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Research Article

STUDIES ON ELEVATED TEMPERATURES AND QUENCHING EFFECTS ON BLENDED CONCRETES

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ABSTRACT
When exposed to fire loads, concrete undergoes strength deterioration. Concrete is likely to be exposed to elevated sustained temperatures during fire accidents. In this study, an investigation is made to compare the compressive strength of cement based concretes containing silica fume and fly ash at elevated temperatures and when suddenly quenched in water. Four concretes of different mixtures with varying amounts of fly ash and silica fume were exposed to elevated temperatures of 150^{0}C, 300^{0}C, 450^{0}C, 600^{0}C, & 750^{0}C for a retention period of one hour. The residual strengths of these specimens were determined by axial compressive strength tests after cooling by sudden quenching in water. Strength and weight losses were compared with the initial values. Some interesting results are discussed and presented in this paper.

Key Words: *Blended Concretes, Fly Ash, Silica Fume, Elevated Temperatures, Water Quenching, Residual Strengths.*

INTRODUCTION
Concrete is the most widely used construction material and has established itself as the most versatile construction material in all the disciplines of civil engineering owing to its high compressive strength and mouldability. However, structural concrete is found to undergo serious damages when it is subjected to elevated temperatures due to accidental fires .The behaviour of concrete when subjected to elevated temperatures has been studied since past few decades and studies indicate strength deterioration with the increase in exposure temperature.
The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced during these exposures. This may result in undesirable structural failures. Therefore, the properties of concrete retained after a fire are of still importance for determining the load carrying capacity and for reinstating fire-damaged constructions.
The factors that influence the strength of cement based concretes and concrete under high temperatures can be divided into two groups: material properties and environmental factors. Properties of aggregate, cement paste and aggregate–cement paste bond and their thermal compatibility between each other (‘‘thermal inconsistency of the ingredients”) greatly influence the resistance of concrete. On the other hand, environmental factors such as; heating rate, duration of exposure to maximum temperature, cooling rate, loading conditions and moisture regime affect the heat resistance of cementitious materials.Nonlinearities in material properties, variation of mechanical and physical properties with temperature, tensile cracking, and creep effects affect the buildup of thermal forces, the load-carrying capacity, and the deformation capability (i.e. ductility) of the structural members. The property variations result largely because of changes in the moisture condition of the concrete constituents and the progressive deterioration of the cement paste-aggregate bond, which is especially critical where thermal expansion values for the cement paste and aggregate differ significantly.
The fire is generally extinguished by water and CaO turns into [$Ca(OH)_2$] causing cracking and crumbling of concrete. Therefore, the effects of high temperatures are generally visible in the form of surface cracking and spalling. Some changes in colour may also occur during the exposure. Elevated temperatures may cause aesthetic and functional deteriorations to the buildings. Aesthetic damage is

generally easy to repair while functional impairments are more profound and may require partial or total repair or replacement, depending on their severity.

The conversion of Calcium Hydroxide into lime and water vapor during heating is not critical in terms of strength loss. Nevertheless, it may lead to serious damage due to lime expansion during the cooling period. The detrimental effects of $Ca(OH)_2$ can be eliminated by using mineral admixtures such as, fly ash, silica fume and granulated blast furnace slag. Due to the pozzolanic reaction between $Ca(OH)_2$ from cement and reactive SiO_2 from these mineral admixtures, the amount of $Ca(OH)_2$ decreases in the system.

In this investigation, the effect of quenching in water on the residual mechanical properties of blended concrete mixtures produced by partial replacement of cement by silica fume and flyash after exposure to high temperatures from 150˚C to 750˚C, in increments of 150˚C, for a retention time of 1 hour, is reported.

Replacement by Mineral Admixtures

It is found that the pozzolans usually incorporated in concrete to enhance strength and durability play an important role in its fire performance. A number of research studies indicated that the addition of silica fume highly densifies the pore structure of concrete, which results in explosive spalling due to the build-up of pore pressure by steam. Since the evaporation of physically absorbed water starts at 80^{o}C, which induces thermal cracks, such concretes showed inferior performance as compared to pure OPC concretes at elevated temperatures. On the other hand, the addition of fly ash (FA), or ground granulated blast furnace slag (GGBS), enhances the fire resistance of concrete .

Cooling Regimes

Mendes, *et al.,* (2000) have studied the effect of ordinary Portland cement (OPC) and OPC/slag concretes when exposed to elevated temperatures, 400^{o}C and 800^{o}C, and based on these studies the following conclusions were made. The critical temperature of 400^{o}C has been reported for OPC paste. Above 400^{o}C, the paste hydrate $Ca(OH)_2$ dehydrates into CaO causing the OPC paste to shrink and crack. After cooling and in the presence of air moisture, CaO rehydrates into $Ca(OH)_2$, resulting in disintegration due to re-expansion of OPC paste. Therefore, their work assessed whether this also applies to OPC concretes. Two cooling methods were used: furnace and water cooling. Following the heat treatment/cooling method, compressive tests and Infrared (IR) spectroscopic studies were conducted. Results showed that after 400^{o}C, water cooling caused all concrete, regardless of the type of blended cement binder, a further 20% loss in the residual strength. After 800^{o}C, water cooling caused OPC concrete a further 14% loss while slag blends presented around 5% loss. IR indicated that the further loss observed in the OPC concrete is due to the accelerated CaO rehydration into $Ca(OH)_2$. Afterward, the non-wetted furnace cooled specimens were exposed to air moisture for one week, resulting in further strength loss of 13%. IR results suggested that slow rehydration of CaO occur with exposure to air moisture. In conclusion, water cooling caused more damage in OPC concrete, while the concrete that has not been wetted undergoes progressive deterioration. This indicates a need to monitor the non-wetted concrete after a fire event has occurred for potential further deterioration.

Bingol and Gul (2009), investigated the compressive strength of normal strength concrete at elevated temperatures up to 700◦C and the effect of cooling regimes were compared in this study. Thus, two different mixture groups with initial strengths of 20 and 35MPa were produced by using river sand, normal aggregate and Portland cement. Thirteen different temperature values were chosen from 50 to 700◦C. The specimens were heated for 3 h at each temperature. After heating, concretes were cooled to room temperature either in water rapidly or in laboratory conditions gradually. Strength loss was more significant on the specimens rapidly cooled in water. Both concrete mixtures lost a significant part of their initial strength when the temperature reached 700◦C.

Peng, *et al.*, (2008), conducted an experimental investigation on the effect of thermal shock during cooling on residual mechanical properties of fibre concrete exposed to elevated temperatures from 200◦C to 800 ◦C. Various cooling regimes were used including natural cooling, spraying water for a series of durations from 5 to 60 min, and quenching in water. The temperature determination results prove that the rapid cooling regimes such as quenching in water, or water spraying for 30 min or more, caused an action of ''thermal shock'' to concrete under elevated temperature, characterized by a high temperature decreasing rate ranged from 25 to 44 min/◦C. The experimental results indicate that, compared with natural cooling, thermal shock induced by water quenching and spraying water caused more severe damage to concrete, in terms of greater losses in compressive strength, tensile splitting strength, and fracture energy. The fact that the impact of spraying water for 30 min or more on mechanical properties was almost the same as that of water quenching, indicates that spraying water for 30 min or more could cause thermal shock to a similar degree to water quenching, which is in good agreement with the results of the temperature determination. Hybrid fibre (steel fibre and polypropylene fibre) can enhance residual strength and fracture energy of concrete subjected to thermal shock induced by rapid cooling from high temperatures up to 800◦C to room temperature.

MATERIALS AND METHODS

Economical mix proportions have been obtained from trial mixes to obtain slump value in the range of 50 – 75 mm. The properties of Ordinary Portland Cement, fine and coarse aggregates are detailed below.
Ordinary Portland Cement 43 grade, Brand Ultra Tech, was used for preparing the concrete specimens. River sand conforming to zone II (I.S 383-1970 grading requirements) with specific gravity 2.65 was used. Coarse aggregates with specific gravity 2.71 satisfying I.S 383-1970 grading requirements for graded aggregates was used.

Fly Ash

The fly ash used for the experiment is from Raichur and the specific gravity is 2.01.

Silica Fume (SF)

'Corniche SF' silica fume used which confirms to IS 15388:2003.
The physical and chemical properties of above materials are tabulated in table 1 and 2

Table 1: Physical properties of Silica Fume

Properties	**SF**
Fineness (m^2/kg)	19700
Specific Gravity	2.20
Density (kg/m^3)	650

Table 2: Chemical composition of Silica Fume (% by mass)

Chemical composition	**SF**
CaO	00.5
SiO_2	90.7
Al_2O_3	00.7
Fe_2O_3	02.2
MgO	01.5

Super-Plasticizer

Sulphonated napthalene polymer based high range water reducing admixture (HRWRA) 'CONPLAST 430' of FOSROC was used. The specific gravity of HRWRA is 1.18. This HRWRA is a brown liquid containing 41.34% solids.

TRIAL MIX DESIGN

The optimum mix proportion to be used for the experimental investigation is determined**.** Trial mix (0.42:1:1.639:0.876:2.045) i.e W/C : Cement : Fine Aggregate : 12.5 mm Coarse Aggregate : 20 mm

Coarse Aggregates, is used for the experiment as the desired strength of M40 is achieved with minimum cement content of 390 kg/m³ and a slump of 55 mm.
Based on the Concrete Mix Design trials, it is planned to cast 10 cm concrete cubes for four different proportions.

1. All OPC
2. 70% OPC , 30% Fly ash
3. 70%OPC, 25% Fly ash , 5% Silica fume
4. 70%OPC, 20% Fly ash, 10% Silica fume

For each series, 50 cubes have been cast and 28 days water cured with the intention of subjecting them to elevated temperatures.

Methodology
Table 3 gives the details of number of specimen required for conducting the exposure studies.

Table 3: Number of specimens to be tested for different temperatures and series

OPC only	Temperatures	70% OPC 30% FA	70% OPC 25% FA & 5% Silica Fume	70% OPC 20% FA & 10% Silica Fume
3	Room	3	3	3
3	150	3	3	3
3	300	3	3	3
3	450	3	3	3
3	600	3	3	3
3	750	3	3	3

A total of 12 cubes containing 3 each for four different series were kept in the electric furnace which were tested for residual compressive strength after the process of sudden quenching in water. Necessary precautionary measures were taken during placing of specimens and handling of specimens before testing. The specimens were subjected to sustained elevated temperatures from 150^0C to 750^0C in increments of 100^0C and in each case retention time was 1 hour. After subjecting to elevated temperature, the cubes were allowed to cool suddenly by quenching in water. For sudden cooling in water, after exposing the cubes to the required temperature, they were removed from the furnace and were placed in the tub of water which was allowed to cool till room temperature. Physical observation of appearance, colour and cracks, were noted before the weight loss of specimen was recorded for assessing percentage loss in water absorption. The destructive tests were performed for ascertaining residual compressive strength evaluation.

Electric Furnace Temperature Build Up
The specimens casted were subjected to elevated temperatures with the help of a Heating Furnace available at NITK Structures laboratory. The maximum temperature level that the furnace can operate at is 1200°C.
The specimens were placed in the furnace, target temperature are existed using the digital user phase and temperature increase is noted for every minute till it reaches the target temperature. The following fig shows the time vs temperature built up for variation for various elevated temperature.
Figure 2 shows the arrangement of specimens inside the heating furnace.

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Destructive testing of specimen were conducted after exposure and cooling by quenching, using an universal compression testing machine.

RESULTS AND DISCUSSION

Cracks

Appearance of cracks after an exposure of 450 ºC was seen on series B & C. After quenching of specimens after 600 ºC exposure, even series D showed visible cracks. No cracks were visible on any series for temperatures at and below 450°C. Prominent cracks were visible at almost all ranges of the mix later on.

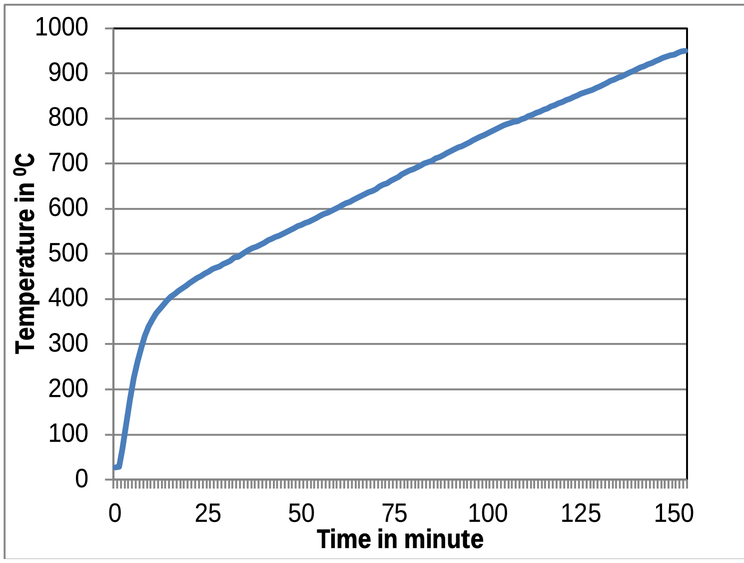

Figure 1: Temperature Vs Time

Figure 2: Specimens inside Heating Furnace

At 600°C, ‘C’ and ‘D’ ranges had highly visible and prolonged cracks on the surface, ‘A’ range cracks were comparable to that of C and ‘B’ range had minute cracks (almost Nil).

At 750°C, OPC showed prominent and prolonged cracks on the surface of the specimen. C and D series showed large cracks on the surface. Series B had less cracks compared to the remaining series due to the presence of only FlyAsh as mineral admixture.

Figure 3: Cracks in OPC (series A) at 750°C

Figure 4: Cracks in B series at 750

Figure 5: Cracks in Series C at 750^{o}C

Figure 6: Cracks in Series D at 750^{o}C

Weight Loss

Initial specimen weights were taken after 28 days of water curing. After exposure to various elevated temperatures and cooled by water quenching. The weights of the specimen were recorded to determine the percentage loss in weight.

For all the four compositions, the weight loss increases with increase in exposure temperature. It is highest for A series, *i.e.*, only OPC, and is lowest for B series, i.e for 70% OPC + 30% Fly Ash.

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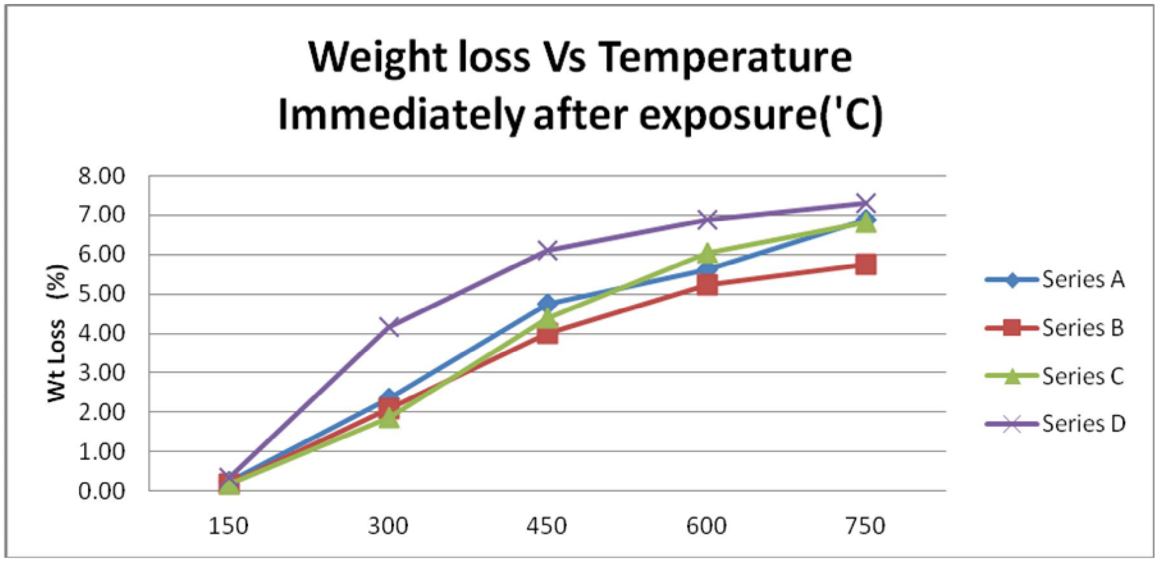

Figure 7: Variation of percentage loss in weight (immediately after exposure) with temperature

Compressive Strength

The graph between Compressive strength and the temperature is also shown in Figure 8. The graph between Residual strength and the temperature is shown in Figure 9.

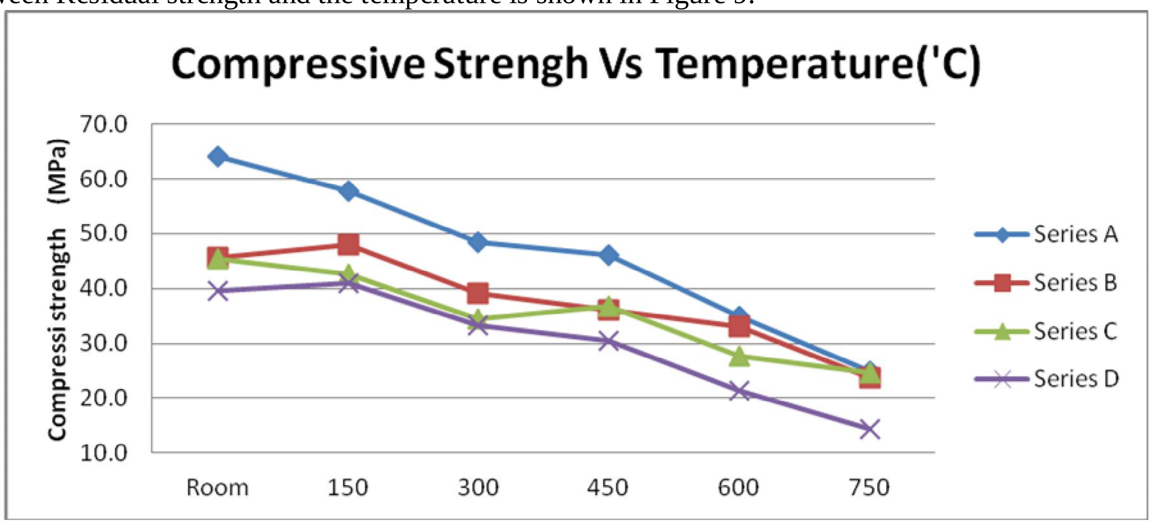

Figure 8: Variation of Compressive strength with temperature

From the above graphs, the residual strength after quenching is seen to be highest in the B series overall and lowest is seen in OPC (A series).

Fly ash inclusion reduces the $Ca(OH)_2$ content which is responsible for the reduction in cracks and hence rise in residual strength in the concrete. The lowest residual strength which showed a reduction of 64% was seen in Series D(OPC 70/FA20/SF10->Dense concrete) 750°C exposure. The concrete with better fire endurance was seen to be Series B (OPC 70/FA30) which is followed by series C(OPC 70/FA25/SF5).

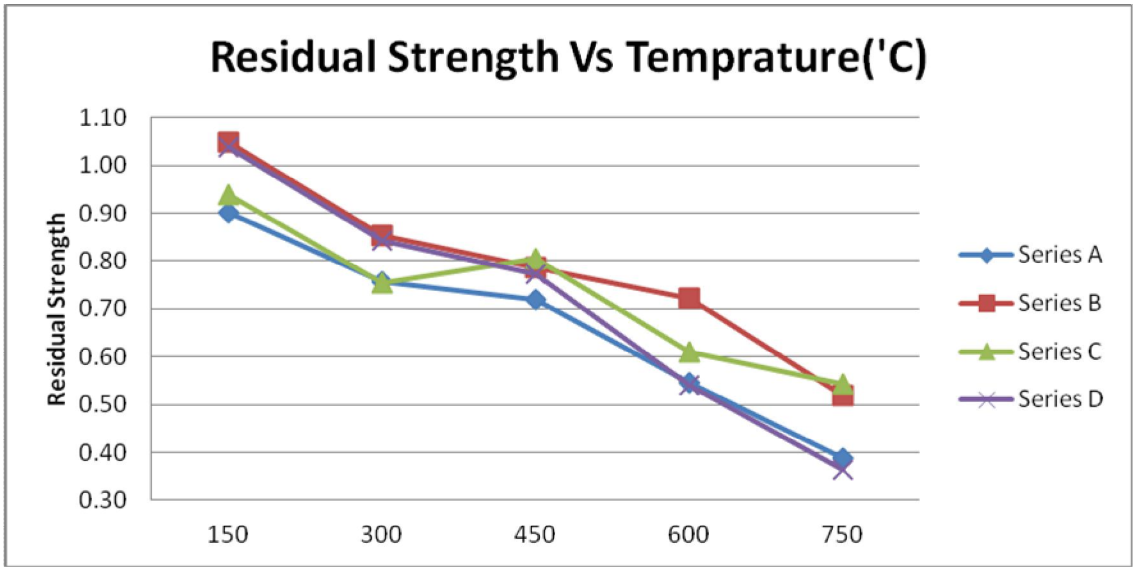

Figure 9: Variation of Residual strength with temperature

The increase of about 5% in Residual Strength at 150°C for series B & D can be attributed to the autoclaving effect i.e. as water gets evaporated to steam, it is trapped within the concrete and this increases the resistance to load.

Exposure at 150^0C has minimal effect on strength for all series.

After 450°C there is a sharp decrease in slope of the graph which indicates that strength reduction is faster at temperatures higher than that .This is mainly due to extensive degradation of concrete specimens at temperatures beyond 450^0C.

CONCLUSIONS

The total percentage weight loss of the specimen increases as the exposure temperature increases, for the present case of sudden cooling by water quenching.

The residual compressive strength generally decreases with increase in temperature except for series C at elevated temperature around 450^0C.

Series B (OPC 70/FA30) specimens show better fire endurance compared to the other series. An increase of 14% strength retention as compared to OPC is seen in this series at 750^0C.

Of the two SF replaced series, series D (OPC 70/FA20/SF10) is seen to have more fire endurance than the other. But a decrease of 64% is seen at 750^0C for this series.

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