the residual ones

Fig. 7-8 shows the variation of compressive strength ratio for NSC and High Strength Concrete (HSC) at elevated temperatures, respectively. The peak and bottom limits of shaded area shows the range of variation of compressive strength as given by Eurocode[21], ASCE[22] and Kodur et al relations. As per Fig. 7, the compressive strength of NSC has a large but uniform variation for the range 20-800 °C. According to Fig 8, the compressive strength of HSC has a greater variation in the temperature range of 200°C to 500°C and less variation for temperature above 500°C. This is mainly because of less number of tests conducted on HSC for a temperature in upwards of 500 °C either due to the spalling or due to shortcomings in the laboratory equipment.

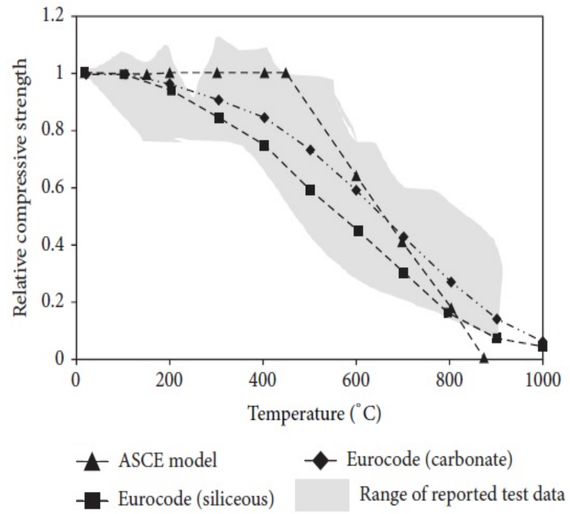


Fig. 7: Variation of relative compressive strength of normal strength concrete as a function of temperature [15]

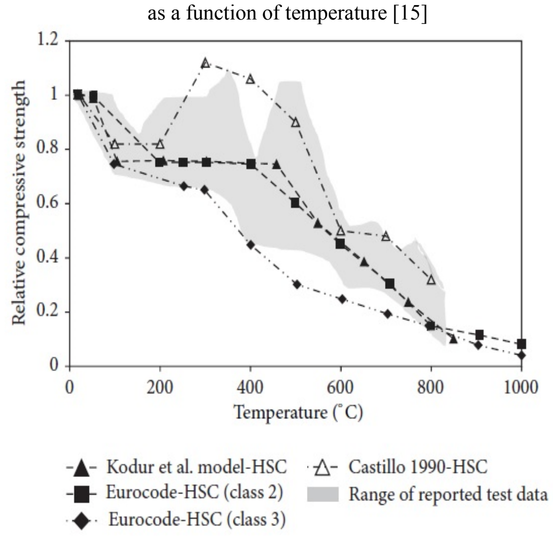


Fig. 8: Variation in relative compressive strength of high strength concrete as a function of temperature [15]

However, a broader variation is witnessed for Normal strength concrete(NSC) for the same range of temperatures which is mainly due to great number of tests conducted for considerations which are already available in the present literature. Overall. It is interested to note that variations in compressive strength of concrete is quite high under elevated temperatures.

Apart from general parameters, other factors which are directly affect compressive strength at elevated temperatures are initial curing, moisture content at the time of testing, and the addition of admixtures (specifically silica fume) to the concrete mix [23-27]. Only few limited studies have been carried out to address the influence of these parameters in the performance of concrete against fire.

*B. Tensile strength*

Compressive strength of concrete is considerably greater than the tensile strength of concrete, and hence it is not usually taken into consideration. However, when fire resistance is focus of discussion, tensile strength of concrete becomes highly significant as cracking in concrete and propagation of micro cracks related to its tensile strength. Moreover, it is one of principal cause of failure in concrete. When fire conditions are considered, tensile strength becomes more essential in cases of fire induced spalling [28]. Though all types of concrete are susceptible to spalling, high strength concrete is more prone as compared to normal strength concrete. As a consequence, to predict the behavior of high strength concrete under fire conditions, understanding of tensile strength of high strength concrete changeable with temperature is extremely essential.

Figure-9 illustrates the variation of splitting tensile strength ratio of normal strength concrete and high strength concrete as a function of temperature as reported in previous studies and Eurocode provisions [21, 29-31].

The shaded portion in the graph represents the variation in splitting tensile strength with conventional aggregates. The reduction in the tensile strength of normal strength concrete with the temperature is related to fragile micro structure of normal strength concrete which allows initiation of cracks [15]. At 300 °C, NSC losses 20% of its initial tensile strength and at 600 °C, there is more prominent damage and tensile strength is about 20% of its initial value.

High strength concrete loses its tensile strength at a rapid rate at elevated temperatures because of development of pore pressure in the microstructure [32]. Tensile strength of concrete can be increased up to 50% greater with the addition of steel fibers [33-34]. Tensile strength of steel fiber reinforced concrete decreases at an inferior rate as compared to the plain concrete for the range of temperature 20-800 °C [35]. It has been reported that it reduces the spread of cracks in the members, for this reason it is extremely beneficial.

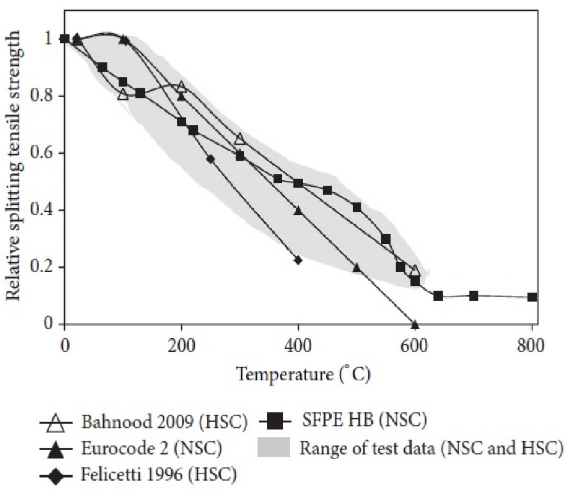


Fig. 9: Variation in relative splitting tensile strength of concrete as a function of temperature [15]

*C. Creep*

Creep can be defined as the increase in strain in a structural member with time due to continued stress. Creep sometimes gets strengthened by moisture dispersion and loss of bond in cement gel (C–S–H). Creep is caused and accelerated mainly by two processes: (a) dehydration of concrete due to high temperatures and (b) acceleration in the process of breakage of bond.

Creep of concrete increases with temperature. Below 100°C, creep in concrete originates in the cement paste, possibly because of the communal approach of contiguous laminar particles of cement gel, which is further expedited by the existence of water in gaps between the particles. Above 100 °C concrete rapidly dries and for this reason the creep rate increase until a steady moisture condition is reached. After the moisture is lost and stable moisture content at a given temperature is reached, the creep rate becomes less than that before loss of moisture [16].

Considering practical point of view concerning the safety of reinforced concrete structures subjected to high temperature during fire, the transient creep of concrete usually has advantageous effects. Undoubtedly, the highest deformations in concrete exposed to high temperature occur in structural member which is most stressed or present in the most stressed zones. Transient creep, at this stage, causes re-distribution of internal forces or stress in the structures. As a result, the parts of the structure which are subjected to the highest stress can be relieved, and the parts which have some spare load bearing capacity before fire may in fire take over the stress which cannot be borne any more by weakened concrete in the most stressed places [36].

## IV. EFFECT OF TYPE OF AGGREGATES AT ELEVATED TEMPERATURE

Several earlier research studies performed on the effect of type of aggregate on concrete when subjected to higher temperature. Result from these studies emphasized that, concrete when exposed to a temperature up to 300 °C, no cracks were observed. The type of aggregates not at all distressed the performance of concrete up to 300 °C. On the other hand, the types of aggregate significantly influences on the performance.

*A. Siliceous aggregates*

At around 600 °C, the siliceous aggregate concrete are generally seen damaged at the boundary. If the temperature is increased further, the concrete with siliceous aggregates weakens. The weakening of concrete is due to the fact that quartz present in siliceous aggregates and sand gets weakens when subjected to change in temperature. Small cracks were found to be developed, which can be seen propagating to the middle by the formation of coupled network [37].

*B. Calcareous Aggregate*

At around 600 °C, Cracks were found to present in the Calcareous concretes. However these cracks were shortest cracks. When exposed to 750°C and subsequently if cooled, similar disintegration and damage at the boundary were observed similar to siliceous concretes [37]. However, this phenomenon is more intense as compared to concrete with other aggregates. This is due to the de-carbonation of $CaCO_3$. Due to de-carbonation reaction, CaO is formed which further reacts with the humidity in the atmosphere and leads to the formation of Portlandite. It suffers a large volume expansion which causes breaking of bond of carbonate aggregates with the paste. Therefore, disintegration along with radial cracks were reported in the previous study [37]. However concrete containing calcareous and siliceous aggregates compared to ordinary concrete with river aggregates, the performance of these aggregate were found to better the river aggregate concretes due to fire resistance property [37].

*C. Silico-Calcareous Aggregate*

At elevated temperature, the Silico-Calcareous concretes were found to be had the largest cracks. However, these cracks are less concentrated and slower when the concrete is exposed to temperature ahead of 750 °C.

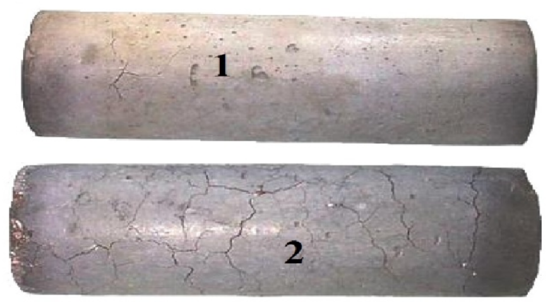


Fig. 10: Effect of heating at 600°C 1) Calcareous concrete 2) Silico-Calcareous concrete [38]

Some studies [40] were also conducted on the difference in behavior of concrete at elevated temperatures with limestone and dolostone aggregates. In Fig. 11, the compressive strength variation is shown with respect to increase in temperature. The compressive strength is shown as the % of original compressive strength (100% at the start of experiment). From Fig. 11, it can be concluded that the limestone concrete suffers more decrease in compressive strength than the dolostone concrete.

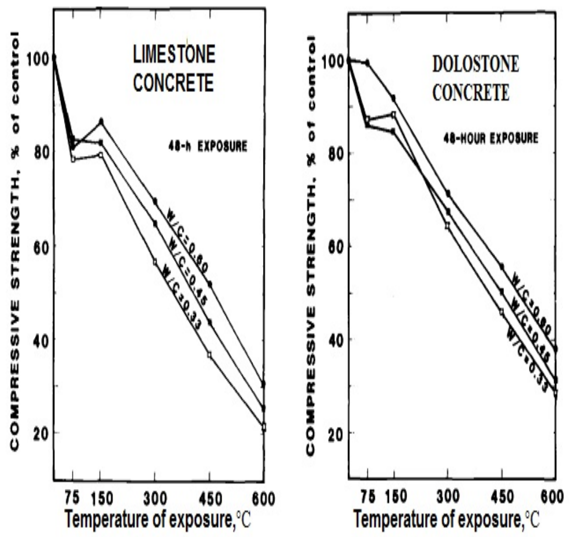


Fig. 11: Variation in % compressive strength of 1) Limestone concrete 2) Dolostone Concrete with increase in temperature [40]

## V. RECOOMENDATIONS FOR SUPERIOR FIRE RESISTANCE CONCRETE

When the temperature of concrete is in the range of 300-800 °C, there is a drastic decrease in the compressive strength of concrete and the specimen totally disintegrates at a temperature of 1200 °C. Reinforcement plays a major role in increasing performance of structures under fire conditions. Use of high grade steel is recommended. The addition of steel fibers will provide the compressive strength. Due to similar behavior, same provisions are suggested splitting tensile strength. It can also be improved by addition of pulverized fly ash and steel fibers in comparison to plain concrete.

Spalling occur due to the low permeability of concrete and low tensile strength of steel reinforcement, may lead to lower fire resistance and might imperil the safe atmosphere for evacuation during fire. The degree of spalling is influenced by concrete strength, type and amount of aggregate, tie spacing and load intensity. By the addition of fibers and improving tie configuration, spalling can be abated to a significant extent and fire performance of concrete can be improved. One of the most effective methods that for reduction of spalling is to create a network of pores in the material. The main advantage is, on heating when steam is generated in the concrete, it will be easy for it to escape through these pores. By providing polypropylene fibers in the material, this condition can be developed. As these fibers will melt at about 170°C, and will leave a grid of open pores, which can make steam evacuation easier, thus contributing to the reduction of internal pore pressure which is one of the cause of spalling. [39].

Type of aggregate is highly suggested. Because it is one of the main factors influencing concrete strength at high temperature. River aggregate in concrete can be replaced by the use of brick and steel industry waste material for increasing the fire resistance. The advantage of using waste material is fire resistance as well as waste management.

Siliceous aggregate concrete has lower strength at high temperature compared to calcareous and lightweight concrete. Therefore, it is better to prefer calcareous aggregate concrete over siliceous aggregate in the situations where concrete might expose to higher temperature.

## VI. CONCLUSIONS

Concrete, at elevated temperatures, experiences appreciable physicochemical changes. These changes sometimes cause adverse effect to performance of concrete and also produce additional complexities. In this paper, the effect different parameters such as aggregates, exposure conditions including temperature and exposure time, hydrated products and other salient factors on the fire resistance of concrete have been comprehensively reviewed. Moreover, the changes in properties of concrete such as colour, compressive strength, tensile strength, creep, spalling and thermal conductivity with respect to different temperature are highlighted in the paper. On the whole, it is clear that fire performance of concrete need to be considered as major design element in modern high strength concrete structure. Moreover, suitable guidelines and specifications to be developed for practical application along with suitable experimental evaluation in laboratory scale as a part of quality assessment similar to materials testing.

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