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Concrete's Odyssey Through Heat: A Review

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Abstract*: Fire is a catastrophic event to which any building can fall victim during its lifetime. Not only does it pose a direct threat to the occupants through the release of harmful gases and devastating heat, but the elevated temperatures themselves also have seriously adverse effects on the structural integrity of entire building. Though undesired, fire is an exigency that cannot be avoided altogether. Therefore, impact of fire on concrete/ RCC deserves minute scrutiny. In this study, a review is carried out based on the experimental studies on the performance of concrete/RCC when exposed to FIRE/ higher temperatures. The compiled test data revealed distinct difference in mechanical properties of normal, high strength, self compacting & improvised concrete. Shape & size of specimens, concrete grade, admixtures, temperature level, applied load, exposure time to heat, rate of heating, rate of cooling, specimen type (stressed/unstressed member), type of cooling etc were the parameters that influenced the test results. Exposure time, exposure temperature & concrete cover were observed to be the principal factors. The outcome of the review helped in identifying the main problem areas, dubious claims & gaps/ lacunae in the research works.

***Index Terms*: Concrete, Fire, RCC, Spalling**

I. INTRODUCTION

Fire is a catastrophic event to which any building can fall victim during its lifetime. Not only does it pose a direct threat to the occupants through the release of harmful gases and devastating heat, but the elevated temperatures themselves also have seriously adverse effects on the structural integrity of entire building. Though undesired, fire is an exigency that cannot be avoided altogether. Therefore fire protection efforts must be made to reduce the impact of such events.

A study of 16 industrialized nations (13 in Europe plus the USA, Canada and Japan) found that, in a typical year, the number of people killed by fires was 1 to 2 per 100,000 inhabitants and the total cost of fire damage amounted to 0.2% to 0.3% of GNP. But one of the advantages of concrete over other building materials is its inherent fire-resistive properties. Concrete is known to exhibit good behavior at high temperature; thanks to its incombustible nature and low thermal conductivity (0.8 W/m at 20oC). However, concrete structures must still be designed for fire effects. Structural components must still be able to withstand dead & imposed loads without collapse even though the rise in temperature causes a decrease in the strength & modulus of elasticity of concrete & steel reinforcement. This paper presents the findings of a thorough review conducted on the findings of research/ investigations conducted on the effect of fire/ high temperatures on concrete/RCC during last 3-4 decades. The outcome of the review helped in identifying the main problem areas & future course of study/investigation.

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II. PRESENT STATE OF ART

Across the globe, structural design for fire safety is mostly based on "Prescriptive Approach." The prescriptive approach involves fire resistance rating of structures & was developed almost 100 years back. The data of course is being modified with new findings but is still conservative. Later half of the nineties brought in a paradigm shift in the fire safety engineering with the onset of the performance based design approach. The recent but nascent trend is to go in for analytical computer modeling by using the Finite Element Method. This paper is aimed at a comprehensive review of the research work conducted & the literature published in the related fields for the last 3-4 decades. Most of the investigations were experimental in nature.

Morley P. D. *et al.* [1] conducted tests on the influence of high temperature on the bond in reinforced concrete. Knowledge of the effects of temperature on the bond strength between steel and concrete in reinforced concrete is important if a complete understanding of its fire resistance and residual capacity for structural performance is to be known. A summary of the strength of concrete and steel during, and after, exposure to elevated temperatures was made. This was followed by a review of the different procedures used for testing bond at ambient temperature. Work carried out on bond at high temperatures was discussed and suggestions made about its relevance to structural performance. Preparations by the authors to investigate this problem more fully with the intention of providing information which would be of use in the design of fire resistance and the reinstatement of fire damaged reinforced concrete components were described.

S. Chandra *et al.* [2] made the earliest trials to study the influence of polymer addition on fire resistance of concrete. Specimens of 2.5 cm and 5.0 cm thick plates and 15.0 cm thick beams were heated in a gas/oil-fired furnace to high temperature of nearly 1000 °C. They proposed that the hydrophobic polymer gave a more open structure of concrete which facilitated the transportation of the steam. It was concluded that the addition of polymer dispersion (1.5 % polymer of the cement weight) helped in avoiding both the development of high vapor pressure and destructive spalling.

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H. *et al.* [3] presented methods for determining the fire resistance of concrete elements exposed to fire based on the prescriptive approach. Their work contained information for determining the fire endurance of simply supported slabs and beams, continuous beams and slabs, floors and roofs restrained to thermal expansion. Information was also given for determining the fire endurance of certain concrete members based on heat transmission criteria.

Khoury Gabriel A. et al. [4] did research work on effect of elevated temperatures on concrete. The transient thermal strain of concrete during first-time heating under load to 600 °C could be described by two main components, the free thermal strain (FTS) and the load-induced thermal strain (LITS), which possessed distinct and different properties. A 'master' LITS curve for concrete was found to exist for temperatures up to about 450 °C. As per the authors, basic creep studies at constant temperatures indicated a marked increase in creep above 550–600 °C for cement paste and lightweight concrete which suggested that the structural, though not necessarily the refractory, usefulness of Portland cement-based concretes in general would be limited to temperatures below 550–600 °C.

The paper by Bruce Ellingwood and T. D. Lin [5] described the results of a major research program to study the behavior of reinforced concrete beams exposed to severe fires. Data are presented from fire tests of six full-scale beams continuous over one support. Four beams were exposed to the standard ASTM El 19 fire, and two to a short-duration high-intensity (SDHI) fire developed using realistic fire-load and compartment-ventilation parameters.

The six reinforced concrete beams were designed according to ACI Standard 318 {Building 1983), with a 20-ft (6.1-m) span and a 6-ft (1.8-m) cantilever. Beams were fabricated using normal-weight concrete (Type I Portland cement, sand, and carbonate gravel aggregate) with a specified compressive strength of 4,000 psi (2.8 MPa) and Grade 60 deformed reinforcing bars. Beam c/s was 9"x21". All beams tested developed shear cracks as early as 90 min after the start of the fire. Flexural cracks formed in the positive moment region approximately 30 min later, and extended rapidly. As a result, all of the beams tested failed in flexure rather than in shear. Despite the substantial internal cracking of the beams that resulted from nonlinear strain gradients at elevated temperatures, shear strength of beams at elevated temperatures did not appear to be a problem. The most important factor affecting the behavior of a properly designed reinforced concrete flexural member would be the temperature history in the reinforcement. In contrast, the compressive strength and stiffness of concrete were less sensitive to variations in temperature at the temperatures typically developed during a fire, and thus accuracy in predicting concrete temperatures carried lesser importance.

Ellingwood Bruce R. [6] dwelt on the heat transfer in slabs of various thicknesses. The ASTM Standard E-119 fire-endurance test ("Standard Methods" 1989) specifies three conditions for failure of reinforced concrete components subjected to a standard fire exposure: (a) Collapse of the component or failure to inhibit passage of flame or hot gases; (b) attainment of the limiting average temperature of 593° C (1,100° F) in the reinforcement; and (c) a rise to 139° C (250° F) of the average temperature of the unexposed surface of the test component. The standard fire exposure is defined by a temperature-versus-time relation (fire curve), which increases monotonically during the rating period and is the same for all building occupancies. While this test may be useful for establishing comparative fire ratings for different structural components, it may not provide a good indication of how they might behave during an actual fire.

The analysis showed that if the ASTM E-119 fire exposures were used, a 150 mm RCC slab would fail the heat-transmission criterion at approximately 3 hours, 45 min. On the other hand a 90mm RCC slab (very common in grid slab toppings) would fail the heat-transmission criterion at approximately 70 min. In contrast a 65mm RCC slab would fail the heat-transmission criterion at approximately 37 min. In a nut shell, size does matter.

Chakrabarti S. C. et al. [7] conducted an extensive test program for assessing the residual strength of concrete after fire. The authors proclaimed that the concrete actually gained some strength between 100 to 300°C in the presence of siliceous & carbonaceous aggregates. Some other researchers too have reported this phenomenon which has more detractors than supporters. As per the authors, concrete didn't lose much of its strength up to 500°C & in fact regained 90% of lost strength up to this temperature after about a year. *The theory of fire affected concrete regaining some of its strength with time is not an established one*. Concrete cubes heated beyond 800°C for 4 hours started crumbling after 2-3 days. In concluding remark the researchers suggested that one way of assessing the residual compressive strength could be by estimating the temperature of exposure (time of exposure being mostly known) & then using the tables & graphs presented by them. The results of a fire load survey carried out in Kanpur, India; were presented by Sunil Kumar et al. [8]. Thirty-five residential buildings with a total floor area of 4256.6 m2 were surveyed. The statistical parameters of the fire load presented in the paper would be useful in the design of fire prevention and firefighting measures of residential buildings. The magnitude of room fire load is related to the use of room. The mean load varied from 66.7 Mcal/m^2 to 203.9 Mcal/m^2 with an overall average of 116.5 Mcal/m^2. The standard deviation of fire load ranged from 20.8 Mcal/m^2 to 148.7 Mcal/m^2 with an average of 61.0 Mcal/m^2 for all rooms. The mean and maximum fire load decreased as the room floor area increased. It was found that the fire load did not depend on the height of the building.

M. M. El-Hawary et al. [9] conducted analytical and experimental study of the behavior of concrete slabs exposed to fire. A finite element computer program based on the time dependent, transit, heat conduction theory with boundary conditions capabilities for heat convection and radiation was developed to study the temperature distributions in concrete slabs subjected to fire. To guarantee the accuracy of the computer program an experimental program was conducted, in which six concrete slabs (400 x 400 x 80mm) were exposed to fire, at different temperatures, and temperatures in different locations of the slabs were measured using thermocouples at different times.

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From the results, good agreement was detected between the experimental and analytical program results. The developed computer program could be used to predict the temperature distribution in concrete slabs, at the required time, which have been subjected to fire.

M. M. El-Hawary et al. [10] conducted a study on behavior of reinforced concrete beams subjected to fire in shear zone and then cooled by water. Eight reinforced concrete beams of size (180 x 20 x 12 cm) were investigated. The beams were divided into two groups with cover thickness of 2cm and 4cm. Each group was subjected to a fire of 650°C for different periods of time i.e. 0, 30, 60, 120 min. Cracking loads, crack propagation and ultimate loads were recorded for each beam.

The results indicated that the ultimate load carrying capacity of the beams exposed to fire for 30, 60 and 120 min were less than those of the reference beams which were tested without exposure to fire. Also, beams with 4 cm cover thickness had approximately 10% less reductions in the ultimate loads when compared with beams with a cover thickness of 2 cm. It was also observed that the deflections of fired beams increased as the fire exposure time increased, and the non-destructive compressive strength decreased as the fire exposure time increased.

Milke James A. [11] provided an overview of state-of-the art engineering methods for structural fire protection applications that could be incorporated into an engineering standard. The overview addressed the technical basis, applicability, and utility of a representative sample of available calculation methods. These methods apply to a wide variety of structural members comprised of concrete, masonry, steel, and timber.

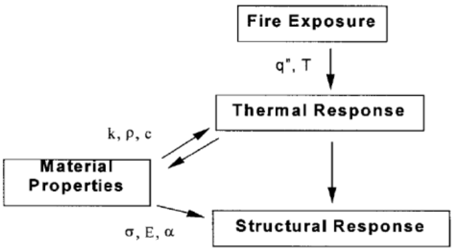

Fig.1. Performance-Based Fire Resistance Analysis

As per the Paper, an analytical assessment of fire resistance would include four principal aspects (Fig. 1):

- Fire exposure
- Material effects
- Thermal response
- Structural response

A description of the fire exposure would focus on the heating conditions associated with the exposure. Material effects would include material properties as a function of temperature along with physical or chemical effects of the elevated temperature exposure. Analyzing the thermal response would help in determining the temperature profile within the exposed structural member. The ability of the structural member to support a load despite the effects of the fire exposure was incorporated in the analysis of structural response. Y. N. Chan", G. F. Peng & M. Anson [12] in their research studied the damage to the normal strength concrete (NSC) and high strength concrete (HSC) with compressive strengths of 39, 76, and 94 MPa respectively, under high temperatures (Fig. 2). After exposure to temperatures up to 1200ºC, compressive strength and splitting tensile strength were determined. The pore structure in HSC and in NSC was also investigated.

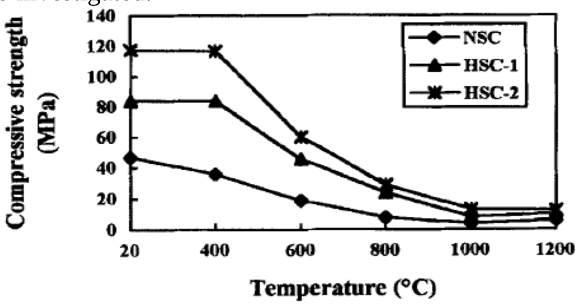

Fig.2. Compressive Strength of 3 Grades of Concrete

The authors casted 100 mm size cubes of three different grades of concrete named NSC, HSC-1, and HSC-2 respectively, using ordinary Portland cement (OPC), crushed granite of sizes 10 and 20 mm, sand and super plasticizer. These specimens were cured in water at 20°C for 28 days and then cured in an environmental chamber with a controlled temperature of 20°C and 75% R.H. At 90 days, three specimens from each batch were heated in an electric furnace. From the viewpoint of strength loss, the authors identified three temperature ranges: 20 to 400°C, 400 to 800°C and 800 to 1200°C. It was found that:-

- The mechanical strength of HSC decreased in a similar manner to that of NSC when subjected to high temperatures up to 1200°C.
- In the range 20-400°C, HSC by and large, unlike NSC, maintained its original strength but in the range 400-800°C, both HSC and NSC lost most of their original strength, especially at temperatures above 600°C.
- The range of 400-800°C within which the unavoidable dehydration of C-S-H gel in OPC paste occurs to a greater degree than within 20-400°C, might be regarded as the critical temperature range for the strength loss of concrete. Above 800°C, only a small portion of the original strength was left for both HSC and NSC.
- Like NSC, HSC lost its splitting tensile strength more sharply than its compressive strength at a temperature of 600°C.
- HSC suffered a marginally smaller loss of mechanical strength but a greater worsening of the permeability-related durability than NSC.

Phan Long T. et al. [13] performed experiments on high-strength concrete (HSC) and normal strength concrete (NSC) at elevated temperatures in order to study the phenomenon of explosive spalling associated with HSC & suggest further research needs. The differences were found to be most pronounced in the temperature range of 200°C to 400°C. A comparison of test results with code provisions on the effects of elevated temperatures on concrete strength showed that the CEN Eurocodes and the CEB provisions were non-conservative.

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Kodur V. K. R. [14] also reviewed the performance of HSC in fire & the associated spalling phenomenon. The increased use of high strength concrete (HSC) in buildings has raised concerns regarding the behavior of such concrete in fire. Spalling at elevated temperatures and the resulting reduction in fire resistance is of particular concern. In this paper, the various issues relating to spalling and its impact on fire resistance were discussed. The spalling phenomenon and its main causes in HSC were presented. This included the critical parameters that influenced spalling in HSC under fire conditions. Design solutions (cures) to minimize spalling in HSC structural members were presented.

Franssen Jean-Marc et al. [15] tried to assess the residual load bearing capacity of structures exposed to fire. In their paper, the application of computer program SAFIR for determining the residual load bearing capacity was illustrated through three case studies; a simply supported beam, a column and a restrained beam. The three elements were modeled in two configurations, steel and reinforced concrete, and were designed to have the same fire resistance ratings. The analysis was carried out in a scenario that included heating under natural fire, cooling down to ambient temperature and then loading to failure. Results from three cases showed that the load bearing capacity was hardly modified by the fire damage, in a simply supported beam, was increased by the effect of an axial restraint, especially in the concrete beam, and was reduced in column, especially in the concrete column.

The beginning of this century brought a slew of papers & publications about the "Performance based" approach as against the "Prescriptive approach" that had an uninterrupted reign for close to a century. Tubbs Beth [16], Sr. Staff Engineer at the world's leading consultancy firm ARUP, reviewed the structural fire protection provisions in the then about to be to be introduced ICC performance based code for buildings and facilities. The paper was intended to provide a background into the development of the ICC Performance Code for Buildings and highlighted how structural fire protection would be addressed within the document. Countries such as the United Kingdom, New Zealand, Australia and Japan had developed and were already using performance-based building codes at that juncture. The common structure of such codes was to provide a document that contained qualitative statements of intent and to also provide at least one set of prescriptive solutions.

Faller George [17] once again of Arup Fire, similarly advocated the performance based approach. His paper presented a performance-based method for calculating fire resistance requirements, based on the time equivalent concept. The t-equivalent calculation was a function of fire load, compartment linings and ventilation conditions. The fire resistance period was calculated and then adjusted to take account of the probability of occurrence of a fire, the consequences of structural failure and the effects of an automatic suppression system.

In steel construction it is often desirable for a steel member to pass through a concrete fire wall rather than being curtailed at the wall. In situations where a steel member penetrates a fire wall, the member will usually be fire protected for a certain length on each side of the wall so as to minimize the heat flow through the steel member and reduce the likelihood of ignition of combustibles on the non-fire (unexposed) side within the adjacent compartment. The testing reported in a paper by I. D. Bennetts and C. C. Goh [18] suggested that it was not necessary to apply fire protection to each side of a penetrating steel member since the resulting temperature rise of the member would be insufficient to cause ignition. The reason would be that although the steel member got heated intensely on the exposed side of the wall, this heat would be readily conducted to the unexposed side where it would be lost by radiation and convection to the surroundings. Some heat would also be conducted into the concrete wall. These mechanisms are illustrated in Fig below:

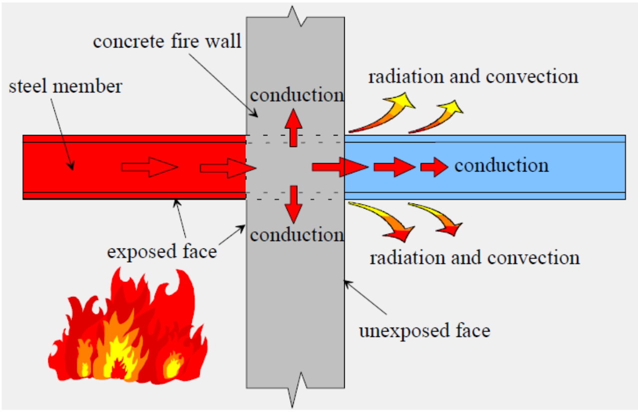

Fig.3. Mechanism of Heat Transfer

High-strength concrete is a material often used in the construction of high rise buildings. Ravindrarajah R. [19] et al. summarized and discussed the degradation of the strengths and stiffness of high-strength concrete in relation to the binder material type. The results showed that the binder material type had a significant influence on the performance of high-strength concrete particularly at temperatures below 800°C. The influence of the binder material type was significantly decreased at temperature of 1000ºC. The strengths and stiffness of high-strength concrete got reduced with an increase in temperature without any threshold temperature level.

As shown in the Fig. 4 & 5, the strength was found to be more susceptible to the elevated temperatures compared to stiffness of concrete. High-strength concrete containing silica fume seemed to be more sensitive to elevated temperature.

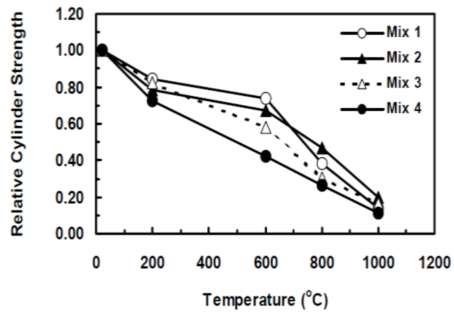

Fig.4. Residual Compressive Strength of Concrete

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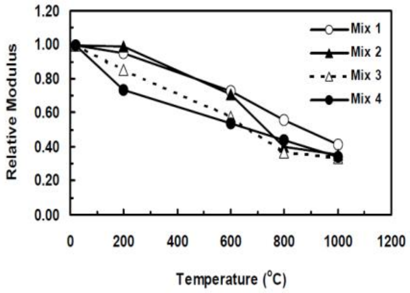

Fig.5. Residual Modulus of Elasticity of Concrete

Colin Bailey [20] presented an eyewitness account of the landmark Cardington Test conducted in September 2001, in which a three year old RCC building's structural behaviour was observed when subjected to full scale fire. The available results and observations presented provided a valuable insight into the holistic behaviour of concrete buildings, when subjected to fire. The tested building was constructed using elements formed from normal and high-strength concrete and was designed for 60 minutes fire resistance, using the UK design Code. High-strength concrete was used for the columns within the fire compartment and since this type of concrete had previously been shown to be susceptible to spalling; polypropylene fiber was added to the concrete mix during construction to alleviate the problem. It was decided that a realistic office fire would be obtained by providing ventilation to the compartment from full-height openings, creating a total area that was equivalent to 12% of the compartment floor area. The fire consisted of timber cribs creating a fire load to the tune of 40 kg/ m^2 (720 MJ/ m^2). The maximum atmosphere temperature that could be recorded during the test was 950°C.

Both the UK and European codified design methods suggested that concrete spalling within the fire compartment should have been nominal and could effectively be ignored during the design. However the test showed that spalling of the floor slab was extensive and exposed the bottom steel reinforcement. Although concrete spalling considerably reduced the flexural strength of the slab, collapse did not occur. This could be attributed to the slab behaving in compressive membrane action, which is currently not considered in codified design methods. Compressive membrane action can only occur at small displacements (typically displacements less than half the thickness of the slab) and can occur in flat slabs. At large displacements tensile membrane action occurs, but its effects are small in flat slabs where the only vertical support is at the columns. However, it should be noted that for tensile membrane action, the reinforcing bars support the load and therefore need to retain their strength during a fire, which can only be achieved if sufficient concrete cover to the bars is maintained.

The test also showed significant lateral displacement of external columns due to thermal expansion of the heated slab. All the columns (which were cast in high-strength concrete) behaved well in the fire with no signs of surface spalling. The main observations from the test showed that designers would need to understand the behaviour of entire structures in fire, to avoid any possibility of premature collapse.

Fig.6. Full scale Cardington Fire test

Chow W. K. [21] proposed a 15-point Fire Safety Ranking System EB-FSRS for Hong Kong to quantify how far the fire safety provisions in existing high-rise buildings deviated from the new codes. Suitable fire safety management could then be worked out in the transition period, based on the scores. Local fire codes were reviewed first to decide what should be the attributes and their weightings. From the reviewing results, three groups of attributes were proposed in the EB-FSRS namely the passive building construction, active fire protection systems (fire services installations), and key risk parameters, all following the local fire safety requirements. The concept was similar to those equivalent concepts on fire safety parameters of the National Fire Protection Association–Fire Safety Evaluation System (NFPA-FSES). But the EB-FSRS was not a ''trade-off'' exercise. Thirty-seven old high-rise buildings were rated by studying their architectural features, interior details, and fire safety provisions. Scores under EB-FSES and NFPA-FSES were also compared. In fact there is an urgent need to carry out similar exercise for all the Metros of India.

Kumar A & Kumar V [22], carried out a study to generate experimental data on residual strength of reinforced cement concrete (RCC) beams subjected to fire for long duration (exceeding prescriptive fire resistance). Six under-reinforced RCC beams were cast with similar cross-sectional details (200*300mm), length (3960mm) and grade of concrete (M:15), clear cover (25mm) & reinforcement. Four beams were exposed to fire for 1 h, 1.5 h, 2 h & 2.5 h duration. The authors have failed to mention the exposure temperature. Thereafter, five beams were load tested for flexural failure by applying a single central point load but the sixth beam, (i.e. beam exposed to fire for 2.5 h) failed in serviceability criterion for its residual deflection due to fire even before testing. Some spalling of concrete was observed in the beam exposed to fire for 2.5 h at the time of removal from furnace, which increased with time under normal weathering conditions. It was found that one hour exposure hardly affected the flexural strength of heated beam as compared to that of companion beam. But 2.5 hour exposure decimated the heated beam & its flexural strength nearly came down to nothing compared to that of companion beam. Reduction in stiffness increased with the increase in fire exposure duration.

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Spalling may be a violent effect to fire-exposed concrete destroying the entire cross-sections or reducing the load-bearing capacity of a construction substantially. Spalling must therefore be considered when designing a concrete construction for fire. From the discussion based on his research & experience, Hertz K. D. [23] in his paper concluded that structurally significant spalling could not be expected if the concrete was not densified by particles smaller than the cement grains such as micro silica and if the moisture content was less than 3% by weight. For moisture content between 3% and 4% the risk could be considered to be small. Most fire safety design is made for indoor constructions, which could be considered to have moisture content below 3–4wt% within half a year from casting. In an indoor construction made of traditional concrete, it would be reasonable to say that documentation for spalling resistance won't be needed. He also concluded that dense concrete had a spalling problem, which needed to be addressed before it could be applied where fire safety was of importance. Often, spalling occurred near the critical point of steam temperature at 374ºC.

Faris Ali et al. [24] undertook a study with an objective to investigate the performance of high and normal strength concrete columns under fire. The research focused on explosive spalling of concrete during fire .The paper included a useful comparison between the performance of high and normal strength concrete columns in fire. The authors concluded that,

- Normal and high-strength concrete columns showed similar susceptibility to explosive spalling under loading only (without restraint).
- Normal strength concrete columns showed higher spalling degrees when tested under restraint.
- In all of the tests conducted, explosive spalling occurred during the first 45 min of the heating. Always minor spalling took place first followed by major and severe spalling.
- A thorough and careful analysis of the test results suggested that the crucial factor in causing explosive spalling of concrete is the random distribution of voids inside the concrete mass.
- The paper illustrated a method of preventing explosive spalling using polypropylene fibres in the concrete. Using polypropylene fibers in the concrete (3 kg/m3) reduced the degree of spalling from 22% to less than 1%.

Fu-Ping *et.al* [25] investigated the stress strain relationship of high strength concrete at high temperature. The temperature range selected for the study was ranging from 20˚C to 800˚C for four different types of high strength concretes. During the course of experimentation, the researchers studied the varying temperature, normalized compressive strength, normalized elastic modulus, stress ratio for different temperatures and concluded that, HSC lost a significant amount of its compressive strength above 400°C and attained a strength loss of about 75% at 800°C. The change of strength in the temperature range of 100– 400°C was marginal. Addition of steel fibers improved the ductility at elevated temperature but had little influence on the variation of modulus of elasticity with temperature. Finally it was concluded that increase in strain in carbonate aggregate was larger than that for siliceous aggregate in high strength concrete.

Manley Bonnie E. [26] through his paper explored how the C3 code set, accredited by the American National Standards Institute (ANSI), dealt with the issues surrounding the rehabilitation of existing buildings in relation to fire safety. If one considers that in any given year, only 2% buildings could be considered "New", the importance of rehabilitation of existing buildings becomes clear.

Shi Xudong; Tan Teng-Hooi et al. [27] conducted a well-funded, meticulously conducted experiment involving sophisticated equipment to assess the effect of bottom cover on fire resistance of beams. Six specimens with different concrete cover (CC) thickness (10–30 mm) were tested to investigate the influence of CC on the properties of reinforced concrete flexural members exposed to fire. The specimens were heated on their bottom and two lateral surfaces.

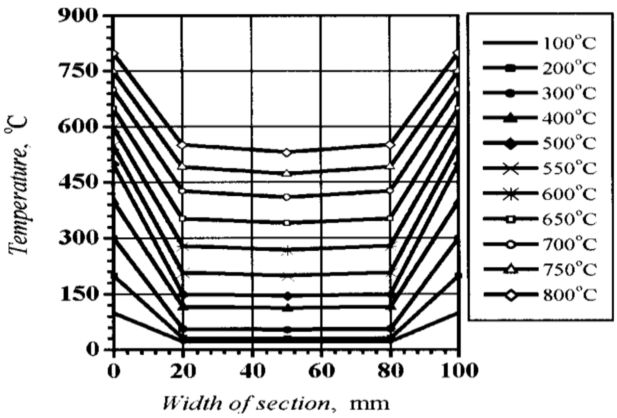

Fig.7. Temperature Distributions across Section Width at 75 mm from Specimen Soffit

It was seen that the mid-section experienced roughly uniform temperature (from 20 to 80 mm from the specimen lateral surfaces) and this was true for any section depth (Fig. 7). Nearer to the lateral surface, there were temperature gradients that varied with the section depth. The further the position was from the specimen soffit, greater the temperature gradients were near the lateral surface. Temperature gradients near the specimen soffit for any furnace temperature were the smallest because heat was transferred upwards by conduction from the heated soffit. Clearly, the temperature at the specimen top surface depended mainly on thermal conduction from the two heated lateral surfaces; they were nearly independent of the temperature distribution near the specimen soffit. Therefore, it could be deduced that the temperature distribution at the top zone was similar for all specimens no matter how much the bottom CC thickness was, or whether the specimen was loaded first before heating. From these test results, it was shown that the bottom CC had significant influence on the specimen ultimate loading capacity during fire, but the extent of this influence would decrease with an increase in the CC thickness. Thus, it would be improper to excessively increase the bottom CC thickness to improve the specimen fire resistance.

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The loaded flexural member would develop micro cracks at its soffit. The width & depth of these cracks would increase with an increased CC, leading to faster heat transfer, resulting in reduced advantage. A concept of the equivalent CC thickness was proposed in this paper to better predict the effect of the CC on the flexural capacity of reinforced concrete members exposed to fire.

To assess and develop information on the fire endurance of fiber-reinforced polymer (FRP) reinforced concrete structural members, a numerical model was applied by V. K. R. Kodur and L. A. Bisby [28] to the analysis of FRP-reinforced concrete slabs. The computer program was validated against data obtained from fire endurance tests on concrete slabs reinforced with steel or FRP bars. Parametric studies were carried out to investigate the effect of a range of parameters on the fire performance of FRP-reinforced concrete slabs. Results of the parametric studies showed that FRP-reinforced concrete slabs had lower fire resistance than slabs reinforced with conventional reinforcing steel. In this context the main factors that influenced the fire resistance of FRP-reinforced concrete slabs were: the concrete cover thickness, type of reinforcement, and the type of aggregate in the concrete rather than slab thickness. A higher fire resistance for FRP-reinforced concrete slabs could be obtained through greater concrete cover thickness and through the use of carbonate aggregate concrete. Based on the parametric studies, a series of simple design charts was presented that could be used to evaluate the fire endurance of FRP-reinforced concrete slabs.

Concrete is a poor conductor of heat, but can suffer considerable damage when exposed to fire. Unraveling the heating history of concrete is important to forensic research or to determine whether a fire-exposed concrete structure and its components are still structurally sound. Assessment of fire-damage concrete structures usually starts with visual observation of color change, cracking and spalling. On heating, a change in color from normal to pink is often observed and this is useful since it coincides with the onset of significant loss of concrete strength. This paper by B. Georgali et al. [29] presents results of cores strength, as well as, optical microscopy investigations of fire-damaged concrete. Samples were taken from concrete of a 15 year old building that had been exposed to fire.

The ten test specimens examined were concrete cores from the first floor of the fire affected building which had been exposed to fire on 5th February 2000. Macroscopic observation showed significant parallel cracking toward to the core axis, a fact that indicated large scale internal cracking because of internal shrinkage, which was caused by overheating followed by rapid cooling (due to fire-extinguishing). Spalling and pop-outs were confined near surface exposed to fire, an indicator of heating at 575ºC. Deeper cracking beyond the depth of the reinforcement indicated that temperature had exceeded 790ºC. Taking into account that the color of the surface exposed to fire had been changed to gray surface, temperature was believed to exceed 800ºC. The results of compressive test showed that the concrete's residual compressive strengths were very low at just @ 30%. This fact indicated that the temperature exposure exceeded 700ºC. Michael L. Tholen *et al.* [30] in their paper gave a brief introduction to the basics of fire terminology including the three limit states enlisted in ASTM E119 & went on to explain a simplistic approach to passive fire design. Based on the age old prescriptive approach, the paper provides the simplest possible guidelines to incorporate fire resisting design features.

The research conducted by Huang Z. *et al.* [31] highlighted the interaction between the cool & hot areas of a burning structure. It became clear that the adjacent cool compartments provided considerable restraint & continuity increasing the fire resistance of portion within the fire compartment. During the first 30 minutes of the fire, tensile forces within the beam increased dramatically, to about 3 times the ambient temperature value. Concrete being weak in tension, the tensile forces were predominantly carried by reinforcing bars. Hence possibility of tensile failure of beam reinforcement in the initial stages of fire could be high, depending on the type of fire & member cross-sectional dimensions.

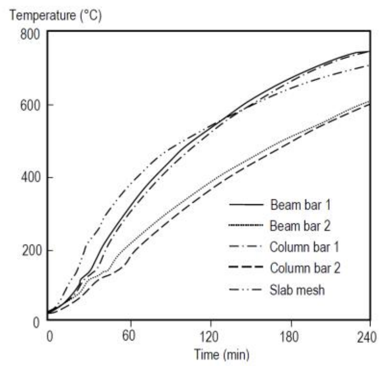

Fig.8. Predicted Temperatures of Main Reinforcement

In Fig. 8 above, the temperature histories of the main reinforcing steel bars in the beam & column sections & the mesh in the slab are shown. The maximum temperatures of reinforcement at 120 minutes & 180 minutes were about 530ºC & 660ºC respectively. In beams or columns, corner bars got heated more than the interior ones. It was obvious that the concrete cover provided very good thermal insulation to reinforcement during fire. This thermal analysis of course assumed no spalling. Finally the authors concluded that the cover to the reinforcement specified in the current design codes looked reasonable provided no spalling took place during fire. Designers should therefore pay attention to prevent concrete spalling.

B. Stawiski [32] made an attempt to study the effect of fire on various building components at different intensities of temperature varying from 100ºc to 600ºc. Non-destructive tests performed by the researchers to carry out strength determination of column and slab were Schmidt Sclerometer and Ultra Sonic probe with std. 40 KHz. At the location of testing, plaster was removed, the humidity of the concrete was determined and sclerometric and ultrasound measurements were carried out and calibration curves were developed for both the tests. From the data, it was observed that in the plot of column data, results showed a large amount of scatter because of varying humidity of concrete.

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The two methods employed consistently indicate that the column upper parts were much weaker than their lower counterparts as during fire the temperature is higher under the ceiling than near the floor. High fire temperature is the cause of larger deformations, stresses, thermal cracks, warping etc. Author also quoted that at temperature of 600°c & above, the drop in strength of steel was to the tune of 50% and more & permanent strength reduction occurred only at temperatures higher than 600°c (for steel). On his study on reinforced concrete, the influence of temperature should be considered separately for steel and concrete. It was observed that as temperature & time of its influence increased the utility of concrete & reinforced concrete decreased. The bond between concrete and steel (mild & ribbed) did not decrease up to a threshold temperature of 300°c.

Richard Barnes and James Fidell [33] conducted a series of tests in which 24 reinforced concrete beams were cast. They were divided into eight sets of three each. The sets were split into fire tested and control. In the control group were an non-strengthened control set, a set strengthened with bonded carbon FRP _CFRP_ plates, and a set with bonded CFRP plates with bolted anchorages. In the fire-tested group were an non-strengthened control set, a set strengthened with bonded CFRP plates, a set with bonded CFRP plates with bolted anchorages, a set strengthened with bonded CFRP plates and a cementitous fire protection system, and a set with bonded CFRP plates with bolted anchorages and a cementitous fire protection system. The unloaded beams were then subjected to a cellulosic fire in a furnace.

The following conclusions were drawn from the above research:

- The bonding (or bonding and bolting) of CFRP plates to the soffit of reinforced concrete beams led to a significant increase in stiffness and strength.
- Beams with CFRP plates bonded to them performed no better than the control beams once they had undergone exposure to a cellulosic fire test. The level of fire protection used was not sufficient to affect this.
- Beams where the CFRP plate had been bonded and bolted and protected with fire protection were stiffer than those beams without fire protection and one beam had a higher failure load.
- The adhesive used to bond the CFRP plates lost its strength when exposed to a cellulosic fire test, even when protected with fire protection (at temperature of 140°C).
- The bolts provided were not sufficient to effectively transfer the stress from the beam to the CFRP plate once the adhesive had been destroyed.
- The resin component of the CFRP plate withstood temperatures up to 310°C but was destroyed in the cellulosic fire test when unprotected. The carbon component of the CFRP plate appeared undamaged at temperatures of up to 950°C. The CFRP looked like a spider's web as it fell away from the beams.

To sum up, sufficient fire protection needed to be given to the CFRP strengthening system such that the adhesive would not lose its strength, through sufficiently thick SFRMs (Spray Applied Fire Resistive Materials). Strength and durability are two key factors influencing the safety and service life of fire-damaged concrete structures. To develop an assessment method for fire-damaged high-strength concrete structures that is convenient for post-fire repair, the effects of concrete strength and aggregate type on the post-fire residual compressive strength of HSC were studied in a paper by Xin Yan et al. [34]. Subsequently, the changes in durability and microstructures were investigated by the rapid chloride-ion penetrability test, the mercury intrusion porosimetry test, and scanning electron microscopy observation, respectively (Fig. 9).

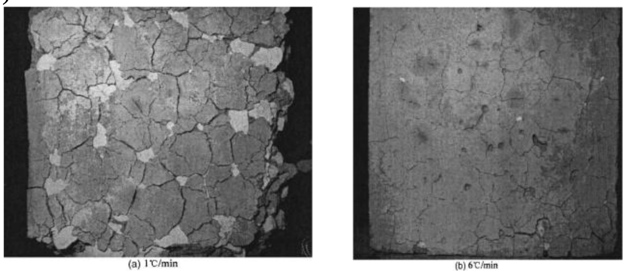

Fig.9. Cube Heated at Slower Rate (left) & Faster Rate (Right)

Based on the test results and further analysis, estimation of the temperature distribution in the fire-damaged concrete element was established by the dichotomy and mercury intrusion porosimetry test and scanning electron microscopy observation. According to the estimated temperature distribution, the post-fire residual compressive strength could be assessed by the strip method and post-fire durability could be assessed by the "two-level" method, respectively. Based on the assessments, the repair method for fire-damaged HSC structures was recommended in steps. The repair depth and fresh concrete strength would be determined according to the principle that they not only met the needs for strength and durability of the fire-damaged concrete element, but also had an optimally economic benefit. An article by Ufuk Dilek [35] summarizes an engineering evaluation of the extent of fire damage to a concrete structure under construction. The fire occurred in a portion of the reinforced concrete structure and visibly damaged a load bearing exterior foundation wall (Fig. 10). The purpose of the assessment was to promptly evaluate the in situ condition of the wall and recommend necessary repair or replacement options prior to commencement of backfilling and the concrete construction to be supported by the subject wall.

Fig.10. Spalling of Concrete Wall after The Fire

The engineering assessment of the damaged wall included a nondestructive evaluation phase consisting of ultrasonic pulse velocity testing and a laboratory testing phase on the concrete cores removed from the damaged wall.

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Dynamic Young's modulus of elasticity and an air permeability index of 25 mm thick disks sawed from the cores were determined. Analysis of properties of 25 mm (1 in.) concrete specimens permitted assessment of the presence and degree of any damage in smaller depth increments compared to the size of a compressive strength core. Significant differences were not indicated by compressive strength of cores; however, the in situ nondestructive testing and laboratory testing of the disks were effective in determining the depth of damage, as a result of the fire. The results of the nondestructive and laboratory evaluation indicated that the distressed zone of the concrete was limited to a near-surface layer of just about 25mm. Repair recommendations were based on removal and replacement of the affected concrete sections identified by the testing program.

Fletcher Ian A. et al. [36] provided a 'state of the art' review of research into the effects of high temperature on concrete and concrete structures, extending to a range of forms of construction, including novel developments. The nature of concrete-based structures means that they generally perform very well in fire. However, concrete is fundamentally a complex material and its properties can change dramatically when exposed to high temperatures. The principal effects of fire on concrete are loss of compressive strength, and spalling – the forcible ejection of material from the surface of a member. Though a lot of information has been gathered on both phenomena, there remains a need for more systematic studies of the effects of thermal exposures. The response to realistic fires of whole concrete structures presents yet greater challenges due to the interactions of structural elements, the impact of complex small-scale phenomena at full scale, and the spatial and temporal variations in exposures, including the cooling phase of the fire. Progress has been made on modelling the thermo-mechanical behaviour but the treatment of detailed behaviours, including hygral effects and spalling, remains a challenge. Furthermore, there is still a severe lack of data from real structures for validation, though some valuable insights may also be gained from study of the performance of concrete structures in real fires. The paper also laid emphasis on the potential significance of cooling on concrete performance. It is not currently known, in the majority of cases, how much spalling exhibited in a real building fire takes place as a result of cooling rather than heating.

The study paper was a useful summary of the studies related to fire & concrete but had a striking resemblance with an article published by Tholen Michael L. et al. [30] in Concrete International, a journal published from USA.

Deterioration of mechanical properties like yield strength and modulus of elasticity is considered as the primary element affecting the performance of steel structures under fire. In this study by Ilker Bekir Topcu and Cenk Karakurt [37], hot-rolled S220 and S420 reinforcement steel rebars were subjected to high temperatures to investigate the post-fire performance of these materials. It was aimed to determine the remaining mechanical properties of steel rebars after fire like situations. Steels were subjected to 20, 100, 200, 300, 500, 800, and 950◦C temperatures for 3 hours and tensile tests were carried out. Effect of temperature on mechanical behavior of S220 and S420 were determined. All mechanical properties were reduced due to the temperature increase of the steel rebars. It was seen that mechanical properties of S420 steel was influenced more than S220 steel at elevated temperatures.

Bilow David N. et al. [38] provided structural engineers with a summary of the complex behavior of structures in fire and the simplified techniques being used successfully for many years to design concrete structures to resist the effects of severe fires. After the 9-11 attack on the World Trade Center, interest in the design of structures for fire greatly increased. Some engineers promoted the use of advanced analytical models to determine fire growth within a compartment and used finite element models of structural components to determine temperatures within a component by heat transfer analysis. Following the calculation of temperatures, the mechanical properties at various times during the period of the fire could be determined. This type of analysis would be very complex and expensive and therefore was not suitable for general structural design.

As per the authors, although testing according to ASTM E 119 was probably the most reliable method, the time and expense required to build and test the assemblies made this method impractical and would actually be unnecessary for most situations. The methods contained in ACI 216.1 were based on fire research performed from 1958 through 2005 and were by far the most commonly used in typical design situations. In this method, the fire resistance (based on the heat transmission end point) of a concrete member or assembly was found by calculating the equivalent thickness for the assembly and then finding the corresponding rating in the charts and tables provided.

The paper by Colin Gurley [39] focused on the findings/recommendations/implications of the NIST (2005) "Final report on the collapse of the World Trade Center towers" that related, particularly, to structural design practice for tall buildings as follows:

- A new role for, perhaps, a new breed of "fire engineer" as members of building project design teams alongside other disciplines: architects/structural engineers/HVAC engineers/ hydraulic engineers/electrical engineers;
- A wider role for structural engineers working with fire engineers to carry out structural analysis during fire so as to ensure burnout without progressive collapse even if a column is lost and sprinklers fail;
- More research on SFRMs (Spray Applied Fire Resistive Materials) and better quality control during and after construction "over the life of the building"; and
- The merits/demerits of nonstructural gypsum core walls as opposed to load-bearing concrete cores.

Kodur V. K. R. teamed up with M. B. Dwaikat [40] to investigate the effect of fire induced spalling on the response of reinforced concrete (RC) beams by applying a macroscopic finite element model. Spalling was accounted for in the model through pore pressure calculations in concrete.

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The principles of mechanics and thermodynamics were applied to compute the temperature induced pore pressure in the concrete structures as a function of fire exposure time. The computed pore pressure was checked against the temperature dependent tensile strength of concrete to determine the extent of spalling. Using the model, case studies were conducted to investigate the influence of concrete permeability, fire scenario and axial restraint on the fire induced spalling and also on the response of RC beams. Results from the analysis indicated that the fire induced spalling, fire scenario, and axial restraint had significant influence on the fire response of RC beams. It was also shown that concrete permeability had substantial effect on the fire induced spalling and thus on the fire response of concrete beams. The fire resistance of HSC beams, with very low permeability, could be reduced by more than 50% due to fire induced spalling in concrete. The fire resistance of axially restrained beams would generally be higher than that of simply supported beams.

Javadian Alireza *et al.* [41] reported the effect of temperature on the flexural tensile strength of plain and steel fibre reinforced concrete. Tensile strength of concrete is one of the primary factors affecting the vulnerability to spalling but information on tensile strength at elevated temperature is limited owing to the difficulty in performing the test. The paper described a study on tensile strength of high strength concrete, with or without steel fibres, at elevated temperatures, using beam specimens made from concrete with compressive strength of 50 MPa (NSC) and 100 MPa (HSC).

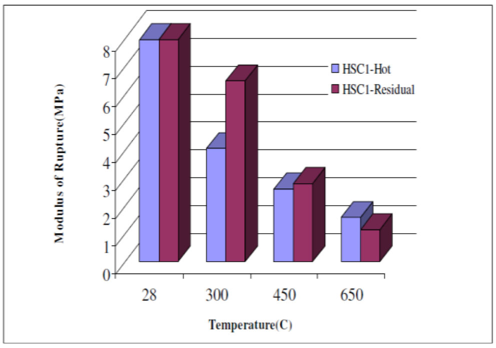

Fig.11. Comparison between the Hot and Residual Flexural Strength for HSC1

To ensure uniform temperature, the specimens were heated first in an electric furnace for a sufficient period to reach an equilibrium state. The test temperatures were 300ºC, 450ºC and 650ºC. The residual strengths of the specimens upon cooling to room temperature were also determined. It was found that the "hot" test results and the "residual" ones were not the same. The residual results (after cooling at room temperature) were found to be slightly higher (Fig.11). This was unlike what had been assumed by many researchers. Both residual and hot flexural strength of high strength concrete with steel fibres were higher than the corresponding values for HSC without fibres.

A new class of materials referred to as high performance materials (e.g., fiber-reinforced polymers (FRP), high strength concrete (HSC), are being increasingly used in urban infrastructure projects. Many of these materials have poor or unknown fire characteristics and addressing the fire safety of these materials and their integration into structural systems are critical for ensuring the safety of the built infrastructure. Kodur V. K. R. [42] in his essay explained the different conditions and complexities associated with characterizing fire hazards in built-infrastructure. The fire resistance problems, and research needs, for emerging high performing materials were outlined. Design strategies for integrating fire safety design with structural design; through a performance based methodology was outlined. Four limit states were outlined for evaluating failure namely: (i) Heat transmission leading to unacceptable rise of temperature on the unexposed surface; (ii) Breach of barrier due to cracking or loss of integrity; (iii) Loss of load-bearing capacity & (iv) Excessive deflection. Construction guidelines for enhancing the fire performance of structures constructed with high performing materials were presented through case studies. For RCC members, addition of 0.15% polypropylene fibres to control spalling was suggested. In case of RCC columns use of lateral ties bent at 135º at corners (in place of the conventional 90º), resulting in better confinement was suggested to control spalling. The paper by Prabir Kumar Chaulia & Reeta Das [43] presented the results of an experimental investigation carried out to optimize the mix proportions of fly ash bricks by Taguchi method of parameter design. The experiments were designed using an L9 orthogonal array with four factors and three levels each. Small quantity of cement was mixed as binding material with fly ash. Water binder ratio was considered as one of the control factors. So the effects of water/binder ratio, fly ash, coarse sand, and stone dust on the performance characteristic were analyzed using signal–to–noise ratios and mean response data. According to the results, water/binder ratio and stone dust played the significant role on the compressive strength of the brick. Furthermore, the estimated optimum values of the process parameters were corresponding to water/binder ratio of 0.4, fly ash of 39%, coarse sand of 24%, and stone dust of 30%. The mean value of optimal strength was predicted as 166.22 kg/cm^2 with a tolerance of ± 10.97 kg/cm^2. Confirmatory experimental result obtained for the optimum conditions was 160.17 kg/cm^2.

Kodur V.K.R. et al. [44] presented an empirical equation for evaluating the fire resistance of reinforced concrete (RC) columns. Data from a large set of experimental studies were analyzed to study the influence of various parameters on the fire resistance of RC columns. The fire test data were utilized to develop a simplified equation for expressing the fire resistance of RC columns as a function of influencing parameters. The validity of the equation was established by comparing the predictions from the empirical equation with data obtained from fire resistance experiments and analytical studies. Predictions from the proposed equation were in good agreement with the test results and computer models, and provided better estimates of fire resistance than those predicted from the prevailing codes of practice. Furthermore, the proposed equation expressed the fire resistance in terms of conventional structural and material design parameters, and thus facilitated easy calculation of fire resistance.

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A Ferhat Bingol et al. [45] investigated the residual bond stress between steel bars and concrete after fire/fire like situations. In this study the effect of elevated temperatures and cooling regimes on the residual bond stress between concrete and steel bars was investigated. Material used for the experimentation was 8mm diameter ribbed steel bars and concrete blocks of grade M: 20 and M: 35 with embedded lengths of 6, 10 and 12 cm. Heating was done at 12 different temperatures ranging from 50 °C to 700 °C. Heated samples were cooled in water and air.

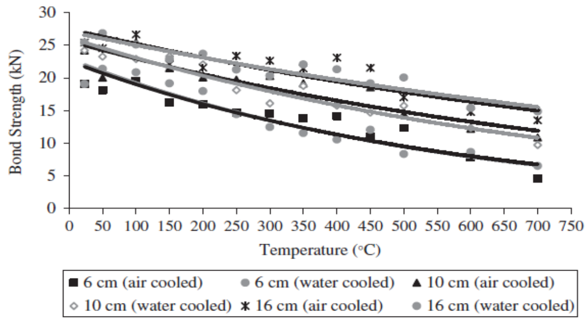

Fig.12. Bond Strengths Between Concrete & Steel Bars

Pull out test was carried out on the specimens and the effect of elevated temperatures on the residual bond strength was investigated by comparing the results against unheated specimen. Based on laboratory observations and results, authors concluded that the bond strength exhibited continuous drop at higher temperatures (Fig. 12). The effect of the cooling regime was less pronounced for the bond strength.

The objective of a paper by Ahmed Chérif Megri [46] is to provide a discussion on the integration of safety and fire protection and several MEP systems into buildings in an effort to achieve the most efficient, economical, and environment friendly design & planning. A building constitutes an integrated collection of systems that together provide a controlled environment for its occupants. As such, in addition to the frames and foundations, such components as fire protection, mechanical, electrical, and plumbing (MEP) engineered subsystems are also a vital part of any building. Considering the variety of subsystems that make up of a building, an overall design and construction process would then require a proper planning for integration of these various subsystems into the building. Furthermore, system integration has also long been recognized as the key to an effective and efficient building operation. The integration process of a fire protection subsystem, along with MEP subsystems, within a building is quite challenging indeed and can have a profound impact on client satisfaction.

Three factors affect the fire protection and MEP systems installed on any building. These are (1) building codes that are basically concerned with safety; (2) budget and customer preferences; and (3) current existing technology. These three factors dictate the nature and function of the fire protection as well as MEP systems installed. Usually, the MEP costs can be from 30 to 35% of the entire project cost, and for hospitals and laboratories can be about 40% or even more of the total cost. In other words, MEP coordination is very important to maintain the allotted budget. All designers agree that the most important parts of any code are the life safety and fire protection requirements. Life safety systems are items such as means of egress, emergency exits, fire alarms, emergency lighting, and handicapped accesses.

The International Building Code categorizes the construction into five types. Type I (fire resistive) is the least combustible and Type V (wood frame) is the most combustible. Type II (noncombustible), Type III (ordinary), and Type IV (heavy timber) are intermediate types. The fire ratings of walls/ceilings/floors are mainly dictated by the International Building Code, 2006.

Active fire protection systems, such as water sprinkler and standpipe, are widely used to protect commercial buildings, residential buildings, and warehouses. Fire protection systems have many functions, including extinguishing the fire, controlling the fire, or providing exposure protection to prevent a chain reaction. Depending on the situation, CO2 or foam may be a more appropriate method than sprinklers. Every space has to be protected by fire extinguishers.

Passive fire protection can provide an effective alternative to active systems. This generally consists of a coating of fire resistant insulating media applied to a steel surface. Fire walls are an important form of passive fire protection used to prevent the spread of fire and the exposure of adjacent equipment to thermal radiation. Having passive protection in place helps reassure building occupants that there will be time to exit before gases, fire, and smoke spread throughout the building. If active systems fail, the passive system is still reliably in place for life safety. After more than 2 years of investigation surrounding the February 2003 Station Nightclub fire in West Warwick, R.I., the National Institute of Standards and Technology investigation fire report contends: “Model codes and standards should require redundancy in passive and active fire protection systems to ensure adequate performance of the structure when one or more of the protective systems is compromised by uncertain behaviors of the building owner or occupants (for example, disabling sprinklers for maintenance).” Performance-based designs (PBD) are alternate methods for satisfying the fire protection and life safety intent of codes and standards applicable to the project. The practice of PBD requires that any proposed solution provides a level of safety and dependability that is equivalent to that anticipated if the prescriptive solutions were followed. *PBD is rarely simple, and never easy, particularly given the diversity of viewpoints arising from the involved stakeholders. The practice of PBD requires skilled individuals with a thorough understanding of fire protection principles. For this reason the application, evaluation, installation, and acceptance of PBD alternatives should be accomplished only by qualified professionals.*

The paper by Masoud Ghandehari et al. [47] presents the results of a study on the effect of high temperatures on the mechanical properties of high-strength concrete. Mixtures were prepared with water to cementitious material ratios of 0.40, 0.35, and 0.30 containing silica fume (SF) at 0, 6, and 10% cement replacement. After heating to 100, 200, 300, and 600°C, the compressive strength, the splitting tensile strength, and the corresponding ultrasonic pulse velocity were measured (Fig. 13).

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Substantial loss of strength was observed for all compositions at 600°C, particularly the silica fume concretes in spite of the superior mechanical properties provided by silica fume at room temperature. The average residual compressive and splitting tensile strengths of the concretes at 600°C were 30 and 25% of the room-temperature strengths, respectively. It was found that the rate of the splitting tensile strength loss was higher than the rate of the compressive strength loss at elevated temperatures and that the ultrasonic pulse velocity measurements slightly underestimated the residual strength of the high strength concretes after exposure to temperature over 200°C. Based on the experiments, the 300–600°C temperature range was found more critical for concretes having higher strength. This is due to their reduced porosity and denser microstructure. The strength loss at 600°C was higher for HSC vis-à-vis the same reported for NSC elsewhere.

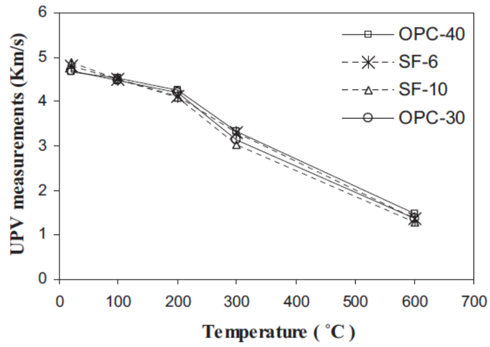

Fig.13. UPV Measurements at Different Temperatures

Gross John et al. [48] published a summary of the Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings. The document integrated state-of-the-art information into a single source document to enable the use of the performance-based approach for fire resistance design, and to provide engineers and code enforcement officials with a technical resource for use in their approach to fire resistance design and evaluation of concrete and steel structures.

Zhaohui Huang [49] in his paper presented a robust model based on the previous "layer procedure" developed by him to also take into account the effects of concrete spalling on the behaviour of concrete slabs under fire conditions. In this study, a detailed analysis of a uniformly loaded reinforced concrete slab subjected to different degrees of concrete spalling under a standard fire regime was first carried out. Further, a series of analysis of floor slabs with different degrees of concrete spalling was also performed on a generic reinforced concrete building. A total of 16 cases were analyzed using different degrees of spalling on the slabs, with different extents and positions of localized fire compartments. It was clear that adjacent cool structures provided considerable thermal restraint to the floor slabs within the fire compartment. And it was evident that the compressive membrane force within the slabs was a major player in reducing the impact of concrete spalling on the structural behaviour of floor slabs in fire. Therefore, concrete spalling has very little influence on the fire resistance of concrete floor slabs in the central fire compartment of the building due to the high thermal restraint provided by surrounding cool structures. However, concrete spalling can significantly reduce the fire resistance of the floor slabs in the corner bay of the buildings because there is very little thermal restraint in those compartments.

In an identical approach to his [44] work, Kodur V.K.R. et al. [50] presented an empirical equation for evaluating the fire resistance of reinforced concrete (RC) beams as well.

Kulkarni D. B. et al. [51] assessed the effect of sustained temperatures on mechanical properties of self-compacting concrete and its comparison with conventional concrete. In order to study the effect of elevated temperature on the compressive strength, flexural strength, tensile strength & impact strength of concrete, 21 cubes (Size 150 mm), 21 cylinders (100mm dia x 200mm height), 21 beams (100mm x100mm x500mm) and 21 plates (250mm x 250mm x 35mm) were cast in both SCC & ordinary concrete, having same grade & w/c ratio. The specimens were cured in a curing tank for 28 days, air dried for a day & then placed in an oven & heated for five hours at different temperatures (28ºC, 100ºC, 200ºC, 300ºC, 400ºC, 500ºC and 600ºC). Results revealed sustained loss of strength on all counts with rising temperature but the self-compacting concrete was always found to be the bigger loser especially beyond 500ºC.

Kodur V.K.R. has done monumental work on effect of fire on structural elements. Results from fire resistance experiments on six RC columns were presented by him in a paper co-authored with Raut N. K. [52]. The test variables included concrete strength, fire scenario, load ratio and the presence of polypropylene fibers in concrete mix. Data from these fire tests were used to validate a macroscopic finite element model specifically developed for tracing the fire response of RC columns. Results from fire tests and numerical studies were used to illustrate the comparative performance of HSC and normal-strength concrete (NSC) columns under design fire conditions.

In Fig. 14, NSC means Normal Strength Concrete, HSC means High Strength Concrete & HSCP means High Strength Concrete with Polypropylene fibres. Results from fire experiments revealed that HSC columns exhibited lower fire resistance than that of NSC columns. However both HSC and NSC columns did not experience failure under most design fire scenarios. The addition of polypropylene fibers to concrete mitigated fire-induced spalling and enhanced fire resistance of HSC columns.

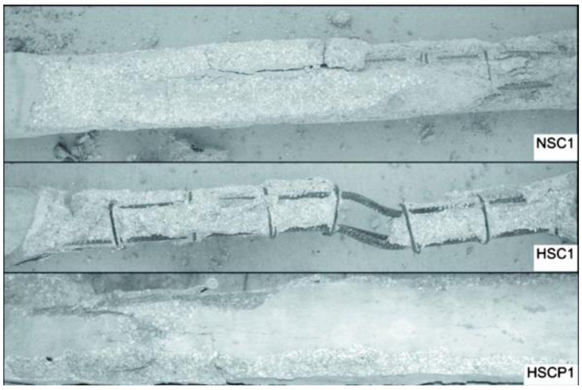

Fig.14. Fire-Induced Spalling NSC1, HSC1, and HSCP1

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Peskava S and Prochazka P.P. [53] demonstrated an extensive research on FRC by using different combinations and the resulting behavior at high temperature. A large scale experiment had been carried out which served a possible improvement of formulation of material properties and comparison of results obtained. Samples used for testing purpose with dimensions 70×70×70 mm, were heated from 150˚C to 1000˚C. Tests were performed in two stages; in the first part measurement of distribution of temperature from thermal source was carried out and in second part complete mechanical test was performed. The above study showed the highest temperature enabled the largest displacement before failure and this happened because of high porosity in the material exposed to high temperature. The fire resistance was influenced by various combinations of fibers and their volume ratios. The authors also subscribed to the idea of more testing before drawing a definite conclusion over the benefits of using fibres in concrete exposed to high temperatures. The flexural behavior of fiber-reinforced polymer (FRP)–strengthened beams after exposure to elevated temperatures in an electrical furnace was investigated by Kiang Hwee Tan and Yuqian Zhou [54]. Externally bonded fiber-reinforced polymer (FRP) systems have been widely used for the strengthening and rehabilitation of reinforced concrete structures since the mid-1990s. They offer advantages over traditional techniques such as steel plate bonding and concrete jacketing because of the low unit weight and non-corrosive nature of the FRP material. However, externally bonded FRP systems also possess some disadvantages such as a relatively high cost. Another major obstacle that hinders them from becoming more widely used is their poor performance under elevated temperatures. Twenty-five specimens making up non-strengthened beams and FRP-strengthened beams were fabricated. Glass and basalt FRP systems were used with and without protective systems, which included a cement mortar overlay and two types of commercially available intumescent coatings. Typical temperature-time histories at the surface of FRP laminates, FRP-concrete interface, internal steel bars, and center of beams were monitored by using two specimens. The other specimens were tested to failure under three-point bending after subjecting them to elevated temperatures. Test results indicated a general decrease in the initial stiffness and ultimate strength of the specimens with an increase in the exposed temperature. The protective systems appeared to preserve the structural integrity of glass FRP systems when the elevated temperature was less than approximately 700°C. Basalt FRP-strengthened beams exhibited smaller deterioration in ultimate strength than glass FRP-strengthened beams.

M. Kanéma, P. Pliya et al [55] in their research had performed the experiment on five concrete mixes subjected to high temperatures with the aim of highlighting explosive spalling. After 28 days of curing, the specimens were subjected to heating-cooling cycles from room temperature to 150, 300, 450, or 600°C. Heating rates were 0.1 and 1°C/min, a fixed exposure time of one hour at the maximum temperature and free cooling were imposed. The authors aimed at investigating the effect of different heating rates and specimen sizes on the thermal stability of ordinary and high-strength concretes.

Five concrete mixtures were designed, keeping constant the absolute volume of aggregates and the absolute volume of the paste. The water to cement ratio (w/c) varied from 0.62 (for B325) to 0.29 (for B500), and the appropriate amount of super plasticizer varied to keep the workability constant. The cement used was CEM I 52.5 N CP2 Portland cement, the aggregates were alluvial gravels composed of silica (70–75%), calcareous (20–25%) and Feldspars (5%). The super plasticizer used was a high water reducer containing modified polycarboxylate. For every heating-cooling cycle, the weight loss of the cylindrical specimens (0.110×0.220 m or 0.160×0.320m) was obtained by a load cell connected to the computer. The specimen mass was recorded every three min during the heating-cooling cycle. It was observed that:-

- The evolution of the temperature difference (i.e., the thermal gradient) between the surface and the center of the specimen was a function of the cementing matrix, the specimen size, and the heating rate.
- For the same concrete mixture and the same heating rate, the thermal gradient in small specimens (i.e. 0.110×0.220 m) was similar to that of large specimens (i.e. 0.160×0.320 m), although spalling took place only in large specimens.
- The thermal gradient in the ordinary strength concrete specimens was higher than that in the high-strength concrete, although the proportion of spalled specimens was greater for high-strength concrete.
- The factors leading to the explosive spalling of the concrete were studied and identified as (1) low permeability, (2) weak water departure from the concrete, and (3) an increase of the thermal gradient.

In a study by M. Bastami et al. [56], the effect of temperature on compressive strength, spalling and mass loss of High Strength Concretes (HSCs) (fc > 65 MPa) was discussed. Average compressive strength of the HSCs was from 65 to 93 MPa, which was optimized by Taguchi's method as a powerful tool for optimizing the performance characteristic of a product/process. This paper presented results of an experimental program on the effects of elevated temperature exposure on the mechanical properties and potential for explosive spalling of HSCs. Effects of four parameters; water to cement ratio (w/c), sand ratio, silica fume ratio and amount of silica fume (**sf**) addition were considered in tests. Mechanical properties of HSCs were measured by heating 150×300mm cylinders at 20◦ C/min to temperatures of up to 800◦ C. The tests included sixteen mixtures; twelve containing sf and four were without sf that were selected by Taguchi's method. The paper presented results of measurement that indicated the effect of sf, cement, fine aggregate, coarse aggregate and water on residual strength, spalling and mass loss of the HSCs. The presence of silica fume had no statistically significant effect on the relative compressive strength while it had an overall statistically significant effect on increasing spalling. The type of aggregate had a significant influence on the thermal properties of HSCs at elevated temperatures.

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In most cases, by increasing sand ratio, residual compressive strength increased while this trend was reversed for coarse aggregate. Compressive strength of different mixes came down to anywhere between 14% & 36% of the normal strength, at 800◦ C.

The knowledge of high temperature thermal properties is critical for evaluating the fire response of concrete structures. A paper by Venkatesh Kodur and Wasim Khaliq [57] presented the effect of temperature on the thermal properties of different types of high-strength concretes (HSC). Specific heat, thermal conductivity and thermal expansion were measured for three concrete types, namely, HSC, self-consolidating concrete (SCC), and fly ash concrete (FAC), in the temperature range from 20–800°C. The effect of steel, polypropylene, and hybrid fibers on thermal properties of HSC and SCC was also investigated.

Results from experiments showed that:

- Temperature had significant influence on thermal conductivity, specific heat, and thermal expansion of HSC, FAC, and SCC. The thermal conductivity generally decreased with temperature, while the thermal expansion increased with temperature up to 800°C. However, specific heat remained almost constant up to approximately 400°C, and then increased up to approximately 650°C before following a constant trend in the 650–800°C range.
- Results from the thermal property tests showed that SCC exhibited higher thermal conductivity and thermal expansion than HSC and FAC in the temperature range of 20–800°C. However, the specific heat of SCC lied between that of HSC and FAC in the 20–800°C temperature range.
- The addition of steel, polypropylene, and hybrid fibers to SCC or HSC did not significantly alter the thermal conductivity. However, the addition of fibers increased the specific heat of SCC and HSC in the 400–800°C temperature range. In the case of thermal expansion, the addition of fibers to SCC increased thermal expansion in the 400–800°C range, while in case of HSC; the addition of fibers decreased the thermal expansion in the 20–800°C range.

The paper by M.V. Krishna Rao et al. [58] investigated the effect of sustained elevated temperature on the properties of ordinary concretes of M 40 grade, containing different types of cements and cured by two different methods. The specimens were heated to 150, 300 and 450ºC for 1 hour duration in a muffle furnace. They were tested for compressive strength after air cooling to the room temperature. The variables considered in the study included type of cementing material, temperature and method of curing. The compressive strength of concrete and weight of concrete decreased with increasing temperature. Loss of strength was more for concrete mix containing silica fume whereas it was comparable for mixes containing OPC & PPC. Specimens subjected to conventional water curing performed relatively better than those subjected to membrane curing.

The paper by A. Rahim et al. [59] presented results of an experimental study undertaken to optimize the residual compressive strength of heated concrete with respect to various mix design parameters using the Taguchi method. The design of experiments (DoE) was carried out by standard L9 orthogonal array (OA) of four factors with three material parameter levels. The factors considered were water-cement ratio, cement content, super-plasticizer dosage and fine aggregate content. The specimens were heated up to 200°C, 400°C, 600°C and 800°C target temperatures and were subsequently tested under axial compressive loads in cooled condition. Based on the results, the material parameter responses of optimum performance characteristics were analyzed by statistical analysis of signal to noise ratio (S/N) and analysis of variance (ANOVA) techniques to maximize the post-fire residual compressive strength of concrete. The test results indicated that the overall most influencing parameter with respect to residual compressive strength of heated concrete was fine aggregate content followed by water-cement ratio, dosage of super-plasticizer and cement content. These observations can be kept in mind while designing the concrete mix for structures liable to be exposed to elevated temperatures. The confirmation tests corroborated the theoretical optimum test conditions. The study further showed that Taguchi method could be used efficiently and economically for designing the experiments and for determining the optimum process parameters.

Shihada Samir *et al.* [60] examined the impact of polypropylene fibers on fire resistance of steel reinforced concrete beams. In order to achieve this, concrete mixtures were prepared by using different contents of polypropylene; 0, 0.45 and 0.67 kg/m^3. RCC beam samples were heated in an electric furnace to a temperature of 400°C for exposure times of 2.5 & 4.5 hours and tested under a central static point load on a universal loading frame. Based on the results of the study, it was concluded that the ultimate residual strengths of RC beams containing polypropylene fibers were higher than those without polypropylene fibers. Furthermore, the researchers found out that RC beams which were prepared using 0.67 kg/m^3 of polypropylene fibers could significantly preserve the residual ultimate strengths during heating.

Fibers aiding & abetting the flexural performance at elevated temperatures is a relatively new finding that needs to be further substantiated. The authors failed to put forward any plausible explanation to the fact as to how the fibers melting at 160-170ºC could help the beam in resisting flexure at much higher temperatures!

Siddesh Pai & Kaushik Chandra [61] conducted a study on the performance of polyester fiber reinforced concrete subjected to elevated temperatures. Various research works have been conducted on the glass fibres, steel fibres and polypropylene fibres subjected to elevated temperatures. However, very little is known about the behaviour of polyester fibres as reinforcement in concrete. Although there are many types of polyester, the term "polyester" as a specific material most commonly refers to polyethylene terephthalate (PET). Polyester fibres increase the tensile strength of concrete thereby reducing the cracks & increasing its durability. Concrete having different percentages of polyester fibres was subjected to different elevated temperatures for an exposure time of 2 hours each & the results were studied.

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The authors observed that the compressive strength of concrete decreased with rising temperatures but the fall was greater when polyester fibres were added. The drop in flexural strength was no different in case of 1% fibres though the addition of 0.5% fibres resulted in an improved modulus of rupture for all temperatures. UV Pulse velocity test results were in consonance with the destructive test results.

The performance of concrete can be improved with the addition of steel fibres to concrete especially when it is exposed to heat. K. Srinivasa Rao *et al.* [62] carried out a study to generate experimental data on standard concrete (grade M: 45) and steel Fiber Reinforced Standard Concrete exposed to elevated temperatures. For each type of concrete, six sets of cubes, cylinders, and beams were cast. Each set contained 5 specimens. A total of thirty cubes, thirty cylinders, and thirty beams of Standard Concrete and Fiber Reinforced Standard Concrete were cast, out of which 5 sets of standard concrete and fiber reinforced standard concrete were exposed to elevated temperatures of 50ºC, 100ºC, 150ºC, 200ºC and 250ºC for 3 hours and the sixth set was tested at room temperature as control concrete. These specimens were tested for compressive strength, split tensile strength, and flexural strength in hot condition immediately after taking out from oven. The results revealed better performance of fiber reinforced standard concrete on all fronts viz. compressive strength, split tensile strength and flexural strength, than standard concrete at all temperatures. The compressive strength of fiber reinforced standard concrete was higher than standard concrete by 6-10 %. The split tensile strength of fiber reinforced standard concrete was higher than standard concrete by 0-12 percentage. The flexural strength of fiber reinforced standard concrete was higher than standard concrete by 0-20 %.

Ashok R. Mundhada & Dr Arun D. Pofale [63] in their paper dealt with the effect of high temperatures simulating a fire, on the modulus of rupture of concrete. Plain cement concrete beams were subjected to elevated temperatures, air-cooled and tested for modulus of rupture. The results were compared with non-heated samples belonging to the same batch & grade of concrete. Three different grades of concrete, M 20, M 25 & M 30 were used (Fig. 15). Two different exposure times, 1 hr & 2 hr were adopted. Exposure temperature ranged from 30°C to 800°C. Total 81 beams of size 100x100x500mm were cast & tested. It was found that up to 250°C, concrete performed well & the drop in its flexural strength was marginal (< 8%). At or around 500°C, the modulus of rupture dropped by one fourth & pointed towards repairs. At or about 650°C, modulus of rupture came down to less than two third of original & led to major retrofitting. At or about 800°C, quality & performance of concrete suffered severely & demanded replacement of affected members. Higher grades of concrete performed only marginally better and the drop in their modulus of rupture was proportional. Beams heated for two hours exhibited more deterioration than those heated for one hour especially after 500°C.

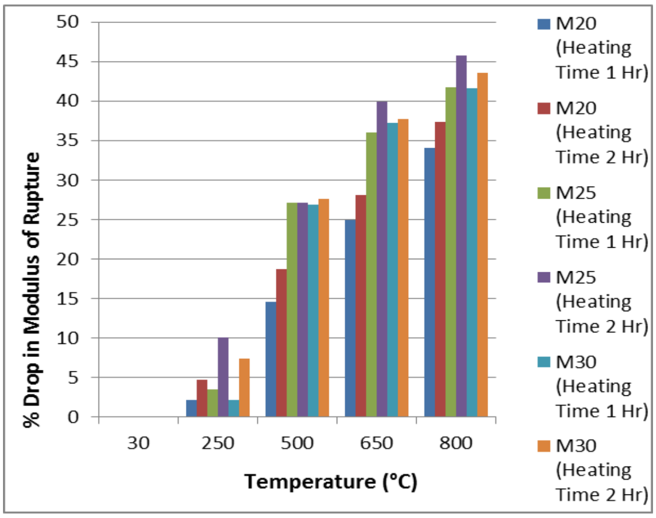

Fig.15. % Drop in Modulus of Rupture at High Temperatures

Gai-Fei Peng & Xu-Jing Niu [64] in their paper presented a review on the effect of fire on normal concrete, high performance concrete (HPC) and ultra-high performance concrete (UHPC). The authors categorized the Period of 1920 to 1970 in concrete research as an exclusive domain of NSC. Period of 1970 to 1994 belonged to both NSC & HSC. Since 1970 it has been commonly accepted that concrete has good fire resistance, meanwhile the scope of research on the effect of high temperature on concrete has been widely enlarged. Researches were carried out not only on the mechanical strength loss, but also on the micro-structure of concrete. Eighties brought in the HPC & the problem of spalling associated with HSC/HPC.

It had been commonly recognized that, as a significant disadvantage of HSC/HPC, explosive spalling was influenced by a couple of factors, including strength grade, moisture content, and specimen size, etc. Internal vapor pressure resulted from moisture content was a main factor governing spalling occurrence. In light of this point, using polypropylene fiber (PP fiber), or other sorts of polymer fiber and even rubber particles, proved to be a good way for alleviating or even avoiding explosive spalling.

The onset of the new century signaled the arrival of a new kid on the block, the ultra-high performance concrete (UHPC). Compared with HPC, UHPC has considerably higher mechanical properties with compressive strength over 100 MPa, and much higher permeation-related durability. UHPC has very dense microstructure, which may be a negative factor under high temperature if the moisture content inside concrete is also high, because it is obvious that considerably high vapor pressure may be easily established under such a condition. UHPC has been found to be prone to severe explosive spalling. The process of vapor pressure build-up in UHPC remains to be explored to identify the spalling mechanism in future research. Furthermore, a standard test method needs to be established for evaluation of spalling behavior of HPC and UHPC and to make results of spalling test in various publications comparable.

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Concrete subjected to fire or high temperature may usually experience four different stages, i.e. heating, temperature maintaining, cooling and post cooling. From the viewpoint of the four stages, heating rate and high temperature level are the two factors which influence the concrete properties more significantly than other factors. Ashok R. Mundhada & Dr Arun D. Pofale [65] in a comprehensive experimental investigation dealt with the effect of high temperatures simulating a fire, on compressive strength of concrete. Ninety concrete cubes of 150 mm size, divided equally over three different grades of design mix concrete viz. M 30, M 25 & M 20 were cast. After 28 days' curing & 24 hours' air drying, the cubes were subjected to non-destructive tests like Thermogravimetric analysis, Schmidt hammer test & US Pulse velocity test before heating. The cubes were then subjected to different temperatures in the range of 200°C to 800°C, for two different exposure times viz. 1 hour & 2 hours in an electric furnace. The heated cubes were cooled at room temperature for 24 hours & then re-subjected to non-destructive tests mentioned above. Change in appearance & weight loss was also studied. Finally, the cubes were subjected to destructive testing on a compression testing machine. Results revealed fairly robust performance up to 500°C. Up to 350°C, concrete remained almost unaffected. At 500°C, strength came down but the structure/ structural members would remain serviceable with reduced factor of safety. Affected structure/ structural members would require minor repairs & patchwork to recuperate. At or @ 650°C, the fall in concrete quality & strength would be a cause for concern. Major retrofitting might be required. Beyond 650°C, concrete stood decimated on all accounts.

III. RESULT ANALYSIS

The experimental investigations on strength & quality of concrete at elevated temperature can be broadly classified into three categories as shown in Fig. 16 [66]. Unstressed residual strength test of air cooled specimens is the most common & popular test because of lesser cost & non-requisition of sophisticated laboratory infrastructure.

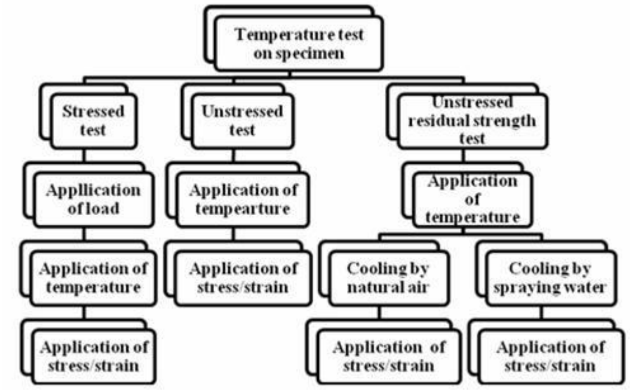

Fig.16. Classification of High Temperature Tests on Concrete

A careful Review of the technical literature brings to light the following points:

1. Although Performance Based Design (PBD) is the flavor of the day, the more than 100 years old Prescriptive Method continues to rule the roost even in developed countries, except for large size projects. This is because of the complexities involved & the lack of proven data base in case of PBD. The complex analytical computer models are a product of the assumptions made & the data input. Error in one or both may lead the structural safety in jeopardy because of "GIGO" (Garbage In- Garbage Out)! In the handful of countries where provisions regarding the performance based design have been introduced in the Codes, the caveat at the end has a statutory requirement; "The PBD must result in fire safety at least equal to the one provided by the Prescriptive Methods" [46].
2. The propensity to push synthetic fibers as a panacea & aphrodisiac for all the problems afflicting concrete needs to be checked [60]. But the positive role played by these fibers in controlling spalling of HSC/UHSC now has incontrovertible evidence [53, 55]. At the same time, addition of combustible materials like rice husk & bamboo sticks (as reinforcement) to concrete must be immediately banned. Fire research has also put a question mark on the use of silica fume in making HSC [2, 23].
3. The claim by some researchers regarding a recovery in strength of fire affected concrete with time [7] sounds dubious & finds no support from most other researchers.
4. Further examinations are needed in order to document material properties for design purposes and for the evaluation of residual strength of structural elements exposed to fire. Literature reveals that researchers adopt different procedures for the application of heat load. Hence, there is a need to carry out an extensive investigation to find out the effect of the variations in the heating procedures.
5. With the rising prosperity of the developing & under-developed world, Concrete, one of the most used materials on earth, is spreading its tentacles globally at a rapid pace. More & more experimentation with the locally available materials & methods is the demand of the day.
6. Not much research has been conducted in India on 'Fire & Concrete' although the investigations have gained some momentum during last 10 years [8, 43, 51, 58, 61, 62, 63 & 65]. Still, effect of fire on concrete made from locally available materials remains under researched & needs more investigations.
7. Study of 'Concrete under Fire' involves too many parameters. It leads to massive & costly experimentation. In a world getting increasingly obsessed with statistical & probabilistic analysis, use of novel methods like Taguchi's Method [66] or Response Surface Methodology devised by Box & Wilson [69] for Design of Experiments would be logical. As of now, the method has been used sparingly for designing & analyzing experiments in Civil engineering in general & in case of concrete at high temperatures in particular. If used, the method can help in reducing the number of experiments/readings in case of expensive experimentations involving fire [43, 59].

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8. The role of plaster as first line of defense against fire is not appreciated & investigated much. Malhotra [67], makes a passing reference to the fire resistance of dense plaster being equal to the fire resistance of concrete (section 8.7 in the book). It means, absence of plaster is tantamount to depriving concrete of its first line of defense. More investigations are needed on plaster's influence.
9. With solid waste disposal becoming a gargantuan problem the world over, construction industry is trying more & more to use waste marble/glass/metakaolin as a partial replacement for aggregates. These improvised concretes have hardly been tested for fire/high temperatures & need to be explored.
10. Researchers make a passing reference to confinement being a factor that may improve concrete's fire performance but there are hardly any experiments linking stirrup spacing to the same. There is a need to investigate this aspect through experimentation.
11. If the fire affected members are retrofitted using polymer wrappings, sufficient fire protection needs to be given to the CFRP strengthening system such that the adhesive would not lose its strength, through sufficiently thick SFRMs (Spray Applied Fire Resistive Materials). [33]
12. The importance of full scale fire tests like Cardington [20] cannot be undermined. However, changing to a full system approach (i.e. testing whole buildings) requires significant effort and resources. Some experts have suggested conducting full scale fire tests on discarded/ deserted structures, ready to be dismantled. But it is doubtful if such dilapidated structures would give any convincing indication of fire performance of buildings standing in good health. Under the circumstances, thorough case studies of standing structures subjected to real time fire gains significance [35].

IV. CONCLUSION

Based on the above discussion, it becomes clear that there is an urgent need in India to conduct more investigations on the journey of concrete/ RCC through fire/ heat with locally available materials. When it comes to improvised concrete (concrete containing industrial waste), this need becomes global. Furthermore, increased use of statistical/ probabilistic methods is recommended as they will reduce the number of experiments/ readings thereby reducing the bloated cost of carrying out such experiments.

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