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A Review on Concrete Structures in Fire

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***Abstract*—**Concrete as a construction material is versatile because it displays high degree of fire-resistance. Concrete's inherent ability to combat one of the most devastating disaster that a structure can endure in its lifetime, can be attributed to its constituent materials which make it inert and have relatively poor thermal conductivity. However, concrete structures must be designed for fire effects. Structural components should be able to withstand dead and live loads without undergoing collapse. The properties of high-strength concrete must be weighed against concerns about its fire resistance and susceptibility to spalling at elevated temperatures. In this paper, the causes, effects and some remedy of deterioration in concrete due to fire hazard will be discussed. Some cost effective solutions to produce a fire resistant concrete will be conversed through this paper.

***Keywords*—**Concrete, fire, spalling, temperature, compressive strength, density.

I. Introduction

THE outstanding fire-proof performance of concrete is due to concrete's constituent materials (cement and aggregates) which, when chemically combined within concrete, form a material that is inert and has relatively poor thermal conductivity [1], [2]. Fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted [3]. In 1988, the "Construction Products Directive" issued by the Council of the European Communities recognized fire safety as one of the six essential requirements which constructions works must satisfy [4]. Depending on the proposed use of the structure, building regulations recommend different levels of compartmentation in different types of building to take account of the likely risk of fire in a particular building type [5]. A relatively new method for determining fire exposure used by fire protection engineers is to first calculate the fire load density in a compartment. Then, based on the ventilation conditions and an assumed source of combustion, the compartment temperature is determined at various times. Another factor considered in the analysis is the effect of active fire protection systems e.g. sprinklers or fire brigades on the growth of the fire [3]. Standard practice for fire-damaged concrete requires that severely fire affected concrete be stripped from the steel reinforcement and pre-stressing tendons, to a depth of at least one bar diameter. The removed concrete is then replaced with polymer modified cementitious materials or cementitious repair materials. This job is accomplished either by use of a hand trowel or by spraying the materials onto the surface [6]. The thermal properties that influence temperature rise and distribution in a concrete structural member are thermal conductivity, specific heat, thermal diffusivity, and mass loss [7]. The thermal diffusivity of a material is defined as the ratio of thermal conductivity to the volumetric specific heat of the material [7]. It measures the rate of heat transfer from an exposed surface of a material to inner layers. The larger the diffusivity, the faster the temperature rise at a certain depth in the material [8], [9]. Thermal conductivity can be reduced by using lightweight aggregates and glass bubbles in place of normal aggregates [10]. The load bearing resistance of the construction can be assumed for a specified period of time [11]. Compressive strength of concrete at an elevated temperature is of primary interest in fire resistant design. The strength degradation in high strength concrete is inconsistent and there are significant variations in strength loss, as reported by various authors. Concrete should be made in controlled conditions to minimize the factors that may affect the thermal expansion coefficient, for example the relative humidity. The mix proportion of the concrete should also be closely regulated, especially the water-cement ratio [12]. Reference [13] showed that addition of steel fibres to High Performance Concrete led to a considerable improvement in static and dynamic modulus of elasticity. Pilot scale experiments on concrete and reinforced concrete structural elements are needed to provide basic validation data for computational modeling [14]. Density of concrete is usually subdivided into two major groups: (1) normal-weight concretes with densities in 2150 to 2450 kg/m^3 range; and (2) lightweight concretes with densities between 1350 and 1850 kg/m^3. When the surrounding temperature rises, concrete starts to lose its moisture. This causes a decrease in the density of concrete. The retention in mass of concrete at elevated temperatures is highly influenced by the type of aggregate used [15], [16]. Density and workability of the fresh concrete significantly affect its fire resistance. Structural lightweight concrete is more resistant to fire than normal weight concrete due to lower reduction in strength at higher temperature because of inherent stability [17]. They provide more insulation due to improved thermal conductivity.

II. Performance of Structural Members at Elevated Temperature

A. Performance of Concrete at Elevated Temperatures

Spalling starts to occur when concrete reaches an elevated temperature of 250^{0}C. From 250–420°C, some spalling occurs. After reaching 300°C, concrete starts to lose its strength. Within 550–600°C, cement based materials experience creep and lose their load bearing capacity**.** At

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600°C and higher, concrete loses its ability to function at its full structural capacity. Major damage is usually confined to the surface at close proximity to the fire origin [18], [19]. A fire-resistance rating typically means the duration for which a passive fire protection system can confine a fire and withstand a standard fire resistance test. Although less amount of strength drop is observed in case of lightweight concrete when compared to normal weight one, rate of temperature drop is higher (Fig. 1).

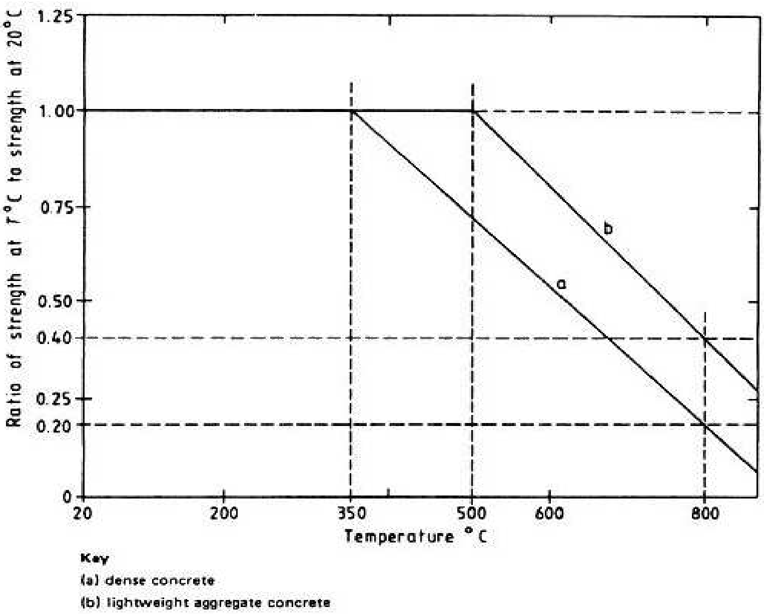


Fig. 1 Variation of concrete strength with temperature [20]

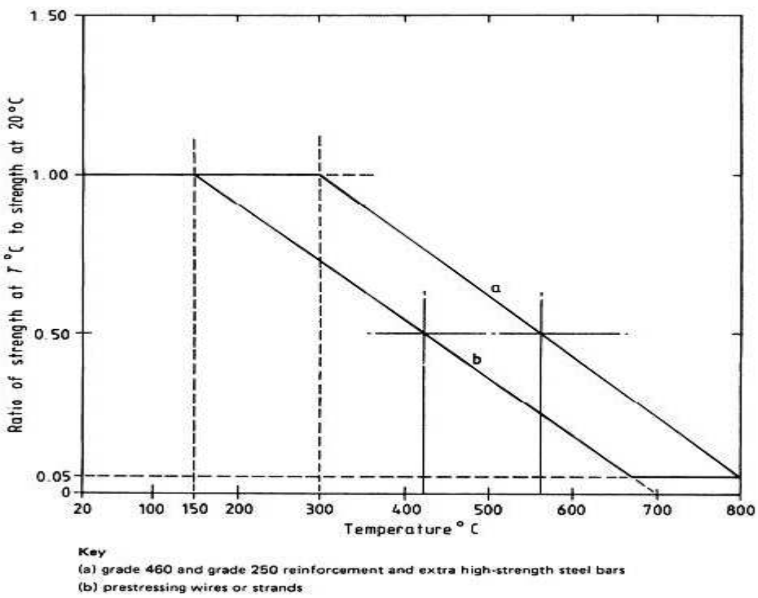


Fig. 2 Variation of steel strength with temperature [20]

B. Performance of Steel at Elevated Temperatures

Steel reinforcement bars need to be protected from exposure to temperatures in excess of 250-300°C. This is due to the fact that steels with low Carbon contents are known to exhibit 'blue brittleness' between 200 and 300°C. Concrete and steel exhibit similar thermal expansion at temperatures up to 400°C; however, higher temperatures will result in significant expansion of the steel compared to the concrete and, if temperatures of the order of 700°C are attained, the load-bearing capacity of the steel reinforcement will be reduced to about 20% of its design value [21]. Steel strength also reduces with temperature. The reduction in strength due to an increase in temperature is markedly lesser in high strength steel than a pre-stress wire member (Fig. 2). Steel ratio and strength of concrete have major influences on the fire resistance of the concrete structures under fire [22].

III. Factors Affecting Properties of Concrete in Fire

Factors affecting fire performance research at IRC and elsewhere shows that the fire performance of high strength concrete (HSC), in general, and spalling, in particular, is influenced by various factors. Original compressive strength of the concrete, moisture content, density, fire intensity, dimensions of members, transverse reinforcement placing, loading, type of aggregate used, fibre reinforcement and water binder ratios are chief factors of concern. Concrete strengths higher than 55 MPa are more susceptible to spalling and may result in lower fire resistance. Higher RH levels lead to greater spalling (when the RH is higher than 80%). The extent of spalling was found to be much greater when lightweight aggregate is used. This is mainly because lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures. The spalling of HSC is much more severe in fires characterized by fast heating rates or high intensities. Thermal spalling increases with specimen size. This is due to the fact that specimen size is directly related to heat and moisture transport through the structure, as well as the capacity of larger structures to store more energy. Both closer tie spacing and the bending of ties at 135° back into the core of the column enhances fire performance. The provision of cross ties also improves fire resistance. Concrete that is under design load while heated loses less strength than unloaded concrete, the theory being that imposed compressive stresses inhibit development of cracks that would be free to develop in unrestrained concrete [23]. Of the two commonly used aggregates, carbonate aggregate provides higher fire resistance and better spalling resistance in concrete than siliceous aggregate. This is mainly because carbonate aggregate has a substantially higher heat capacity. Also, concrete containing limestone and calcareous aggregates performs better at high temperatures than concrete containing siliceous aggregates [24]. For example, quartz-based aggregates increase in volume, due to a mineral transformation, at about 575°C and limestone aggregates will decompose at about 800°C [25]. The addition of polypropylene fibres minimizes spalling in HSC members under fire conditions [26]. Concrete with a higher aggregate-cement ratio suffers less reduction in compressive strength; however, the opposite is true for modulus of elasticity. Loss of elastic modulus, due to a fire, is marginal for a concrete with a lower water cement ratio [23]. For concrete structures, lateral displacement of columns at slab–column joints due to thermal expansion of the slabs might pose additional risk to the global stability of the structure [27].

IV. Reasons of Structural Failure Due to Fire

The methodology by NFIRS system [28] included a review of news sources, technical literature, as well as interviews with a wide range of individuals knowledgeable in structural fire protection. Twenty-two fires were identified that caused either partial or total collapse of a multistory structure. Some reasons of structural failure due to fire are as follows:

A. Stages of Fire Development

Once a material is ignited, fire spreads across fuel objects until it becomes fully developed. Fire spreading rate depends upon fuel composition, orientation, surface to mass ratio, incident heat and air supply. Fire spreads to other object by radiation from flame or from smoke layer [29].

B. Physical and Chemical Response to Fire

Most porous concretes contain a certain amount of liquid water [30]. This begins to vaporize if the temperature exceeds 100°C, usually causing a build-up of pressure within the concrete. In practice, the boiling temperature range tends to extend from 100 to about 140°C due to pressure effects. A blend of these physical and chemical changes in concrete results in the reduction of the compressive strength of the material.

C. Spalling

Spalling may significantly reduce or even eliminate the layer of concrete cover on the reinforcement bars, thereby exposing the reinforcement to high temperatures, leading to a reduction in the strength of the steel and hence a deterioration of the mechanical properties of the structure as a whole.

Fig. 3 Spalling of concrete

D. Cracking

Geogali & Tsakiridis [31] made a case study of cracking in a concrete building subjected to fire, with particular emphasis on the depths to which cracking penetrates the concrete. It was found that the penetration depth is related to the temperature of the fire, and that generally the cracks extended quite deep into the concrete member. Major damage was confined to the surface in close proximity to the fire origin, but the nature of cracking and discolouration of the concrete pointed to the concrete around the reinforcement reaching 700°C. Cracks which extended more than 30 mm into the depth of the structure were attributed to a short heating/cooling cycle due to the fire being extinguished.

Fig. 4 Crack development in concrete structure due to fire

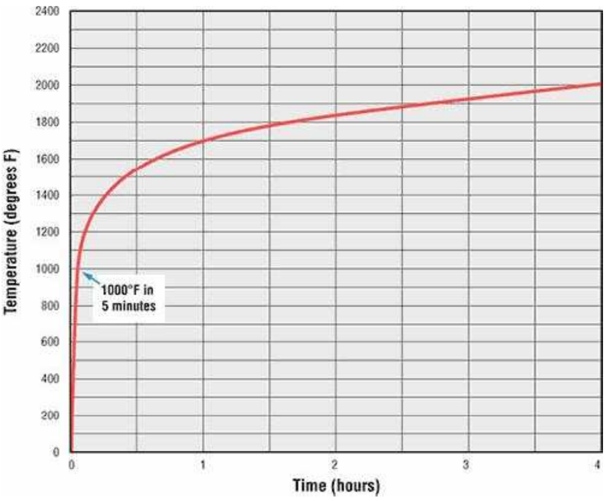


Fig. 5 Time temperature curve

V. Test Methods to Evaluate Effect of Fire on Damaged Concrete

The most common test method for determining fire resistance in the United States is the ASTM Standard E 119 Test Methods for Fire Tests of Building Construction and Materials [32], [33]. To help prevent building fires from spreading and protect lives and property, building codes require that walls, partitions, roofs and floor/ceiling assemblies in sensitive locations carry particular fire ratings [34]. In ASTM E-119 tests, specimens of tested assemblies are exposed to controlled heat until one of the following occurs: the average temperature measured on the unexposed side of the specimen increases by 250° F; heat, flame or gases escape to the unexposed side; or the specimen collapses under load. To qualify for fire ratings of 1 hour or more, specimens also must pass a hose stream test to simulate firefighting conditions. There are two options for the hose stream portion of the test—one using a duplicate specimen that has been exposed to heat for only half the required time and one using the specimen that has just passed the entire heat duration. As testing every conceivable combination of unit size, shape and core area is infeasible, the standard industry practice is to calculate the fire resistance of untested concrete by the equivalent thickness method. Using information manufacturers provide on the content and equivalent thickness of particular masonry units, designers can consult standard tables or perform simple calculations to determine a specific assembly's fire rating. Time temperature curve given by ASTM E 119 is given in Fig. 5.

A. Visual Inspection

The visual inspection of the fire affected structure and the status of some of the components of the structure such as aluminum, glass panes, etc. after the fire suggest the approximate temperature to which the structure was subjected [35].

B. Ultrasonic Scanning

The UPV (Ultrasonic Pulse Velocity) measurement (Fig. 6) is one of the various non-destructive test methods used to evaluate concrete integrity and – more generally – the level of damage in the material. In particular, the velocity of sound in concrete is a high-quality thermal-damage indicator, due to its sensitivity to any change of the Young's modulus. When concrete is exposed to fire, the increase of temperature in the deeper layers of the material is rather slow and progressive. Because of this (due to the rather low thermal diffusivity of concrete), this process produces significant temperature gradients between the outer and inner layers of any given concrete structure (i.e. between the surface and the core). UPV technique may also be applied to determine the reduced quality of concrete by means of indirect or direct techniques on cores [36], [37].

C. Core Sampling and Testing

Tests on core samples give direct evidence on residual compressive strength and temperature to which the concrete member is subjected to during fire. The pulse velocity values of these core samples can be compared to confirm the estimated temperature and the accuracy of estimation of the depth of damaged concrete. Studies on core samples reveal that their density and compressive strength bear a relation which helps to confirm the estimated temperature.

Fig. 6 UPV testing of concrete member

D. Residual Strength of Steel

To assess the residual properties of the reinforcement, samples from different locations are to be collected and tested for yield and ultimate strength, percentage elongation and modulus of elasticity. The reduction in the strength and modulus of elasticity will give an approximation of the temperature to which the member has been subjected to during fire.

VI. Effects of Fire on Concrete (Case Study)

The Windsor Tower or Torre Windsor (officially known as Edificio Windsor) was a 32-storey concrete building with a reinforced concrete central core [38]. A typical floor was two-way spanning, 280mm deep waffle slab supported by the concrete core, internal RC columns with additional 360mm deep steel I-beams and steel perimeter columns. Originally, the perimeter columns and internal steel beams were left unprotected in accordance with the Spanish building code at the time of construction. The Windsor Tower was completely gutted by the fire on 12 February, 2005. A large portion of the floor slabs above the 17th floor progressively collapsed during the fire when the unprotected steel perimeter columns on the upper levels buckled and collapsed.

VII. Some Engineering Solutions to Improve Fire Safety

Fire safety engineering is the application of science and engineering principles to protect people and their environments from the destructive effects of fire and smoke. Main principles of fire engineering are: continuity of operations; property protection and life safety. Fire protection is the lessons and practice of extenuating the unnecessary effects of fires. Several methods are used to protect concrete from fire. Insulating board systems through gypsum board and calcium silicate board are used generally. In addition, man-made mineral fibre systems are used in some cases. Fire walls, fire separation or barrier walls or penetration protection may also be utilized.

A. Fire Wall and Barrier Wall

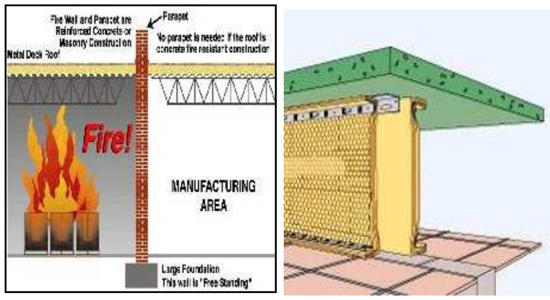
Firewall is a passive fire protection system that has protected openings. This wall (Fig. 7 (a)) extends continuously from the foundation to or through the roof. Generally, it is located in accordance with the locally applicable building code. Purpose of firewall is to subdivide a building into separate fire areas so that it restricts the spread of fire from one side to other. A barrier wall is designed to limit the spread of fire and smoke from a controlled fire (Fig. 7 (b)).

B. Fire Door

A "fire door" is the door that is tested and listed to stop fire only. Smoke may pass around the sides of the door (Fig. 8).

C. Penetration Protection

Penetrating items are steel, ferrous or copper pipes, tubes or conduits. Annular space between the item and the fire-resistance-rated wall must be filled to maintain the fire-resistance rating with filling material - concrete, grout, or mortar (Fig. 9). Separation in buildings by structural elements prevent horizontal and vertical spread of fire [39]



(a) (b)

Fig. 7 (a) Fire Wall (b) Barrier Wall

(a) (b)

Fig. 8 Fire Door (a) Vertical (“Roll-Up”) Fire Doors (b) Horizontal (“Sliding”) Fire Door

Fire following earthquake (FFE) is a serious threat to structures that are partially damaged in a prior earthquake potentially leading to a quick collapse of the structure [40]. Test results confirmed the need for the incorporation of FFE into the process of analysis and design [40].

Fig. 9 Fire penetration protection system

VIII. Conclusion and Recommendations

In this paper, several reasons of structural failure and degradation of concrete structures due to fire have been summarized. Moreover, the actual effects of fire on concrete and different technology to improve fire resistance capacity of concrete members have been described. Improved structural design methodology, improved testing for fire protection materials, technologies, and systems, changing building operations and maintenance functions while sustaining the technologies, systems, and materials that constitute elements of the fire protection system must be introduced to reduce fire hazard. Detailed studies of the performance of concrete structures in real fire incidents can also assist greatly in advancing knowledge of real-world behaviour. Some recommendations that can be developed through this study are as follows:

- Thermal diffusivity of a concrete member can be reduced by using lightweight aggregate and Styrofoam in concrete.
- Density can be reduced by replacing of normal weight aggregate with a lightweight aggregate as lightweight concrete is less vulnerable to fire.
- Elastic modulus and tensile strength of concrete can be increased through introduction of steel fibres in order to perform better during fire.
- The repair measures such as cement grouting for improving the core concrete and using weld mesh for spalled areas are to be adopted as retrofitting measures.
- Closer transverse reinforcement spacing and utilization of carbonate aggregate instead of silicious aggregate must be considered during design.
- Spalling in HSC members can be minimized through addition of polypropylene fibres.

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