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STATAE OF THE ART REPORT ON THE ASSESSMENT OF FIRE-DAMAGED RC BRIDGES

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Abstract

The objective of this paper is to provide an overview of the assessement of fire-damaged RC structures. In order to meet this objective, the effects of fire or elevated temperatures on the properties of normal, concrete constituent materials and RC structures are summarized. Also, the effects of fire or elevated temperatures on high-strength and self-compacting concrete materials are noted and their performance compared to normal concretes. A review of the different assessement techniques is presented. Design considerations and analytical techniques for evaluating the response of reinforced concrete structures subjected to fire or elevated-temperatures conditions are also presented and disscused.

1. Introduction

Often the initial response when looking over a fire-damaged structure is one of despair and horror at the extent of damage. This situation is exacerbated by the amount of non-structural debris lying around, together with, the acrid smell of many combustion products. In most cases, the damage is not as severe as initially thought, even though immediate decisions must be taken on the short-term safety of the structure and whether any temporary propping is necessary or, indeed, whether some demolition work is necessary. This decision will often need to be taken very quickly after the fire that will generally be based on a visual survey and expert judgement. It should be pointed out that the assessment of fire-damaged structures is very much a black art that it relies heavily on experience. It is also to be noted that it is at this point, the owner's, or occupier's, insurance company will become involved, as even if the structure is capable of being saved, it will be a matter of economics as to whether there should be repair or demolition and complete rebuild [1-5].

This question can often be answered after a thorough visual inspection has been carried out.

2. Visual Inspection

The aim of the visual inspection is to determine:

1. the short-term stability of the structure and
2. the extent and severity of the fire.

2.1 Stability

If possible, the original drawings for the structure should be consulted at this stage. These allow assessment of how the structure transmits the applied loading and enables the principal load carrying members to be identified, as well as those providing structural stability. The inspection needs to check any excessive deformation, deflection or cracking in the main load-carrying members and integrity at the connections between the main members. In the case of concrete construction, attention should be given to damage due to spalling on beams and columns as this may reduce the load-carrying capacity of the member due to excessive temperature rise in any reinforcement. Where the fire has only affected part of the structure, it is essential that the inspection also extends to any part of the structure not damaged directly by the fire; it is possible that a substantial redistribution of forces can occur into the unaffected part of the structure. This redistribution of forces has been noted from theoretical work on concrete frames by [5] where moments in the frame remote from the fire affected compartment exceeded the design moments, when the structure behaved during the fire in a totally different manner to the way it was designed, in that forces were redistributed away from the fire by columns acting in tension to transmit forces to the relatively cool upper stories of the structure.

2.2 Estimation of fire severity

The first method of obtaining a rough estimate of the fire severity is by the use of the fire brigade records in terms of the number of appliances called out, the length of time taken to fight the fire, the length of time between the fire being noted and the arrival of the brigade, the operation of any automatic fire detection or fire-fighting equipment and the degree of effort required to fight the fire. Since most materials have known specific melting or softening temperatures, some typical data are given in table 1.

Table 1 Melting point data [5]

Material behaviour	Approximate temperature (°C)
Softening or collapse of polystyrene	120
Shrivelling of polythene	120
Melting of polythene	150
Melting of polystyrene	250
Darkening of cellulose	200–300
Soldered plumbing adrift	250
Lead plumbing melts or softens	300–350
Aluminium softens	400
Aluminium melts	650
Softening of glass	700–800
Melting point of brass	800–1000
Melting point of silver	950
Melting point of copper	1100
Melting point of cast iron	1100–1200

3. Damage Assessment

This needs carrying out in a series of stages. The first stage involves a complete fully detailed survey of the structure. The second stage ascertains the residual strength of both the individual members and of the complete structure.

3.1 Structural survey

For all structures, the first stage is to carry out, where appropriate, a full line and level survey. This is needed to assess the residual deformations and deflections in the structure. The measured deflections should be compared with those for which the structure was designed. Care should be taken to note the effect of any horizontal

movements due to thermal actions during the fire. Such effects of horizontal movement are often apparent away from the seat of the fire.

3.2 Materials testing

3.2.1 Concrete

The only common destructive test is to take concrete cores usually 40 mm diameter from the fire-damaged zone and test the cores in compression according to the relevant standard, e.g. BS 1881: Part 120: 1983, and then relate the measured strength to an equivalent cube strength using appropriate empirical formulae. Great care is needed with the use of cores to assess residual strengths as it is necessary to attempt to extract cores free from any reinforcement, although the presence of reinforcement can be allowed for in assessing equivalent strengths. A further problem in heavily damaged structures is the ability to obtain cores of sufficient integrity to be tested. It is also necessary to obtain cores from an undamaged part of the structure where concrete of a similar specified grade was used. To aid the assessment of loss of strength, it is useful if at all possible to obtain the original cube or cylinder control test records when the structure was built. It is also useful if any colour changes in the concrete along the length of the core are noted, as this can help assess the residual strength of parts of the structure where it may not be possible to extract cores.

3.2.1.1 Ultrasonic pulse velocity (UPV) measurements

Although the apparatus for this is conveniently portable, the results obtained are not very sensitive and have the disadvantage of being comparative in that a reference is needed to establish base values of strength and pulse velocity. The test may either be carried out by measuring the time taken to transmit a signal through the member or by measuring the time taken for a reflected signal to travel from transmitter to receiver. In the former case, it is necessary to be able to gain access to both sides of a member, together with the further limitation that the thickness cannot exceed about 200mm. In the latter case, the surface must be good enough to allow a series of readings to be taken and that a similar procedure is used for the reference value. Provided reference values of both the pulse velocity and strength are known, then it is possible to estimate the loss in strength if the loss in UPV is known. It has been demonstrated from test results that the loss in strength ($1 - \sigma c,\theta/\sigma c,20$) is related linearly to the loss in pulse velocity ($1 - U\theta/U20$) by an equation of the form

$$\left(1 - \frac{\sigma_{c,\theta}}{\sigma_{c,20}}\right) = k_1 \left(1 - \frac{U_\theta}{U_{20}}\right) + k_2 \qquad (1)$$

where $\sigma c,\theta$ and $U\theta$ are the compressive strength and UPV at a temperature θ and $\sigma c,20$ and $U20$ are the reference strength and UPV, respectively, and $k1$ and $k2$ are dependant on the concrete age and composition [5] proposed a rather complex method capable of determining the loss in elastic modulus within the fire-damaged zone using the reflection method. [5] suggests that a linear degradation model of elastic modulus with temperature is adequate.

3.2.1.2 Schmidt hammer

This will only measure the properties of the concrete in the surface layer and requires a clean smooth surface to give reliable results. It also needs calibrating for a given concrete and is not suitable where knowledge of the concrete properties are required within the element.

3.2.1.3 Petrographic analysis

In this technique, thin slices from cores are examined under a microscope and the isotropy, density and type of cracking are observed. [4] suggests that when the temperature exceeds 500◦C the cement paste appears anisotropic under polarized light. The crack patterns also change: below 300◦C, the cracks form between the

boundaries of the aggregate and the mortar matrix, whereas above 500◦C the cracks will also tend to pass through the matrix. More recently it has been demonstrated [5] that it is possible to quantify the relationship between crack density and temperature reached due to heating Fig. (1). With the unexplained exception of siliceous aggregate concrete containing PFA, the correlation between temperature θcd at which the crack density increases above base value and the temperature θcs at which compressive strength loss starts to occur is good Table (2). The ability of change in crack density to predict the position of the 325◦C isotherm (at which compressive strength loss starts to occur) is illustrated in Fig. (2).

Table 2 Values of initial crack density and strength transition temperatures [5]

Concrete type	Initial crack density (C_0) mm/cm^2	θ_{cd} (°C)	θ_{cs}(°C)
OPC/Siliceous	0,29	350	325
OPC/PFA/Siliceous	0,36	250	325
OPC/GGBS/Siliceous	0,26	350	350
OPC/Limestone	0,31	300	325
OPC/Granite	0,24	400	400

3.2.1.4 Stiffness damage test

This is a type of compression test carried out on cylindrical specimens 175mm long and 75mm diameter under a limited stress range of 0 to around 4,5MPa under cyclic loading with the strains being measured over the central 67mm [5]. Measurements are then taken for variously defined elastic moduli and of hysteresis between the loading cycles. The test results from concrete uniformly heated up to temperatures of 470◦C confirm data on residual Young's modulus and may provide an alternative method of performance assessment at moderate temperatures.

3.2.1.5 Surface permeability

The use of air permeability and water sorpity tests on heated concrete to ascertain damage measured by surface pull-off tensile strength using an epoxy bonded 50mm diameter steel disc. The 150mm cube specimens were heated by an imposed flame for two hours at a prescribed surface temperature. The tensile strengths will be those of the surface (as will the air permeability and water sorpity), but the cube strengths will to some extent be a function of the temperature distribution in the specimen.

3.2.1.6 Hammer

Although not a scientific method in the generally accepted sense of the word, this method is probably the best to give a very quick, albeit crude, assessment of concrete quality and strength. An overview of traditional non-destructive testing on fire-damaged concrete is given in [5]. For reinforcement, similar techniques are available to structural steel. It should, however, be noted that where specimens are taken from either tensile steel in beams or compressive steel in columns, the elements or structure must be propped since removal of the specimen will reduce the strength of the member. It may be possible to remove samples from shear links at the mid-point of a beam or a column without propping.

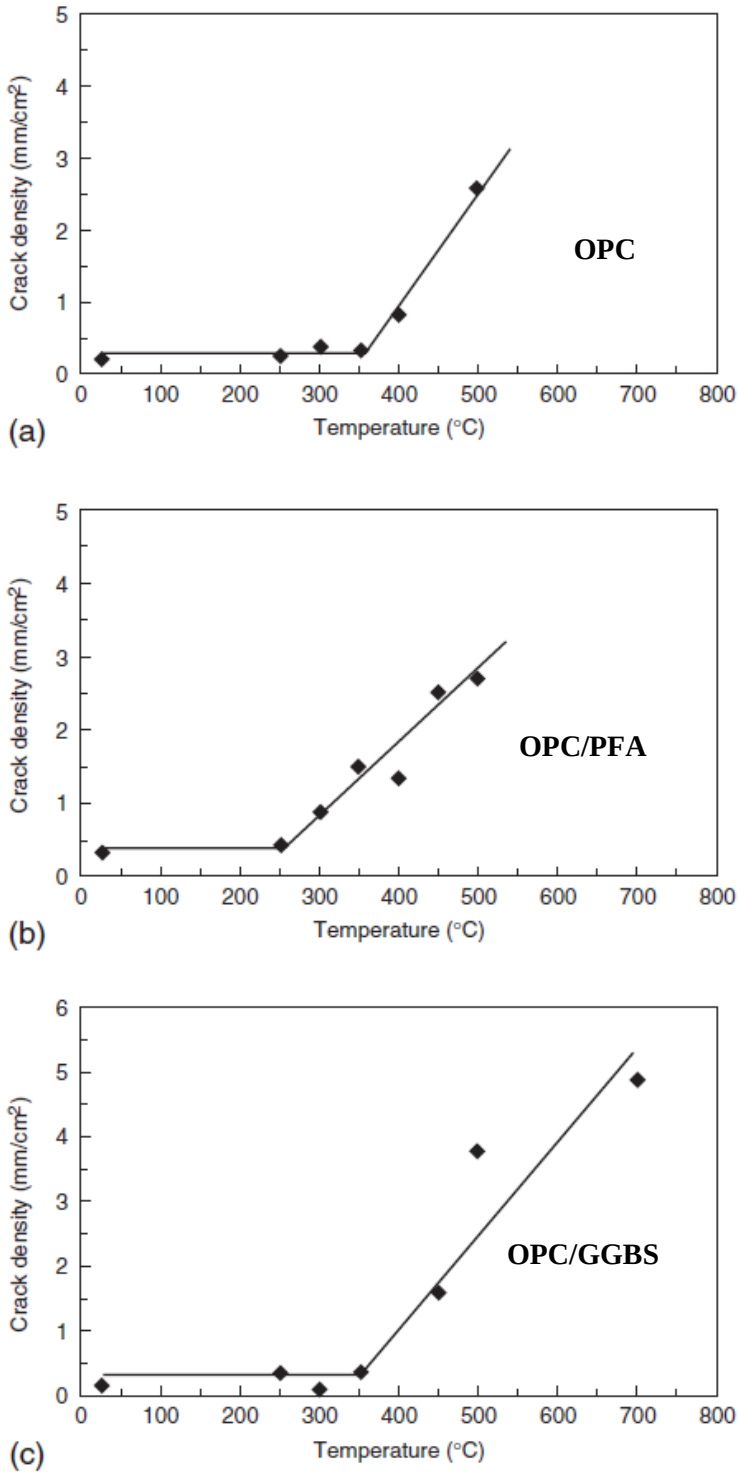

Figure 1 The development of crack density with temperature for concretes made with siliceous aggregate and: (a) Ordinary Portland Cement (OPC); (b) OPC/PFA; (c) OPC/GGBS cements; (d) limestone and (e) granite. [5].

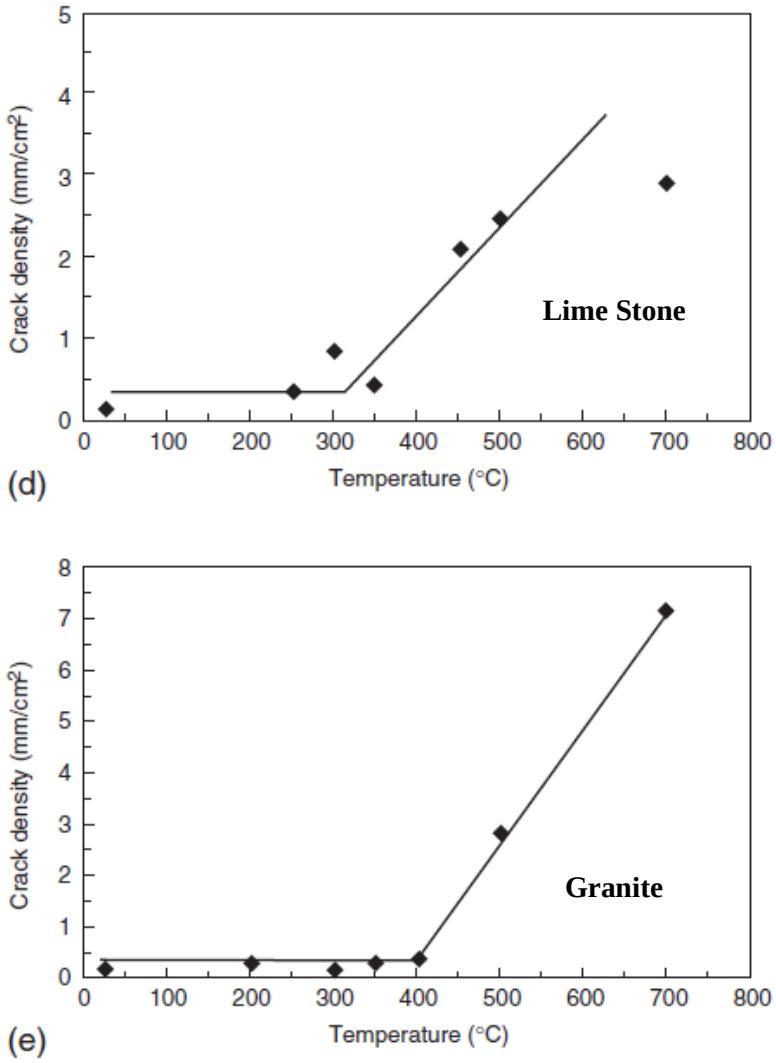

Figure 1 Continued

3.2.1.7 Thermoanalytical Techniques of Concrete Materials

Thermal analysis has been defined by the International Confederation of Thermal Analysis (ICTA) as a general term which covers a variety of techniques that record the physical and chemical changes occurring in a substance as a function of temperature, [4]. This term, therefore, encompasses many classical techniques such as thermogravimetry (TG), evolved gas analysis (EGA), differential thermal analysis (DTA), and differential scanning calorimetry (DSC), and the modern techniques, such as thermomechanical analysis (TMA) as well as dynamic mechanical analysis (DMA), and dilatometry, just to name a few. The application of thermal analysis to the study of construction materials stems from the fact that they undergo physicochemical changes on heating.

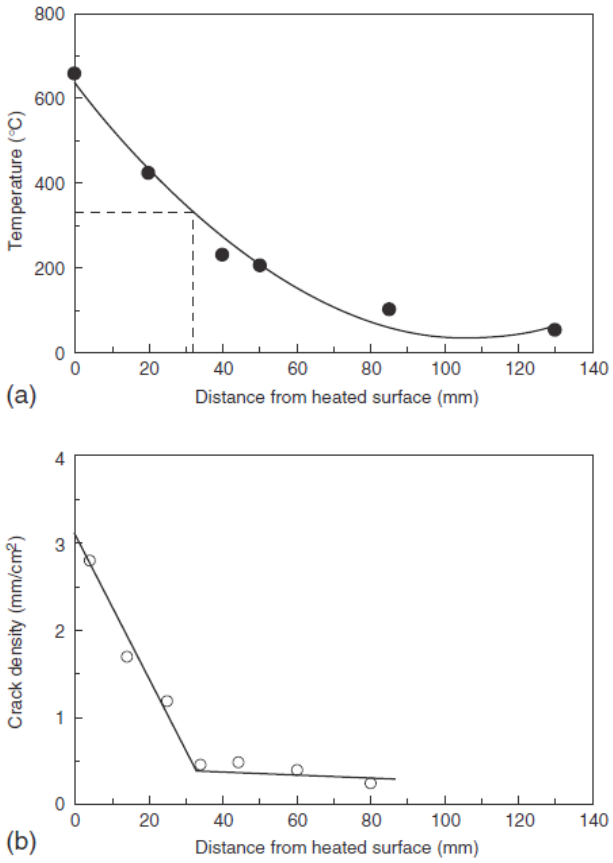

Figure 2 (a) Temperature distribution and (b) crack density for an OPC–siliceous aggregate concrete cylinder heated from one end [5].

3.2.1.7.1Classical Techniques

Ever since the invention of DSC, there has been much confusion over the difference between DTA and DSC. The exact ICTA definition of *DTA* is a method that monitors the temperature difference existing between a sample and a reference material as a function of time and/or temperature assuming that both sample and reference are subjected to the same environment at a selected heating or cooling rate. [4] the plot of ΔT as a function of temperature is termed a DTA curve and endothermic transitions are plotted downward on the *y*-axis, while temperature (or time) is plotted on the *x*-axis. DSC curve as shown in Fig (1), on the other hand, has been defined as a technique that records the energy (in the form of heat) required to yield a zero temperature difference between a substance and a reference, as a function of either temperature or time at a predetermined heating and/or cooling rate, once again assuming that both the sample and the reference material are in the same environment. The plot obtained is known as a DSC curve and shows the amount of heat applied as a function of temperature or time. As can be seen from the above definitions, the two techniques are similar, but not the same. The two yield the same thermodynamic data such as enthalpy, entropy, Gibbs' free energy, and specific heat, as well as kinetic data. It is only the method by which the information is obtained that differentiates the two techniques.

- **Differential Thermal Analysis and Differential Scanning Calorimetry**
  A little over a hundred years ago, two papers were published by Le Châtelier dealing with the measurement of temperature in clays; the first entitled On the Action of Heat on Clays and the second On the Constitution of Clays. The experiment described in these papers was not a truly differential one since the difference in temperature between the clay and reference material was not measured. The apparatus consisted of a Pt-Pt/ 10%-Rh thermocouple embedded in a clay sample, which in turn was packed into a 5 mm diameter Pt crucible. The crucible was then placed in a larger crucible, surrounded with magnesium oxide and inserted into an oven. Le Châtelier used a heating rate of 120 K min-1 and recorded the electromotive force of the thermocouple on a photographic plate at regular time intervals. As long as no phase change occurred in the clay, the temperature rose evenly and the lines on the plate were evenly spaced. If, however, an exothermic transformation took place, then the temperature rose more rapidly, and, therefore, the lines were unevenly spaced and closer together. An endothermic transition, on the other hand, caused the measured temperature to rise more slowly, and the spacing between the lines was much larger. To ensure that the measured temperatures were correct, he calibrated his instrument with the aid of boiling points of known materials such as water, sulfur, and selenium, as well as the melting point of gold. Since Le Châtelier's experiment does not fit the ICTA definition of DTA, his main contribution to the development of DTA was the automatic recording of the heating curve on a photographic plate. True differential thermal analysis was actually developed twelve years later [4].
- **DSC**
  The DTA calorimeter, sometimes called DSC. The term DTA calorimeter is more appropriate since this system actually measures ΔT directly from the experiment. Unlike conventional DTA however, the experiment is performed at quasi-equilibrium conditions, i.e., sample mass is less than 10 mg, slow cooling/heating rate, and only one calibration coefficient needs to be measured for the entire temperature range. This, therefore, yields quantitative data but by definition remains a DTA instrument. The other two categories of DSC apparatus are true calorimetric instruments in that the calorimetric information is obtained directly from the measurement, i.e., no conversion factor is required to convert ΔT into readily used energy units as the thermometric data is obtained directly. A constant is still required to convert the energy term into more suitable units. The main goal of any enthalpic experiment, which is to determine the enthalpy of a sample as a function of temperature, is attained by measuring the energy obtained from a sample heated at a constant rate with a linear temperature or time programming. These two DSC instruments are designed so that the temperature of the metal block, which contained the sample, was slightly lower than the temperature of the sample itself. To maintain the sample at the same temperature as the block, power was supplied to the sample. The main disadvantage of this apparatus was that a correction factor had to be applied to account for the heat transfer between the surrounding medium and the block. Both the heat flux and power-compensation DSC instruments overcome this drawback because, as the name suggests, they are *differential* instruments. The heat-flux instruments measure the flux across a thermal resistance, whereas the power compensating differential scanning calorimeters measure the energy applied to the sample (or the reference) by an electrical heater in order to maintain a zero-temperature differential. The amount of heat required to maintain the sample temperature and that of the reference material isothermal to each other is then recorded as a function of temperature. Moreover, in power-compensation DSC, an endothermic transition, which corresponds to an increase in enthalpy, is indicated as a peak in the upward direction (since power is supplied to the sample), while an

exothermic transformation, a decrease in enthalpy, is shown as a negative peak. This, therefore, differs from the DTA curve since the peaks are in opposite direction and the information obtained is heat flow, rather than ΔT, as a function of temperature see Fig. (3). Also, as will be shown later, the integration of a DSC curve is directly proportional to the enthalpy change.

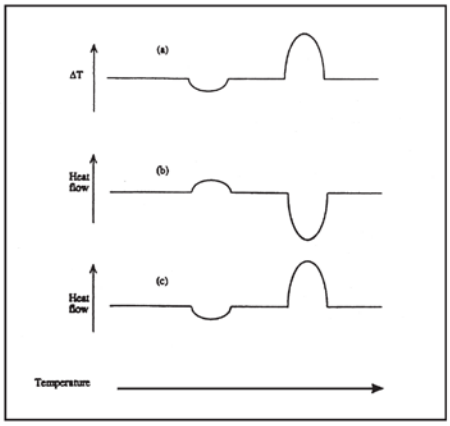

Fig. 3 Comparison of curves obtained on heating by (a) DTA, (b) Power-compensatig DSC, and (c) heat-flux DSC.

- **Thermogravimetry**

Thermogravimetry (TG) measures the change in mass of a material as a function of time at a determined temperature (i.e., isothermal mode), or over a temperature range using a predetermined heating rate. Essentially, a TG consists of a microbalance surrounded by a furnace. A computer records any mass gains or losses. Weight is plotted against a function of time for isothermal studies and as a function of temperature for experiments at constant heating rate. Thus, this technique is very useful in monitoring heat stability and loss of components (e.g., oils, plasticizers, or polymers). Thermogravimetry is also widely used both in studies of degradation mechanisms and for methods for service lifetime prediction measurements.

- **High Resolution TG**

Reactions investigated by TG are, by nature, heterogeneous. Therefore, experimental results are affected by weight, geometry, and particle size of the specimen. Moreover, temperature calibration and thermal gradient in the material can also affect the results. Hence, low heating rates should be used to alleviate the problem and to obtain good resolution under non-isothermal conditions. With complex systems such as polymers and fiber reinforced composites, good resolution is essential to obtaining reliable results and kinetic parameters that can be used to compare the stability of different systems and assess their lifetime.

3.2.1.7.2 Modern Techniques

- **Thermomechanical Analysis (TMA)**

Thermomechanical analysis (TMA), as defined by ASTM E473-85, is a method for measuring the deformation of a material under a constant load as a function of temperature while the material is under a controlled temperature program.

- **Dielectric Analysis (DEA)**

Dielectric analysis (DEA) or dielectric thermal analysis (DETA) is another important thermoanalytical technique that is rapidly evolving. This technique measures two fundamental electrical characteristics of a material—capacitance and conductance—as a function of time, temperature, and frequency. The capacitive nature of a material is the ability to store electric charge whereas the conductive nature is the ability to transfer electric charge. The parameters measured in dielectric analysis are permitivity

(ε´) and the loss factor (ε´´) . [4] The former is the alignment of the molecular dipoles in the material and the latter represents the energy required to align the dipoles or move trace ions. DEA is used in the characterization of thermoplastics, thermosets, composites, adhesives, and coatings, and it is complementary to other thermoanalytical techniques such DSC, DMA, TG, and TMA. DEA is an important technique because it has high inherent sensitivity, wide frequency range, and the ability to easily detect rheological changes that occur during heating of uncured materials as shown in Fig (4).

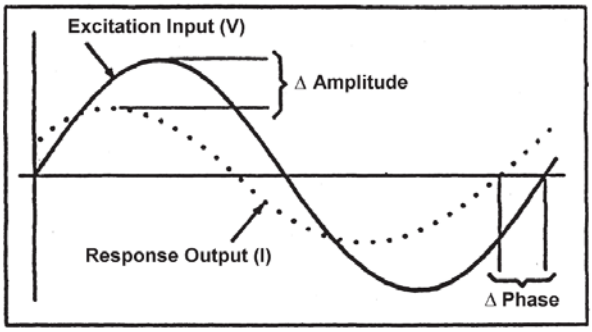

Figure 4. DEA excitation and response. The mobility of ions and dipoles is measured applying a sinusoidal voltage to the sample and measuring the current. [4]

- **Conduction Calorimetry**

The reaction of various types of cements and their components with water is an exothermic process. The intensity of heat liberated with time depends on the type of chemical, surface area, reactivity, etc. Measurement of the total heat and rate of heat development provides information on the kinetics of hydration, degree of hydration, mechanism of hydration, the effect of additives, setting phenomenon, etc. Conduction calorimetry finds extensive applications in concrete technology.

- **Applications**

Conduction calorimetry has been widely used for a study of the hydration reactions of various cementitious systems. Tricalcium silicate, being the dominant compound in portland cement, determines to a large extent the strength and other properties of concrete. Conduction calorimetric curves of tricalcium silicate and portland cement show five steps during the hydration process Fig. (5) and Fig. (6). [4] In the first stage, as soon as the silicate or cement comes into contact with water, Ca and OH ions are released into the solution phase. This is followed by a rapid release of heat that ceases within 10–12 minutes. This is called the pre-induction period. In the second stage, the reaction is slow, and it is known as the dormant or induction period. This may be extended or shortened by a few hours by the addition of a small amount of chemicals, known as chemical admixtures. In the third stage, the reaction proceeds rapidly and accelerates with time, releasing a maximum amount of heat at the end of the acceleratory period. At this stage, a rapid crystallization of calcium hydroxide occurs. In the fourth stage, there is a slow deceleration. At the final stage, there is only a limited formation of products, and at this stage the reaction is diffusion controlled. Thus, conduction calorimetry permits determination of the rate and amount of hydration as a function of temperature, the water: cement (w/c) ratio, the type of admixture added, the particle size of the starting material, etc [4] and [5].

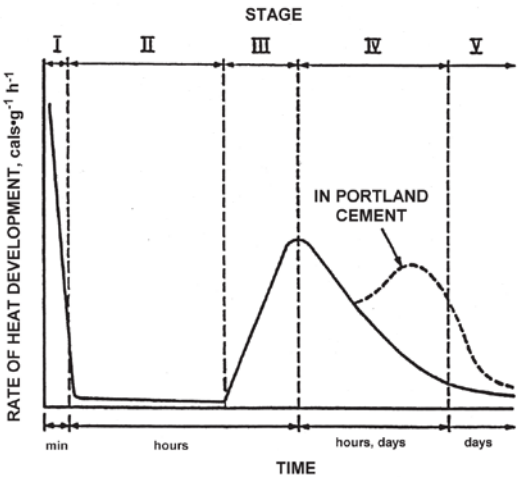

Figure 5. Conduction calorimetry curves of hydrating tricalcium silicate and cement.

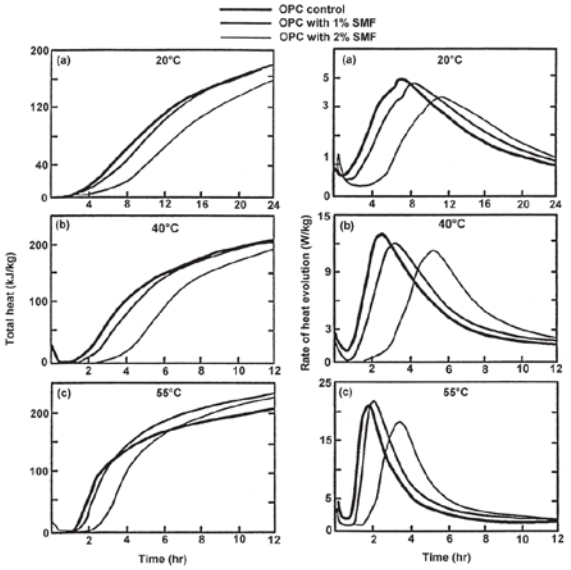

Figure 6. Conduction calorimetric curves of superplasticized cement at different temperatures.

3.2.2 Steel

There are essentially two approaches that may be used to assess residual steel strengths for steel. The first is to remove test coupons or samples and subject those specimens to a standard tensile test. Care should taken in removing test specimens in that the damaged structure is not further weakened, and that again any necessary propping should be used. The second is to use non-destructive tests of which the most suitable is a hardness indentation test usually measuring the Brinell hardness. There is a direct, sensibly linear, relationship between the Brinell hardness number (BHN) and tensile strength [5] as shown in Fig (7). It is important that care is taken in using this test since a number of results are needed before the strength estimates are statistically reliable.

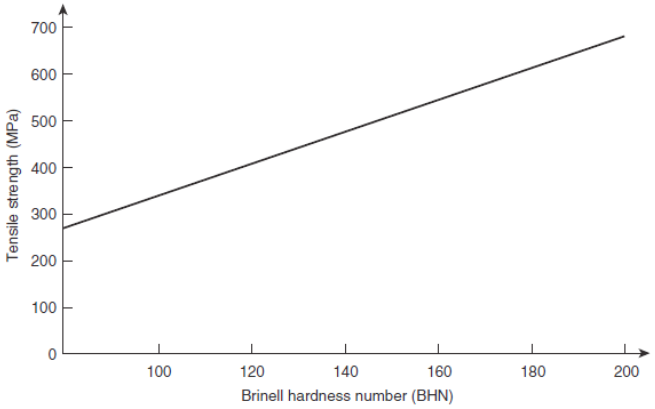

Figure 7 Relationship between steel strengths and Brinell hardness number (BHN) [5].

4. Strength Assessment of the Structure

This can either be performed using materials strength data derived from testing regimes described in the foregoing section, or by assessment of the temperatures within the structural element and knowledge of residual, i.e. post-heating and cooling, properties of materials. Often, it should be noted that combination of these two approaches will be needed. Effectively, any strength assessment of an element of a structure can be undertaken using the same basic approaches as outlined in previous chapters for the assessment of structural performance at elevated temperatures. Use can also be made of experimental results from residual strength tests on fire affected members.

4.1 Residual properties

Besides the residual properties of concrete and steel, it is also necessary to consider materials of a more historical nature such as wrought or cast iron, as fire damage is no respecter of history!

4.1.1 Concrete

The only essential property of concrete required for the assessment of fire damage is the residual compressive strength. Typical strength data for normal strength concrete from Malhotra [6] and Purkiss [5] are plotted in Fig. (8) through (11). From the plotted data, it may be observed that older, historical concretes appear to give a worse performance than more modern concretes. both support the data by Purkiss, in that, normal strength concrete loses about 25% of its strength at 400◦C, 60% at 600◦C and 85% at 800◦C. The residual strength of concrete is lower than that strength measured at elevated temperatures as there is further degradation on cooling caused by differing thermal properties between the aggregate and the cement matrix. Fig (12) through (15) represents the physical properties of concrete during exposure to fire or elevated temperatures. Stress relaxation, Creep, Thermal conductivity and volumetric specific heats for normal and lightweight concrete were discussed as shown in Fig (12) through (15).

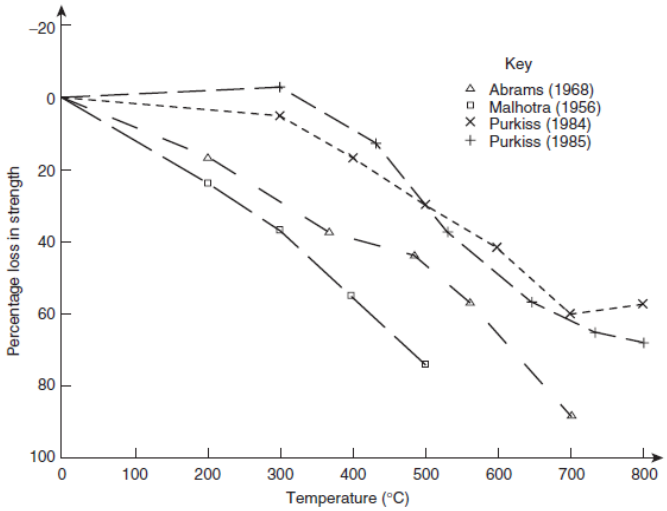

Figure 8: Variation of residual strengths of concrete with temperature [6] and [5].

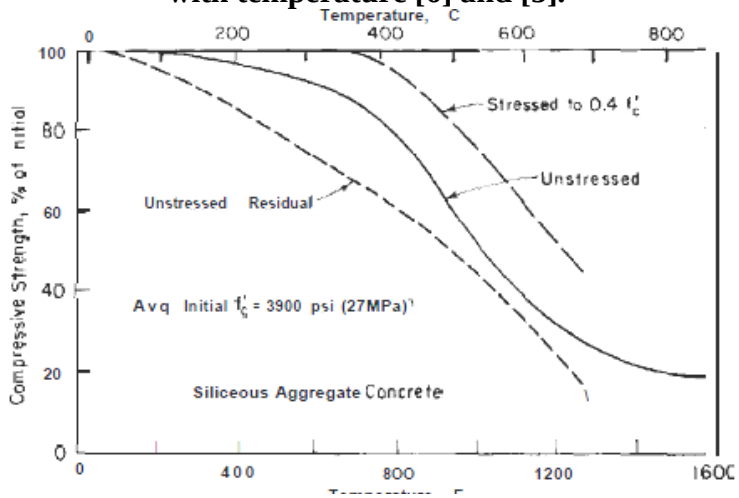

Fig. 9: Compressive strength of siliceous aggregate concrete at high temperature and after cooling.

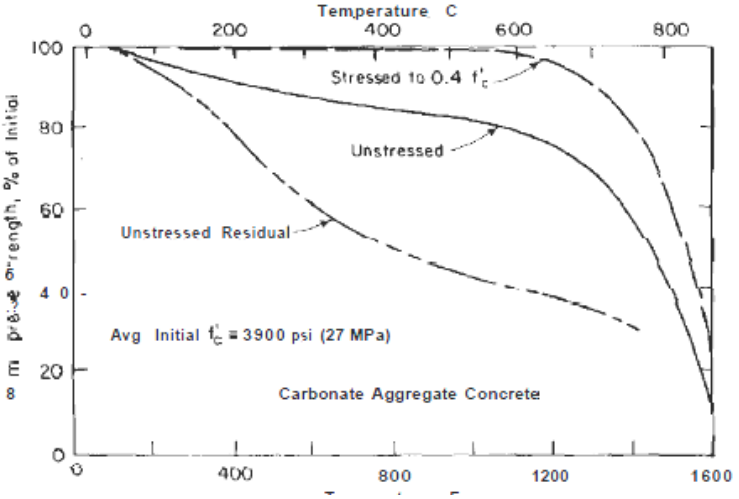

Fig. 10: Compressive strength of carbonate aggregate concrete at high temperature and after cooling.

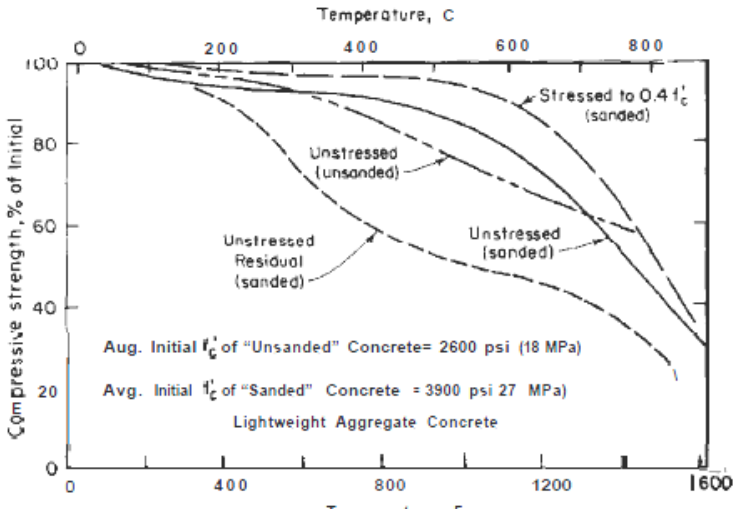

Fig. 11: Compressive strength of lightweight aggregate concrete at high temperature and after cooling.

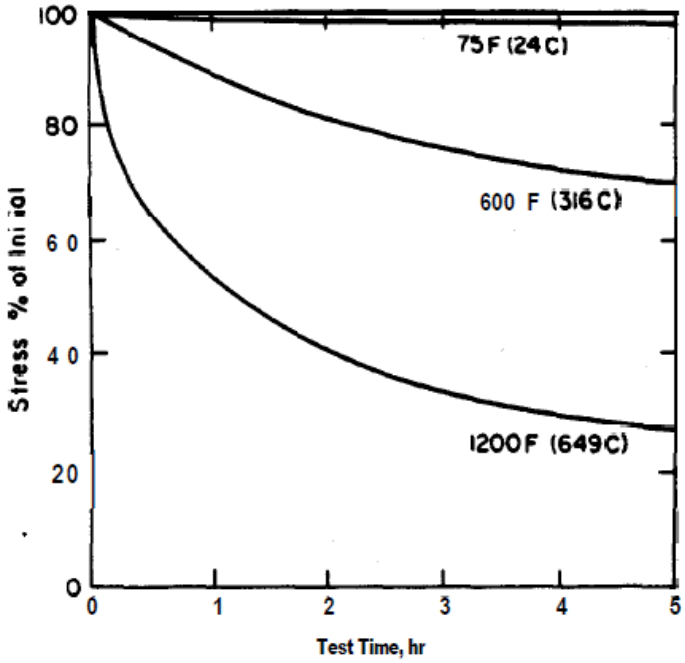

Fig. 12: Stress relaxation of a carbonate aggregate concrete.

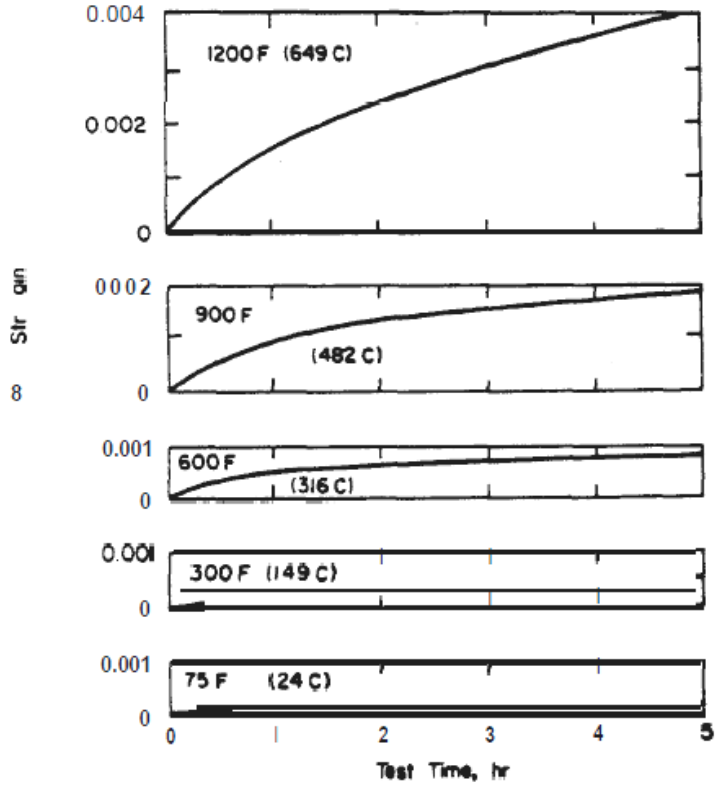

Fig. 13: Creep of a carbonate aggregate concrete at various temperatures [applied stress=1800psi (12Mpa), Fc=4000Psi(28Mpa)].

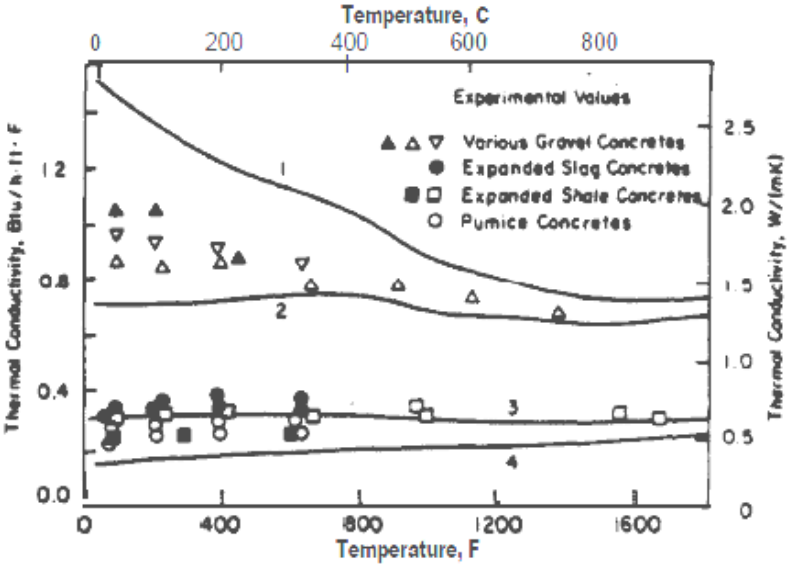

Fig. 14: Thermal conductivity of four "limiting" concretes and some experimental thermal conductivity data.

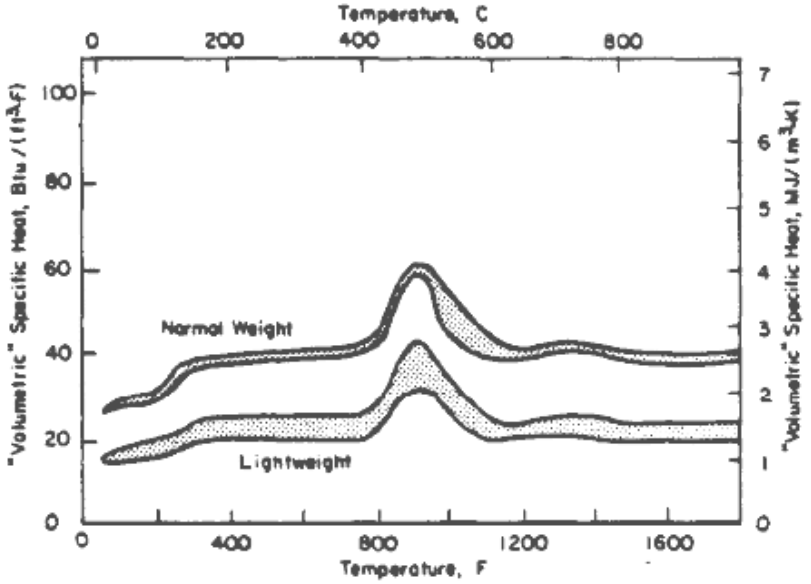

Fig. 15: Volumetric specific heats of normal weight and lightweight concretes.

- **High performance concrete**
  Phan and Carina [7] present data on residual compressive strength loss on high performance concretes with and without silica fume. The concretes with silica fume behaved better than those without. The mixes with silica fume retained between 75 and 100% of their ambient strengths between 20 and 300◦C with the concrete having a lower water/cement ratio behaving appreciably better.
- **Self-compacting concrete**
  In reference [8] through [15] Mechanical and physical properties of SCC were studied and discussed and also provide much of the available data on residual properties of self-compacting concrete of strengths between 15 and 60MPa which can be summarized by the following formulae:
  Residual compressive strength:

$$E_{stat,res} = f_{c,20}(90{,}507 - 0{,}000263\theta - 0{,}00152 f_{c,20}) \qquad (2)$$

  subject to the limit $5 \leq fc,20 \leq 60$ MPa.

4.1.2 Reinforcing and pre-stressing steels

Data on such steels are presented in Fig. 4.16 [5], where it is seen that the yield strength for reinforcing steel shows an increase above ambient strength at temperatures below about 550◦C, but a decrease at temperatures above 550◦C. Pre-stressing steels show no change in strength below 300◦C, but a substantial drop after this point such that at 800◦C only around 50% of strength remains.

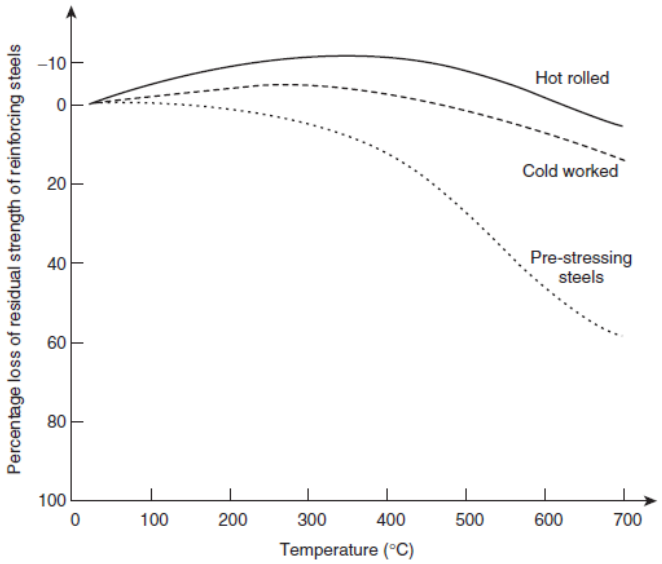

Figure 16: Variation of residual strengths of reinforcing and pre-stressing steels with temperature [5].

4.2 Determination of temperatures within an element

The methods used here are exactly the same as used to assess the performance of structures during a fire. If standard solutions based on exposure to the standard furnace test are used, then the fire equivalent time will need calculating to enable such methods to be used to give realistic answers. Purkiss [5] reported visually observed colour changes in heated concrete. However, such changes can be difficult to observe by eye alone often due to the type of aggregate. The application of colour image analysis techniques can overcome this problem. By determining the change in hue when concrete is heated, there is an obvious change in the frequency of occurrence of red [5]. The other primary colours yellow and green appear to have little impact. When a temperature range of 20–500◦C is examined, it is noticed that an increase in hue values occurs at temperatures of around 250–300◦C. For situations where there is a thermal gradient, the onset of change in hue values corresponds with a temperature level of around 300◦C table (3).

Table 3 Colour changes in heated concrete [5]

Concrete type	Colouration	Temperature (°C)	Condition
Siliceous	Normal	0–300	Normal strength
	Pink	300–600	Loss in strength
	Whitish-grey	600–900	Weak and friable
	Buff	above 900	Weak and friable
Limestone	Grey	0–200	Normal strength
	Light pink	200–400	Loss in strength
	Dull grey	400–600	Poor

5. Conclusions:

1. Depending on the SEM results, it was found that the crack width increased by about 99% at 800^{o}C compared to the crack width of specimens which were not subjected to fire.
2. Depending on the XRD results, the peaks characterizing in the "quartz" phase is increased with increasing temperature from (300 to 600 ^{o}C) compared to control specimen at ambient temperature.
3. Depending on the XRD results, the intensity of the peaks of "dolomite" increases as temperature increases up till 600 ^{o}C, where a sharp decrease was noticed in the intensity of peaks at 800 ^{o}C.
4. Depending on the DSC results, it is noticed that the peak of intensities of the main endothermic characteristic for calcium hydroxide and calcium silicate hydrate increase by increasing temperature till 300 ^{o}C. While there is a complete disappearance of the endothermic characterized the calcium silicate hydrate, at 800 ^{o}C.
5. It is concluded that the microstructure of concrete exposed to fire does not dependent on the mechanical properties of concrete.

References:

[1] **V. P. Bushev, et al., (1978)**. Fire Resistance of Buildings. AMERIND Publishing Co. PVT, LTD. New Delhi Bombay Calcutta, New York.

[2] **D. J. Naus, (2005)**. "The Effect of Elevated Temperature on Concrete Materials and Structures - A Literature Review". NUREG – XXX, ORNL/TM – 2005/553.

[3] **NIST GCR 07-910 NIST, (2007)**. "Fire Resistance Testing for Performance-Based Fire Design of Buildings". Final Report. National Institute of Standard and Technology.

[4] **V. S. Ramachandran, et al., (2002)**. "Handbook of Thermal Analysis of Construction Materials. NOYES Publications", Wiliam Andrew publishing, Norwich, New York, U.S.A.

[5] **J.A. Purkiss, (2007)**. "Fire Safety Engineering Design of Structures". Elsevier, BH.

[6] **Malhotra HL, (1956)**. "Effect of Temperature on the Compressive Strength of Concrete", Magazine Concrete Research, PP. 85-94.

[7] **Phan LT, Carino N.J, (1998)**, "Review of Mechanical Properties of HSC at Elevated Temperatures". ASCE. Material Journal. 10 (I), PP. 58-64.

[8] **S. Bakhtiyari et al., (2011).** "Self-Compacting Concrete Containing Different Powders at Elevated Temperatures – Mechanical Properties and Changes in the Phase Composition of the Paste". Thermochimica Acta 514. 74–81.

[9] **Mucteba, Uysal, (2011)**. "Self-Compacting Concrete Incorporating Filler Additives: Performance at High Temperatures". Construction and Building Materials 26. 701–706.

[10] **Neelam Pathak, Rafat Siddique,** (**2012**). "Properties of Self-Compacting-Concrete Containing Fly Ash Subjected to Elevated Temperatures". Construction and Building Materials 30. 274–280.

[11] **Patrick Bamonte, Pietro G, Gambarova, (2012)**. "A Study on the Mechanical Properties of Self-Compacting Concrete at High Temperature and After Cooling". Materials and Structures. Published online.

[12] **E. Annerel, L. Taerwe,** (**2011**). "Evolution of the Strains of Traditional and Self-Compacting Concrete During and After Fire". Materials and Structures 44:1369-1380.

[13] **M.A. Helal, Kh. M. Heiza, (2010)**. "Effect of Fire and High Temperature on the Properties of Self Compacted Concrete". CICE 2010 The 5th International conference on FRP composites in civil engineering, September 27-29, , Beijing, China.

[14] **Michael Stegmaier, Hans-Wolf Reinhardt, (2004)**. "Fire Behaviour of Plain Self-Compacting Concrete (SCC) ". Otto-Graf Journal vol. 15.

[15] **H. Mostafaei et al., (2009)**. "Recent Developments on Structural Fire Performance Engineering- A State of the Art Report". No. 275, **January 26**.

[16] **Khaled Heiza, (2012),** "Behaviour and Analysis of Reinforced Concrete Structures Subjected to Fire or Elevated Temperatures" State-Of-The-Art-Report, Submitted to the Scientific-Permanent Committee for Promotion, Structural Engineering and Construction, Egypt, May 2012.

[17] Kh. Heiza "State of the art review on assessment of fire-damaged RC structures" , Eighth Conference on Egyptian Rural Development October 2012. Egypt.

[18] Kh. Heiza "State of the art review on effect of fire on constituentes of concrete" , Eighth Conference on Egyptian Rural Development October 2012. Egypt.

[19] Kh. Heiza "State of the art review on effect of fire on reinforced concrete elements" , Eighth Conference on Egyptian Rural Development October 2012. Egypt.

[20] Kh. Heiza "State of the art review on fire safety of rc structures" , Eighth Conference on Egyptian Rural Development October 2012. Egypt.

[21] Kh.Heiza "Performance of Self-Compacted Concrete Exposed to Fire or Aggressive Media", The Journal of CRL Letters, Vol. 3 (2) – June 2012.

[22] Heiza Kh. and Marzouk H., "State-of-The-Art-Review on the Effects of Fire on Bridge Components Reinforced with FRP Internal Reinforcement", Proposal submitted to Canada Ministry of Transportation of Ontario Highway, March 2013.

[23] Heiza Kh. and Helal M., "Towards a World Stratigy for Fire Specifications to Protect Reinforced Concrete Structures against Fire", Symposium and Exhibtion Quality Control Laboratories in Structural Projects. Riyadh, Saudi Arabia 21-23 April 2013.

[24] Kh. M. Heiza "Effect of fire and elevated temperature on the reinforced concrete structures-Mechanics and design" , First edition 2014.

[25] Kh. M. Heiza ”Design of reinforced concrete structures subjected to fire according to NFPA-5000 – Building construction and safety code" , Second edition 2015.
[26] "Building Construction and Safety Code-NFPA-5000", 2015.