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# IMPACT OF HIGH TEMPERATURES ON MULTIBLENDED CONCRETES

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Abstract - *Concrete gets affected either by the service environment to which it was exposed or physical – chemical causes due to the reasons residing within. The reduction in engineering properties of concrete such as strength, elastic modulus, and durability occur due to variety of chemical and physical causes such as corrosion of reinforcements, sulphate and sea water attack, carbonation, freezing and thawing, thermal effects, abrasion, and nature of materials (e.g., type of aggregate and cement blend).*

*In case of accidental fire, concrete subject to high temperature which leads to severe deterioration and it undergoes a number of transformations and reactions, thereby causing progressive breakdown of cement gel structure and consequent loss in its load-bearing capacity, reduced durability, increased tendency of drying shrinkage, structural cracking, and associated aggregate colour changes.*
*The behaviour of concrete in fire depends on its mix proportions and constituents and is determined by complex physicochemical transformations during heating. Normal-strength concretes and high-performance concretes micro structurally follow similar trends when heated. Failure of structural concrete in fire varies according to the nature of the fire; the loading system and the type of structure. Failure could occur from loss of bending or tensile strength; loss of bond strength; loss of shear or torsional strength; loss of compressive strength; and spalling of the concrete.*
*Assessment of the condition of concrete and extent of damage after the fire is an important requirement for taking possible corrective measures for its rehabilitation. Therefore, systematic parametric studies on simulated conditions of temperatures such as that generally experienced during an accidental fire in concrete structures are of utmost importance. The present study considered the thermal effects on concrete and reported the physicochemical, mineralogical, and morphological changes in pre- and post fired concrete.*

*The effect of a high temperature on concrete covers changes taking place in cement paste, aggregates, as well as the interaction of these two constituents, that result in changes of mechanical and physical characteristics of concrete. This paper presents the effect of a high temperature on selected physical properties of concrete such as compressive strength for quantitative assessment and ultrasonic pulse velocity testing to assess qualitative assessment; it also includes colour change and spalling effects.*

*Key Words:* Concrete, high temperature, fire damage, mechanical properties, residual properties.

## 1. INTRODUCTION

Interest in the behaviour of concrete at a high temperature mainly results from the many cases of fires taking place in buildings, high-rise buildings, tunnels, and drilling platform structures. During a fire, the temperature may reach up to $1100^{0}$ C in buildings and even up to $1350^{0}$ C in tunnels, leading to severe damage in a concrete structure [1]. However, in some special cases, even much lower temperature, may cause explosive destruction of concrete, thus endangering the bearing capacity of the concrete element. Nevertheless, concrete is considered a construction material that satisfactorily preserves its properties at high temperature. Owing to concrete's fairly low coefficient of thermal conductivity, the movement of heat through concrete is slow, and thus reinforced steel, which is sensitive to high temperature, is protected for a relatively long period of time. When concrete is heated under conditions of fire, the increase in temperature in the deeper layers of the material is progressive, but because this process is slow, significant temperature gradients are produced between the concrete member's surface and core inducing additional damage to the element. Fundamental issues related to the impact of high temperature on concrete involve identification of the complex changes that take place in concrete while heated. This concerns both the physical and chemical changes taking place in the cement matrix. The analysis is complicated due to the fact that cement concrete is a composite consisting of two substantially different constituents: cement paste and aggregates. The effects of the various changes taking place in heated concrete are the alterations of its physical, thermal, and mechanical properties. Research has demonstrated [Khoury *et al.* (1992)], that changes in the strength of concrete as a function of temperature are related to, inter alia, concrete composition the type of aggregate used, the water/cement ratio, the presence of pozzolana additives, etc. Important factors are also the rate of heating and the time of concrete exposure to high temperature.

The increase in temperature resulted in water evaporation, C-S-H gel dehydration, calcium hydroxide and calcium aluminates decomposition, etc. Along with the increase in temperature, changes in the aggregate take place. Due to those changes, concrete strength and modulus of elasticity gradually decreases, and when the temperature exceeds 300$^0$C, the decline in strength becomes more rapid. When the temperature of threshold value of 500$^0$ C is passed, the compressive strength of concrete usually drops by 50% to 60%, and the concrete is considered fully damaged. The Euro code method of calculating the load bearing capacity of reinforced concrete members subjected to a fire is based on this assumption.

Concrete cubes prepared from ordinary Portland cement (OPC) of known chemical, mineralogical, and physical performance characteristics and fired to various temperature regimes up to 800$^0$ C in steps of 100$^0$ C for a constant period of 5 h have been studied to establish the effect of elevated temperatures. The changes in physical state of concrete were studied by measuring ultrasonic pulse velocity (UPV) and consequent deterioration in the compressive strength with increase in temperature.

## 2. IMPACT OF TEMPERATURE ON CONCRETE MATRIX

2.1. Cement Paste - The heating of cement paste results in drying. Water gradually evaporates from the material. The order in which water is removed from heated concrete depends on the energy that binds the water and the solid. Thus, free water evaporates first, followed by capillary water, and finally by physically bound water. The process of removing water that is chemically bound with cement hydrates is the last to be initiated. The mechanical properties of cement paste are strongly affected by chemical bonds and cohesion forces between sheets of calcium silicate hydrate (C-S-H) gel. It is assumed that approximately 50% of cement paste strength comes from cohesion forces (important C-S-H gel sheet area); therefore, the evaporation of water between C-S-H gel sheets strongly affects the mechanical properties of the cement paste [Feldman *et al.* (1968)]. However, when the cement paste is heated in moist sealed conditions, hydrothermal reactions may take place. This phenomenon, called internal autoclaving [Piasta *et al.* (1989)], may occur in large members where, due to heating, moisture is transformed into water vapour. In these conditions chemical and physical changes may take place. The process of simultaneously exposing the material to high pressures and temperature is a well-known technology in the prefabrication of concrete. This may well activate changes in the microstructure of hydrates and often increases cement paste strength. The nature of the phase changes will depend upon the mineralogical composition of the cement, its C/S ratio (moles of lime per mol of silica; $CaO/SiO_2$), the amount of fine particles (quartz or silica fume), and the temperature and pressure levels that have been reached [Verbeck *et al.* (1972)]. Heating the cement paste with a C/S ratio around 1.5 to temperature above 100$^0$ C produces several forms of calcium silicates, in general highly porous and weak. When the C/S ratio is close to 1.0 and the temperature is above 150$^0$ C, a 1.5 to 1.0 to be morite gel can form. At temperature between 180$^0$ C and 200$^0$ C, other silicates such as xonolite and hillebrandite may be formed.

Recently, micro structural changes of heated cement pastes have been studied by neutron diffraction [Castellote *et al.*(2004)]. This research demonstrates the temperature at which the main products of hydration of Portland cement, including portlandite, ettringite, calcite, lime, larnite, and hydrated calcium silicate (C-S-H gel), are present. During heating, ettringite decomposes first, even before the temperature reaches 100$^0$ C. C-S-H gel dehydration is progressive and takes place from the very beginning of material heating. It is worth noting that the structure of the cement paste is partially damaged due to dehydration at the temperature of 105$^0$ C, which is standard for the drying of materials. As soon as cement paste is heated to temperature of 500–550$^0$ C, the portlandite content rapidly drops, as it decomposes according to the following reaction:

$$Ca(OH)_2 \rightarrow CaO + H_2O\uparrow.$$

The portlandite decomposition reaction explains the observed increase in CaO content in cement paste at the temperature of approximately 550$^0$ C [5,7]. The CaO created in this reaction makes the elements made of the Portland cement practically redundant after cooling.

The dehydration process of the C-S-H gel reduces its volume, which in turn increases the porosity of the cement matrix. Moreover, during heating, the cement paste experiences a slight expansion up to temperature of approximately 200$^0$ C [5, 6, 8, 9] although the intense shrinkage begins as soon as this temperature is exceeded. This significantly contributes to the porosity evolution of the cement paste. Due to heating total pore volume increases, as does the average pore size.

2.2. Aggregate - Aggregates occupy 70–80% of the volume of concrete and thus heavily influence its thermal behaviour. The term "thermal stability of aggregates" is employed [2] to describe aggregates effect on concrete performance at high temperature. "Thermally stable" aggregates are characterized by chemical and physical stability at high temperature, which is determined by dilatometric, as well as thermogravimetric, and differential thermal tests. Considering concrete behaviour at high temperature, a suitable aggregate would be one with a low thermal strains coefficient as well as negligible residual strains. Mineralogical composition determines aggregate thermal strains, since all minerals differ in their thermal expansion properties. The type of minerals governs the chemical and physical changes that take place during heating. For example: quartz aggregates and sands change at 574$^0$ C due to the ß -a quartz inversion. This physical transformation involves a volumetric increase. The carbonate stones (limestone and dolomite) are stable up to 600$^0$ C. At higher temperature, carbonate aggregate decomposes into CaO and $CO_2$ (700$^0$ C). Additionally, the CaO formed during de-carbonation may hydrate when cooling, with a consequent 44% expansion. The polymineralic stones may be prone to the disintegration that results from the thermal incompatibility of its components. For those stones differences in thermal strain can cause inter-crystalline stresses and failure. The further heating of aggregate leads to its melting. The melting temperature varies along the mineralogical composition, for most igneous rock it is above 1000$^0$ C. The melting temperature of granites is 1210–1250$^0$ C, while basalts melt at 1050$^0$ C, which is accompanied by gas release and expansion.

### 2.3. Cement paste and aggregate interaction in concrete during heating.

The heating of concrete makes its aggregate volume grow, and at the same time it causes the contraction of the cement paste which surrounds it. As a result, the cement paste-aggregate bond is the weakest point in heated cementitious material. To a large extent, damage to concrete is caused by cracking, which occurs arising due to mismatched thermal strains between the coarse aggregates and the matrix. Table 1 lists the changes that take place in concrete components: cement paste and aggregates. The changes are listed according to the temperature of their occurrence and were compiled on the basis of [2, 5] and [7].

Table 1: The list of changes taking place in concrete during heating

| Temperature range | Changes |
|---|---|
| 20$^0$–200$^0$ C | Slow capillary water loss and reduction in cohesive forces as water expands;<br>80$^0$ –150$^0$ C ettringite dehydration;<br>C-S-H gel dehydration;<br>150$^0$–170$^0$ C gypsum decomposition ($CaSO_4 .2H_2O$);<br>physically bound water loss; |
| 300$^0$–400$^0$ C | Approx. 350$^0$ C break up of some siliceous aggregates (flint);<br>374$^0$ C critical temperature of water; |
| 400$^0$–500$^0$ C | 460$^0$–540$^0$ C portlandite decomposition: $Ca(OH)_2 \rightarrow CaO + H_2O$; |
| 500$^0$–600$^0$ C | 573$^0$ C quartz phase change β - α in aggregates and sands; |
| 600$^0$–800$^0$ C | Second phase of the C-S-H decomposition, formation of β-$C_2S$; |
| 800$^0$–1000$^0$ C | 840$^0$ C dolomite decomposition;<br>930$^0$–960$^0$ C calcite decomposition: $CaCO_3 \rightarrow CaO + CO_2$, carbon dioxide release;<br>ceramic binding initiation which replaces hydraulic bonds; |
| 1000$^0$–1200$^0$ C | 1050$^0$ C basalt melting; |
| 1300$^0$ C | Total decomposition of concrete, melting. |

## 3. EXPERIMENTAL PROGRAM

The behaviour of concrete in fire depends on its mix proportions and constituents. In this study, M30 grade of concrete was used with its ingredients, Ordinary Portland cement, fly ash, fine aggregates, coarse aggregates and admixture. Different proportions of fly ash were used to study the effect of high temperatures on multi blended concrete.

### 3.1. Properties of Ingredients

The properties of concrete are significantly influenced by the basic properties of constituent materials. Therefore, the preliminary properties of Ordinary Portland cement, fly ash, fine aggregates, coarse aggregates, admixture and mixing water are evaluated according to relevant codes. Care has been taken to ensure that the same type of OPC, fly ash, fine and coarse aggregates were used throughout this investigation.

Cement: The cement used throughout the test programme was OPC (43 grade) confirming to IS: 8112-1989. The chemical and physical properties of the cement were tested as per the IS: 4032-1985 & IS: 4031-1988 [19] respectively.

Superplasticizer: High range water reducing admixture called as super plasticizers are used for improving the flow or workability for lower water-cement ratios without sacrifice in the compressive strength. This super - plasticizer is available with standard specifications of ASTM C 494 Type G and IS: 9103-1999.

Fine aggregate: The fine aggregate used was locally available Badarpur sand. The fine aggregate was tested for

its physical requirements as per relevant IS 2386 (Part I to VII)-1963 and it confirmed to IS: 383-1970.
Coarse aggregate: Properties of the aggregates which influence the properties of both the fresh and the hardened concretes have to be considered when the concrete is proportioned. The coarse aggregates were locally available crushed quartzite aggregates. The coarse aggregate was tested for its physical properties as per relevant IS 2386 (Part I to VII)-1963 and it confirmed to IS: 383-1970 for wearing as well as non wearing surfaces.

Water: Water used for mixing and curing was tested as per IS: 3025 – 1964 and IS: 456 – 2000.

## 4. MIX DESIGN PROCEDURE

The main object of concrete mix design is to select the optimum proportions of the various ingredients of concrete which will yield fresh concrete of desirable properties like workability and hardened concrete possessing specific characteristic compressive strength and durability.

Besides these requirements it is essential that the concrete mix is prepared as economically as possible by using the least possible amount of cement content per unit volume of concrete, with due regard to the strength and durability requirements as per IS 456-2000. Since concrete is produced by mixing several discrete materials, the numbers of variables governing the choice of mix design are necessarily large.

The concrete mix proportions were calculated as per IS 10262-2004 [16]. The trial mixes were performed to arrive at the required mix proportions for M30 grade of concrete. The normal mix proportion is given in Table 2. The fly ash is also added in 20% and 30% of replacement of cement in different mix proportions. During trials, slump was measured and the water content and dosage of admixture are adjusted for achieving the required workability based on trial and error method. The mix proportions are reworked for the actual water content and checked for durability requirements.

Table 2: Designed Mix Proportion

| Mix No. | Cement kg/m³ | Fly ash kg/m³ | F.A. kg/m³ | C.A. kg/m³ | w/c | S.P. % by wt of cem. |
|---|---|---|---|---|---|---|
| $M_1$-0 | 364.91 | 0 | 698.68 | 1228.19 | 0.43 | 2 |
| $M_2$-0 | 291.93 | 72.98 (20%) | 698.68 | 1228.19 | 0.43 | 1 |
| $M_3$-0 | 255.44 | 109.47 (30%) | 698.68 | 1228.19 | 0.43 | 1 |

### 4.1. Preparation of Specimens

The cube specimens of size 150 mm x150 mm x150 mm were cast as per procedure laid down in IS: 516 -1959 (Reaffirmed 2004) [17] for each mix of concrete to determine the compressive strength. These specimens were air dried for 24 hr before they were cured for 7 and 28days for performing compressive strength test. Fig. 1 & 2 shows the mixing and casting of cubes in laboratory.

Fig. 1: Mixing of multiblend Concrete

Fig. 2: Casting of Cubes

### 4.2. Curing of the Specimens

The specimens were removed from the moulds after 24 hr from the time of adding the water to the ingredients. The specimens then marked for identification. These specimens were then stored in water for the required period of curing.

### 4.3. Ultrasonic pulse velocity and Compressive Strength Test

The water-cured cubes were dried in air at a temperature of $27^0 \pm 2^0$ C with relative humidity (RH) > 90% prior to getting exposed to a high-temperature regime up to $1000^0$ C in steps of $100^0$ C in a hot-air oven/muffle furnace for a constant retention period of 5 h. The air-dried pre- and post fired concrete cubes were assessed for their physical deterioration by ultrasonic pulse velocity (UPV) measurement by cross-probing method using portable ultrasonic non destructive digital indicator tester as per

IS:13311Part I (1992) [18]. The test setup for *Non Destructive Testing using Ultrasonic Pulse Velocity Method* is given in Fig.: 3.

### 4.4. Compressive strength

Compressive strength of a material is defined as the value of uni-axial compressive stress reached when the material fails completely. The fired cubes after cooling to ambient temperature were immersed in water for 48 h before testing for compressive strength. The cube specimens of size 150 mm x 150 mm x 150 mm are then tested in accordance with IS: 516 – 1969. The test setup for evaluation of *Compressive Strength is given* in Fig.: 4.

Fig. 3: Non Destructive Testing using Ultrasonic Pulse Velocity Method

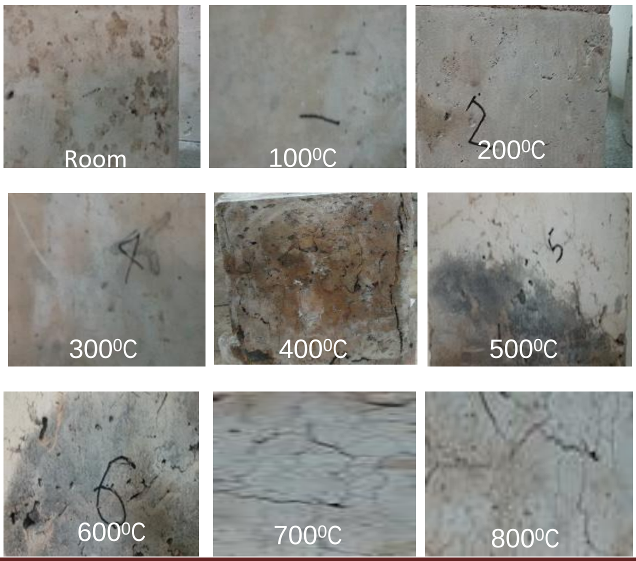
Fig. 4: Compressive Strength Testing under 200T CTM

## 5. RESULTS AND DISCUSSION

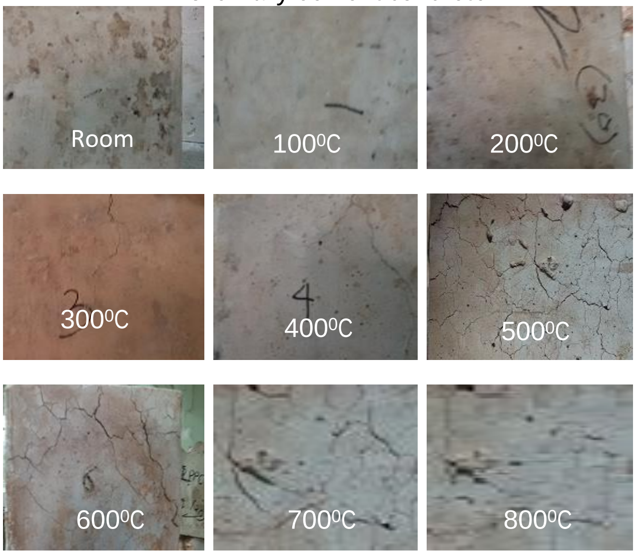
This paper presents the results of the investigation of the cement concrete behaviour at a high temperature from room temperature to 800$^0$C. It has been shown that the colour change of heated concrete might be the first indication of the potential deterioration of concrete due to heating. There are many ways to evaluate the deterioration. However, in this paper, compressive strength and ultrasonic pulse velocity tests are taken in to account for evaluate the deterioration of concrete exposed to a high temperature. The possible explanations of the observed gradual decrease of mechanical properties have been discussed in detail. Moreover, the important role of water was put forward in the context of the changes of concrete properties. By drying material, the extent of the phenomenon is significantly reduced, or even eliminated, at up to 400$^0$ C. Above this temperature, the mismatch of thermal deformations between the aggregates, which expand, and cement paste, which undergoes shrinkage, prevails and results in the development of cracks. Significant cracking continues, thus altering the material mechanical properties.

### 5.1. Colour Change of Heated Concrete

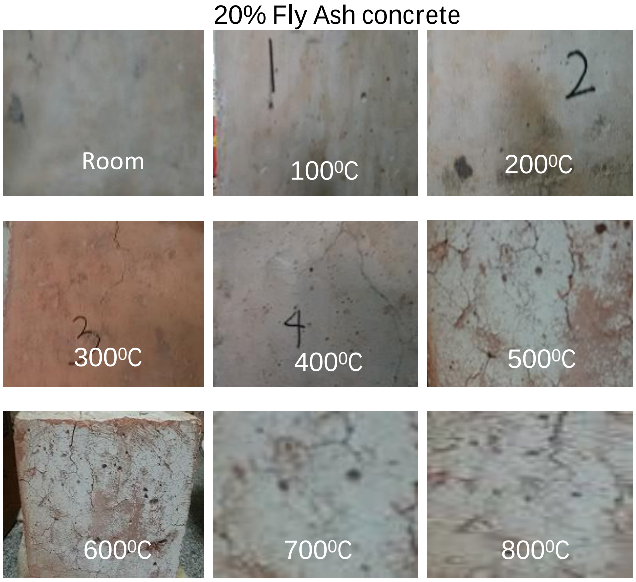
It is generally agreed [10, 11] that when heated to between 300$^0$C and 600$^0$C concrete containing siliceous aggregates will turn red; between 600$^0$ C and 900$^0$C, whitish-grey; and between 900$^0$C and 1000$^0$C, a buff colour is present. The colour change of heated concrete results principally from the gradual water removal and dehydration of the cement paste, but also transformations occurring within the aggregate [10–12]. The most intense colour change, the appearance of red colouration, is observed for siliceous riverbed aggregates containing iron. This colouration is caused by the oxidation of mineral components [10–12]. While siliceous aggregates turn red when heated, the aggregates containing calcium carbonate get whitish. Due to calcination process $CaCO_3$ turns to lime and give pale shades of white and grey. In general two approaches can be adopted when the colour change of concrete is analysed [12]. First, the external surface of the element can be examined. This involves observation of an element's outer walls (in particular, the cement paste). The other possibility is to observe surface with visible aggregates (sample cored or sawn out from the element). When it is necessary to evaluate the condition of concrete after a fire, colour change is a physical property of concrete that is used as an assessment method [10, 11].



Ordinary Cement concrete




20% Fly Ash concrete




30% Fly Ash concrete

Fig. 5: Colour Change in Concrete

In this study the results of cement concrete with OPC, 20% flyash and 30% flyash have been discussed. The physical appearance of the concrete cubes at different temperatures has been shown in Fig. 5. The visual observation of all the three cases (concrete with OPC, 20% flyash and 30% flyash) shows that concrete heated between 300⁰ C and 600⁰ C turned red. After 600⁰C onwards the concrete changes whitish-grey colour, the cracking of concrete also started. At 800⁰C heavy destruction of concrete observed.

## 5.2. UPV measurements

UPV measurements carried out on fired concrete cubes (with OPC, 20% flyash and 30% flyash) at 7days age and 28days age of concrete cubes have been discussed. The results are represented graphically as shown in Fig. 6 & 7 respectively. At 7days age, the concrete shows a reduction of velocity from 5.5 to 0.5 km/s with the increase in temperature from 100⁰ to 700⁰ C in case of concrete with OPC, reduction of velocity from 4.8 to 0.2 km/s in case of concrete with 20% flyash and 5.1 to 0.3 in case of 30% flyash concrete. The same pattern was observed at 28days age of concrete also. It indicates consequent gradual deterioration in the quality of concrete with OPC, 20% flyash and 30% flyash. Pulse transmission pattern across the cubes shows gradual decrease in its velocity with rise in temperature, and beyond 300⁰ C, it decreases rapidly due to the sharp deterioration in the physical state of fired concrete (as shown in Fig. 6 & 7). At 800⁰ C, the pulse could not be transmitted through the cubes indicating total deterioration in their physical state. However, in case of flyash concrete the improvement in the results was observed at higher temperatures in later ages of concrete.

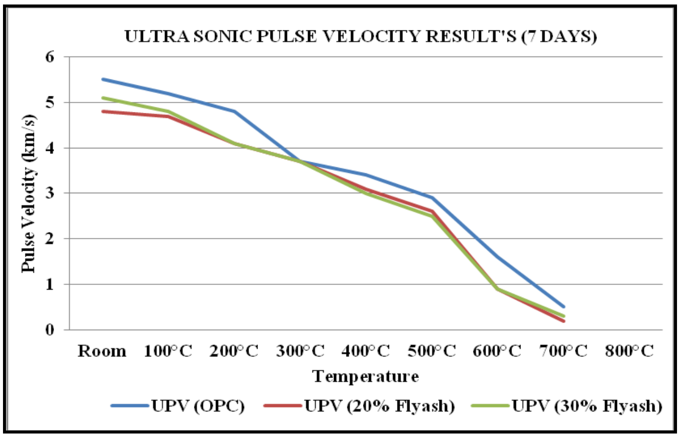



Fig. 6: Change in Ultrasonic Pulse Velocity with Temperature at 7days

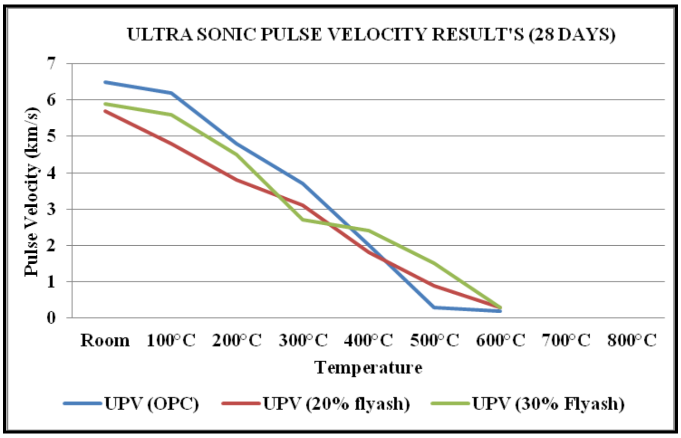



Fig. 7: Change in Ultrasonic Pulse Velocity with Temperature at 28 days

## 5.3. Evaluation of compressive strength

Changes in mechanical properties that occur during heating are the result of changes taking place in concrete. Those material factors include physico-chemical changes in cement paste and aggregates as well as the incompatibilities between them listed in Table 1. Other factors affecting the material damage level are as follows: heating rate, maximum temperature, time of exposure to temperature, load applied during heating, moisture content of the material, etc. The testing method itself has an important influence on the evaluation of the properties of heated material. The most common way to study the influence of high temperature on the properties of concrete is to expose the material to high temperature, cool it down to room temperature, and then carry out testing, such as compression or tensile tests. The testing after cooling gives the residual values corresponding to the post-fire performance of concrete. The lower values of residual mechanical properties are attributed to supplementary damage due to additional stresses caused by cooling. The extent of stresses depends on, among other things, the rate of cooling. As a result, rapid cooling or quenching results in higher levels of damage. The extent of damage done during the cooling phase may increase when moisture is absorbed from the surroundings. Rehydration of CaO the product of portlandite and/or calcium carbonate decomposition – results in a 44% increase of volume, causing the development of cracks.

Compressive strength carried out on fired concrete cubes (with OPC, 20% flyash and 30% flyash) at 7days age and 28days age of concrete cubes have been discussed in this section. The results are graphically represented in Fig. 8 & 9 respectively for 7 days and 28 days age of cubes. The compressive strength at 7days age of concrete with OPC shows a reduction of 26.22 to 4.75 MPa, concrete with 20% flyash shows 17.10 to 2.33 MPa and concrete with 30% flyash shows 15.96 MPa to negligible with the increase in temperature from 100$^0$ to 800$^0$ C. Also, the compressive strength at 28 days age of concrete with OPC shows a reduction of 36.5 to 5.6 MPa, concrete with 20% flyash shows 29.7 to 4.9 MPa and concrete with 30% flyash shows 26.7 to 3.8 MPa with the increase in temperature from 100$^0$ to 800$^0$ C. It has been observed that the rate of strength gain in 28 days in case of Concrete with OPC is about 28% and in case of concretes with 20% & 30% flyash is about 40%. Also in case of flyash blended concrete the rate of deterioration is progressively less with the increase in temperature from 100$^0$ to 800$^0$ C; it shows that the flyash blended concrete is more beneficial than concrete with OPC in later ages or performance of blended concrete will be better in high temperatures during the service period of the structures.

Also, it has been observed that concrete cubes exposed to different temperature regime for a constant period of 5 h have negligible effect on their compressive strength up to 300$^0$ C but suffer a significant loss of strength subsequently, due to the loss of crystal water resulting in the reduction of the $Ca(OH)_2$ content, besides the changes in the morphology and microcrack formation. Khoury [4] has made a similar observation that compressive strength of concrete declines sharply above 300$^0$ C. The reduction in the average compressive strength with temperature shows distinct distress beyond 700$^0$ C.

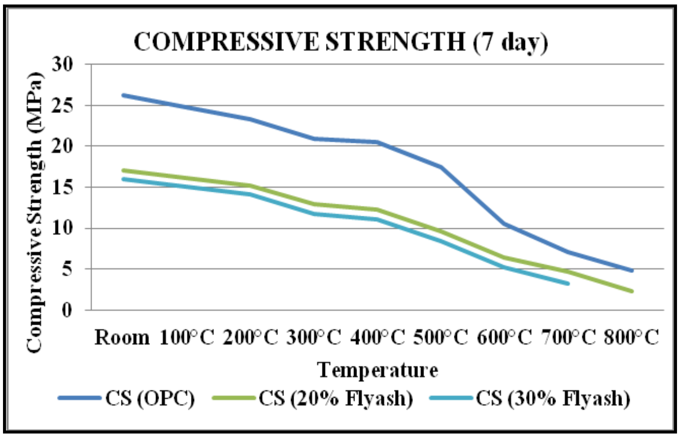



Fig. 8: Change in Compressive Strength with Temperature at 7days

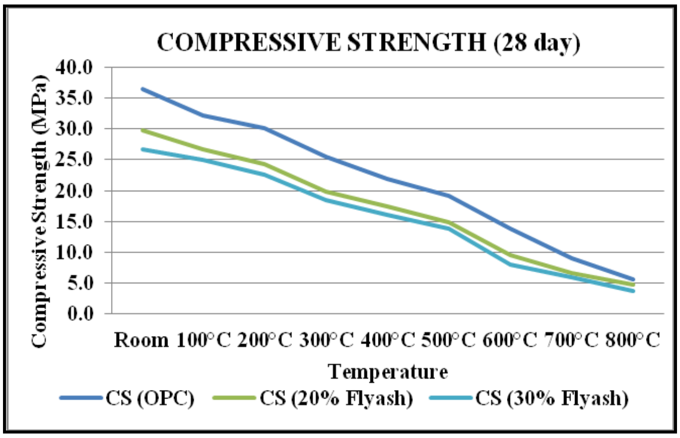



Fig. 9: Change in Compressive Strength with Temperature at 28days

## 6. CONCLUSIONS

1. The drastic reduction in pulse velocity across the concrete cubes between 300 and 700$^0$ C is noticed. It indicates that the physical state of concrete deteriorates rapidly beyond 300$^0$ C.
2. Reduction in the compressive strength of concrete exposed to higher temperatures beyond 500$^0$ C is quite rapid. The pulse could not be transmitted through the cubes indicating total deterioration in their physical state, it indicates the complete decomposition of portlandite beyond 700$^0$ C results in total deterioration of concrete.
4. The decrease in compressive strength and ultrasonic pulse velocity with increase in temperatures can be used for assessing the condition of building elements subjected to accidental fires.
5. After a fire, if the temperature is found to have reached beyond 500$^0$ C in a structural element, a detailed survey should be carried out to determine its structural integrity.

6. However, in case of blended concrete the deterioration is progressively less than normal OPC concrete.

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